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# Social cost of household emissions: cross-country comparison across the economic development spectrum

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# Abstract

Household consumption accounts for the largest share of the global anthropogenic greenhouse gases (GHG) emissions. The literature assessing the environmental impacts of household consumption is mostly focused on developed economies, thus, leaving a critical gap when it comes to assessing the impacts of household consumption and of related environmental policies in developing countries. Therefore, in order to fill this gap, this study analyzes household consumption-based emissions for high income, upper middle income, lower middle income, and low-income countries from six different geographical regions. It assesses the sector-wise CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O-footprints and evaluates their social costs. The study methodology employs an environmentally extended multiregional input-output model from the EORA26 database which uses a common 26-sector classification for all countries. The findings show that household consumption accounts for 48–85% of the national CO<sub>2</sub>-footprints. (The values are similar for CH<sub>4</sub> and N<sub>2</sub>O.) Developing economies have lower CO<sub>2</sub>-footprints of household final consumption than developed economies, but exert a higher pressure on the environment with respect to CH<sub>4</sub>- and N<sub>2</sub>O-footprints per capita. That highlights the necessity to focus environmental policies in developing countries on tackling CH<sub>4</sub> and N<sub>2</sub>O on a first-priority basis. The study also identifies those sectors where the social costs of aggregated  $CO_2$ ,  $CH_4$  and  $N_2O$  emissions make up a substantial share of the industries' output, thus, indicating the level of technological efficiency of the respective economies and the industries where more stringent environmental regulation should be implemented.

**Keywords** Environmentally extended multiregional input–output analysis · Social costs of emissions · Environmental impact of household consumption · Developing countries

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# **1** Introduction

The effects of human-induced climate change are being experienced worldwide (IPCC, 2022). Climate change has already caused a shift in geographical ranges and seasonal activities for many species. On the whole, the positive effects of climate change on crop yields, such as through carbon fertilization, have been outweighed by negative effects across different regions and crops (Pachauri & Meyer, 2014). Anthropogenic greenhouse gas (GHG) emissions are considered to be the main cause of the current observed climate change (Pachauri & Meyer, 2014).

Household consumption accounts for the largest share of the global GHG emissions worldwide. Recently, the consequences on the environment due to society's consumption behaviors have attracted policy attention to sustainable consumption and production (Cox et al., 2013). The focus of Sustainable Development Goal (SDG) 12 is to ensure responsible consumption and production (United Nations, 2020). Failure to achieve this SDG jeopardizes accomplishing the majority of the other SDGs (United Nations, 2020). At the same time, out of all of the SDGs, SDG 12 includes the largest number of indicators that cannot currently be monitored globally (Ritchie & Mispy, 2018), highlighting the need for researchers, policymakers and practitioners to contribute more to fill this critical gap. In this regard, without consumers' engagement, policymakers and industry leaders can only be partially successful in combating environmental problems (United Nations Division for Sustainable Development, 2013). Sustainable consumption has its main task in decreasing the depletion of natural resources and reduction in damage (Bilharz et al., 2008).

Consumers are not able to or cannot be motivated to act sustainably in all of the spheres; therefore, identifying the options with the most significant environmental impact through which consumers can make a difference is highly important. Doing so will help avoid spreading consumers' limited resources across many options that make only a marginal contribution to sustainable consumption (Bilharz et al., 2008).

Given the importance of identifying priority fields of action with major environmental relevance to consumers, assessing the environmental footprint of final household consumption and estimating its social costs are necessary. This kind of analysis is particularly valuable for developing countries with their catching up and rapid adoption of lifestyles of developed countries, taking into account that the majority of research on assessing the environmental impact of household consumption are conducted for either developed economies (e.g., Tukker & Jansen, 2006; Ivanova et al., 2016; Mach et al., 2018; Steinegger, 2019; Castellani et al., 2019; Moran et al., 2020; He et al., 2020; Feng et al., 2021; Zsuzsa Levay et al., 2021; Hassan et al., 2022) or China (e.g., Lei et al., 2022; Liu et al., 2021; Mi et al., 2020; Sun et al., 2021).

Today, the primary approaches in the environmental impact assessment of households are macroeconomic accounting and home economics (Spangenberg & Lorek, 2002). Macroeconomic accounting allocates all of the production inputs to producing consumption goods, including the usage of resources and the release of pollution to households as final users. Home economics assesses households' environmental impact on the basis of daily consumption activities with no regard for upstream impact generation (Spangenberg & Lorek, 2002). Spangenberg and Lorek (2002, p. 132) state that "any meaningful impact assessment must be based on a life cycle approach," which is why macroeconomic accounting that measures the economy's physical throughput is preferable.

Life cycle assessment (LCA) was first applied in the 1970s (Klöpffer & Grahl, 2014) as an instrument for quantitatively estimating the environmental impacts of goods and services that occur during their lifetimes (Steinegger, 2019). In subsequent years, many different types of LCAs were developed. However, the LCA approach still includes two drawbacks. First, LCA does not account for the emissions embodied in international trade; second, it does not show the environmental impact of one household per year (Steinegger, 2019). Environmentally extended input-output (EEIO) tables were created that relate environmental data to economic input-output tables to produce consumption-based indicators and to overcome the second disadvantage (Steinegger, 2019). The first EEIO analysis framework was developed in Isard et al. (1968) and Leontief (1970). At the same time, when EEIO is applied, the simplified assumption is used that imported goods are manufactured using the same production technology as domestic goods (Hertwich, 2011; Lenzen et al., 2006; Tukker & Jansen, 2006). This approach causes incorrect results, as demonstrated by Peters and Hertwich (2006) and Weber and Matthews (2008). EEIO needs to be extended to multiregional EEIO (EEMRIO), which takes into account international trade (Davis & Caldeira, 2010; Hertwich & Peters, 2009; Ivanova et al., 2016; Steinegger, 2019), to overcome this drawback.

EEMRIO analysis allows for interrelationships among the sectors in the global economy to be captured and the emissions embodied across products' value chains to be related to their final consumers (Kitzes, 2013; Wiedmann, 2009). EEIO (and EEMRIO) analysis traditionally assumes full consumer responsibility when allocating environmental impacts generated in the entire production chain of goods to the final consumers of these goods. A consumer makes the ultimate decision to buy these products (Lenzen et al., 2007) as via supply chains in the end, all production is linked to households (Moran et al., 2020). However, the concept of "shared responsibility" is more appropriate when deriving policy implications on the basis of this type of analysis because both consumers and producers make decisions that affect the final consumption environmental footprint.

When estimating the environmental impact associated with GHG emissions, the common practice is to convert the emissions to CO<sub>2</sub>-equivalent values using the Global Warming Potential (GWP) metric (e.g., Hertwich & Peters, 2009; Ivanova & Wood, 2020; Ivanova et al., 2016; Song et al., 2019; Tukker et al., 2013). This aggregation approach applies the same treatment to GHGs generated in different processes with various atmospheric residence times and potential for mitigation (Fernández-Amador et al., 2020). Moreover, aggregating GHGs using the GWP metric includes choosing a time horizon for aggregation, most commonly 100 years, although no scientific evidence exists to support the preference for this period over others (Fernández-Amador et al., 2020; Fesenfeld et al., 2018; Myhre et al., 2014). The results vary significantly depending on the time horizon. For example, in Fernández-Amador et al. (2020), the anthropogenic methane emissions during 1997–2014 were equal to either 30% or 95% of the GWP of  $CO_2$  emissions depending on whether a 100- or 20-year period was used for computing. In addition, such an aggregation using the GWP metric results in inconsistencies in the economic evaluation of GHGs. These inconsistencies occur because the economic estimate of climate damages associated with  $CO_2$  includes both a damage function with a power-law response to warming that increases over time and economic discounting with a diminishing value over time (Shindell et al., 2017). Because the impacts of non-CO<sub>2</sub> GHGs differ from those of carbon dioxide, an appropriate economic evaluation of the damages attributable to them needs consistency across time and impacts (Shindell et al., 2017).

Thus, a research gap exists in separately assessing the environmental impacts of household consumption with regard to different GHGs and performing the economic evaluation of these impacts. Using the EEMRIO analysis enables these impacts to be estimated with respect to different industries/commodities, allowing for the identification of not only priority fields of action for consumers, but also sectors with the largest mitigation potential for which a difference could be made from the production side. Another research gap lies in performing the aforementioned analysis for countries at different development levels, with a special focus on the least and medium developed countries because they are underrepresented in the EEMRIO analysis research.

In this study, the notion "footprint" is used in the meaning of "embodied emissions," that is emissions "produced by a product or service throughout its whole production process" (Zhang et al., 2020). This study addresses the research gaps previously discussed by fulfilling the following objectives:

- To evaluate the CO<sub>2</sub>-, CH<sub>4</sub>-, and N<sub>2</sub>O-footprints of household consumption for purposefully and carefully selected countries at different economic development levels and with different geographic settings;
- 2. To estimate the social costs of the corresponding footprints;
- 3. To identify key actionable policy lessons from such a comparative analysis.

Our study makes a contribution in a number of ways. First, it estimates the GHGs footprints of household consumption and their social costs separately for  $CO_2$ ,  $CH_4$ , and  $N_2O$  emissions and shows that this analysis improves the precision of the social costs evaluation and can result in a more targeted environmental policy based on the composition of the GHGs footprints. Second, to our best knowledge, it is the first research of environmental impact assessment using the EEMRIO framework in which a large number of developing countries are presented and compared. Third, in addition to defining the areas of high impact behavior for consumers, the article also identifies those sectors where the social costs of aggregated  $CO_2$ ,  $CH_4$  and  $N_2O$  emissions across the value chain make up a substantial share of the industries' output, thus, indicating the level of technological efficiency of the respective economies and the spheres where more stringent environmental regulation in relation to industries should be in place.

The study aims to provide a snapshot cross-country analysis and does not set as an objective to track the changes in time for a number of reasons. First, the input–output analysis relies on the assumption that there are no dramatic changes in the economic structure from the prior year to the target year (Wang et al., 2015). Second, although the concept of the Social Cost of Carbon dates back to 1980s, studies estimating them surged at the beginning of the twenty-first century (for example, Clarkson & Deyes, 2002; Etchart et al., 2012; Hope, 2011; Nordhaus, 2017; Stern, 2007; Tol, 2011) but were focused only on CO<sub>2</sub> emissions. The estimation of the social costs of non-CO<sub>2</sub> emissions have followed quite recently and are very moderate in number (for example, Marten & Newbold, 2012; Shindell, 2015; Shindell et al., 2017). As our study focuses on separate analysis of GHGs, using the social costs of non-CO<sub>2</sub> emissions together with the EEMRIO results based on 2015 data seems to be the most reasonable decision.

The remainder of the article is structured as follows. Section 2 presents the methodology, Sect. 3 summarizes and discusses the main results, and Sect. 4 outlines the conclusions. Section 5 describes the limitations and future research frontiers.

	Full EORA	EORA26	GTAP	EXIOBASE (version 3)	WIOD (release 2016)	OECD
Time coverage	1990-2021	1990–2021	2004, 2007, 2011, 2014	1995–2011	2000–2014	2005–2015
Countries	190	190	121	44	43	64
Sectors	National detail	26	65	163	56	36

 
 Table 1
 Characteristics of existing databases for EEMRIO analysis. Source https://worldmrio.com/; https:// www.gtap.agecon.purdue.edu/databases/v9/; https://www.oecd.org/sti/ind/input-outputtables.htm#IOTFig1; https://www.exiobase.eu/index.php/about-exiobase; http://www.wiod.org/home

# 2 Material and Methods

#### 2.1 Environmentally extended multiregional input–output analysis

A number of global databases allow EEMRIO analysis: EXIOBASE, full EORA and EORA26, Global Trade Analysis Project (GTAP), World Input–Output Database (WIOD), and the Organization for Economic Co-operation and Development Input–Output Tables (OECD). The major trade-off in these databases is between covering many countries and including a high level of harmonized sector details. EORA and GTAP are most suitable for analyses focusing on developing economies because they provide data on a larger set of countries than do all other databases (Table 1).

Although these global databases aim to achieve the same goal, various implementation details account for a significant divergence among the results obtained by researchers using different datasets (Moran & Wood, 2014). The main sources of divergence include differences in environmental production accounts and their allocation across sectors, estimations of sectoral inventories when empirical data are unavailable, and differences in economic structures and final demand. High sensitivity of the GHG-footprint in relation to perturbations in the final demand has been observed (Moran & Wood, 2014). Even after harmonizing environmental production accounts for  $CO_2$  emissions from fossil fuel burning among different models (EXIOBASE, WIOD, the OpenEU MRIO based on the GTAP, full EORA, and EORA26), Moran and Wood (2014) show that the difference between the model results still lies in the range 5–30% per country.

This study employs EORA26 (Lenzen et al., 2015) because it includes data for many developing countries and, in contrast to the full EORA, allows for a comparison among the same sectors of different countries. The analysis is based on the data from 2015 as it was the latest data available from EORA26 at the period when the study was carried out (2020–2021). As the economic structure does not change significantly from one year to another (Wang et al., 2015), the results of this research are still viable to the present time. To ensure the credibility of our estimates and to address the issue of EEIO results divergence among different datasets, the study applies the scenario method (see 2.2 Economic estimate of EEIO results).

Acquiring the following two types of raw data for the EEIO analysis is necessary: a sector-wise balanced input–output table in which the total outputs of each sector are equal to the total inputs to that sector and a measurement of direct environmental impacts attributable to each sector (Kitzes, 2013). The key assumptions of the EEMRIO analysis are

homogeneity and a fixed input structure. Homogeneity means that each 1 USD sold from a given sector to any other sector in the global economy and to final consumers represents the same product (or service) and bears an identical embodied environmental impact. As EEMRIO analyses are linear models, constant, fixed input proportions are required to produce a sector's output, thus, a fixed input structure is assumed (Kitzes, 2013). EORA26 EEMRIO also uses the industry technology assumption, that is, an industry employs the same technology to produce each of its products.

The general EEMRIO model used to estimate the emissions' intensities embodied in consumption per monetary unit is as follows:

$$F_i = f_i * (I - A)^{-1} \tag{1}$$

where  $F_i$ : the total intensity vector of emissions *i* embodied in the consumption across sectors, which contains information on the total amount of emissions *i* (in tons) generated anywhere in the global economy, in any sector, to eventually produce 1 USD of output to final consumers from a given sector.  $f_i$ : the transposed direct intensity vector of sectoral emissions *i* released per monetary unit of output. *I*: the identity matrix. *A*: the matrix of technical coefficients that represent a sector's intermediate inputs per unit of sectoral output;  $(I - A)^{-1}$  is also known as the Leontief inverse, the elements of which report the information on both direct and indirect inputs requirements to produce one unit of final demand.

The total embodied emissions i derived by consumption per sector are obtained as follows:

$$E_{ik} = F_i * y_k \tag{2}$$

where  $E_{ik}$ : the vector of sector-wise emissions *i* footprints caused each year by all of the sales to final demand category *k* in tons.  $y_k$ : the vector of final demand category *k* in units of monetary value. The EORA26 EEMRIO model has six categories of final demand: (1) household final consumption, (2) non-profit institutions serving households (NPISH), (3) government final consumption, (4) gross fixed capital formation, (5) changes in inventories, and (6) acquisitions less disposals of valuables. Then, the total emissions *i* footprint of household consumption per capita in a country is calculated as follows:

$$E_{i1}^{t} = \frac{\sum E_{i1}}{p} \tag{3}$$

where *p*: the total population of a country in 2015. The data were obtained from the United Nations, Department of Economic and Social Affairs (United Nations, 2019).

Here, the EEIO analysis is performed using the statistical program R version 4.0.2 (2020-06-22) (Bates et al., 2020).

# 2.2 Economic estimate of EEIO results

Social costs represent all direct and indirect losses incurred by third persons or the general public as a consequence of unrestricted economic activities (Kapp, 1963). The US government defines the social cost of carbon as being "intended to include (but not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change" (Interagency Working Group on Social Cost of Carbon, 2013). What concerns the social costs of non-CO<sub>2</sub>

Table 2Social costs of $CO_2$ , $CH_4$ , and $N_2O$ (USD per ton)	Discount rate	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O
(Shindell, 2015; Shindell et al., 2017)	3%	81.16	4109.52	42295.48
	1.4%	301.78	7487.44	70873.50

Original values were converted to USD 2015

emissions, they encompass the impacts on the same spheres (e.g., health, agriculture) even if their effects are exercised through processes different than those for  $CO_2$  (Shindell, 2015).

The choice of a discount rate plays an important role in evaluating future damages. Significant discussions have been generated about selecting the appropriate discount rate in analyses of climate change. Stern (2007) placed most of the importance on strong action now to combat climate change and used a discount rate of 1.4%. Nordhaus (2007) argued that selecting the discount rate should be consistent with the behavior reflected in market interest rates and preferred higher discount rates (3%; 4.3%).

To make the transition from analyzing the respective footprints in physical units to estimating them in monetary values, this study uses the results of the evaluation of the  $CO_2$ and  $CH_4$  social costs from Shindell et al. (2017) and the N<sub>2</sub>O social costs from Shindell (2015) under scenarios with the two discount rates 1.4% and 3% (Table 2), which use the DICE 2007 IAM damage function (Nordhaus, 2008).

The social costs are modeled over 350 years, but the results exhibit minimum sensitivity to variations beyond 150 years because of the warming limit (Shindell, 2015).<sup>1</sup>

Attaching the monetary value to the total emissions *i* footprint of a country's household consumption per capita and to the embodied emissions *i* derived from consumption per sector enables not only to perform their economic evaluation separately, but also to come to the aggregation of the respective emissions ( $CO_2$ ,  $CH_4$ ,  $N_2O$ ) without incurring any aggregation bias in contrast to the common practice of using  $CO_2$ -equivalent values based on the GWP metric:

$$E_1^{im} = \frac{\sum_{i=1}^3 \sum E_{i1} * S_i}{p}$$
(4)

where  $E_1^{m}$ : the aggregated footprint of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions of a country's household consumption per capita in monetary values.  $S_i$ : is the social costs of emissions *i*.

$$E_1^m = \sum_{i=1}^3 F_i * y_1 * S_i$$
(5)

where  $E_1^m$ : the vector of aggregated CO<sub>2</sub>-, CH<sub>4</sub>-, and N<sub>2</sub>O-footprints sector-wise caused each year by all of the sales to final demand category 1 (household final consumption).

<sup>&</sup>lt;sup>1</sup> Health-related effects are also included in social costs: (1) climate-health impacts from the altering climate for  $CO_2$ ,  $CH_4$ , and  $N_2O$ , and (2) composition-health impacts from degrading air quality (via ozone) for  $CH_4$ .

$$F^{m} = \sum_{i=1}^{3} f_{i} * (I - A)^{-1} * S_{i}$$
(6)

where  $F^m$ : the aggregated intensity vector of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions embodied in consumption across sectors, which shows the total social costs of these emissions (in monetary values) occurring anywhere in the economy, in any sector, to produce 1 USD of output to final consumers from a given sector. In this regard, emissions costs that amount to 40 cents and more for the production of 1 USD of output for a given sector show that more stringent environmental regulations should be considered across the value chain. As according to Nordhaus (2007), the social costs resulting from carbon emissions could equal the carbon tax in an optimal regime.

#### 2.3 Selection of countries for the analysis

Three criteria were applied for selecting the relevant countries:

- A) Data availability;
- B) Geographical diversity;
- C) Level of development.

According to the first criteria from the EORA26 EEMRIO table for 2015, only those countries were selected for which a sector-wise balance (a sector's input  $\approx$  a sector's output) is observed. One hundred and thirty-nine countries fulfilled this criterion. As a second criterion, the World Bank classification of geographical regions was used: (1) East Asia and Pacific, (2) Europe and Central Asia, (3) Latin America and Caribbean, (4) Middle East and North Africa, (5) North America, (6) South Asia and (7) Sub-Saharan Africa. For the third criterion, the current World Bank classification of countries by income level was applied: (1) high income (HIC), (2) upper middle income (UMC), (3) lower middle income (LMC) and low income (LIC).

Because this study demonstrates a special focus on developing economies, from each geographical region, one UMC and one LMC (or LIC) country were selected for the analysis. In North America, only HIC nations were found, which is why no country fulfilled the selection criteria for this region. In South Asia, the only UMC country was the Maldives, but it was considered not quite representative of the region. Instead, Sri Lanka was selected. Sri Lanka exhibited the second largest gross national income per capita in the region, although it was in the LMC category. As a result (Fig. 1), the countries selected in each region, on the one hand, fit the global pattern of UMC or LMC (or LIC) development (the blue vertical line in Fig. 1 separates the two groups of countries) and, on the other hand, exhibit at least a 30% difference between their GDP per capita at a regional level.

The only HIC country selected for the analysis was Germany, for two reasons. First, Germany exhibited one of the strictest permissible emissions levels for air pollutants on the continent. Second, in the European context, Germany played the leading role in the use of emission-reducing technologies (Weidner, 1995). Between 2007 and 2013, Germany tripled its number of clean technology patents (Smith, 2015), which is why benchmarking the results of developing economies using such a country is worthwhile.



**Fig. 1** Regional GDP per capita (excluding high income) and country GDP per capita for 2015 in current USD for selected economies. Author's construction based on World Bank (2020a, 2020b)

## 3 Results and discussion

Table 3 presents the structure of the  $CO_2$ -footprint by the final demand category in the countries under analysis. The structures of the CH<sub>4</sub>- and N<sub>2</sub>O-footprints do not differ much from the CO<sub>2</sub>-footprint (tables B.1 and B.2 in Appendix B). The share of the footprint attributable to the final household consumption varies between 48.37% and 84.56%. The share of household consumption takes the first place among all the other demand categories. Ivanova et al. (2016), who analyzed the GHG-footprint structure for a sample of mostly HIC and UMC countries using the EXIOBASE database for 2007, found that the share of households in the GHG-footprint amounted to  $65 \pm 7\%$ . The share of household consumption in the carbon footprint of the USA reached 70% in 2012 and in the United Kingdom—69% for the same year (Mi et al, 2020). In contrast to these findings, in some LMC economies (Myanmar and Pakistan), this share is definitely higher (approximately 84%). On the whole, except for Jordan and Kenya, in the sample of countries being analyzed, LIC and LMC economies tend to exhibit a higher share of household consumption in the CO<sub>2</sub>-footprint (67.63–84.56%) than HIC and UMC nations (48.37–65.69%). One possible reason is that the share of gross fixed capital formation is generally larger in UMC and HIC countries because they have much more construction and infrastructure development.

The CO<sub>2</sub>-, CH<sub>4</sub>-, and N<sub>2</sub>O-footprints attributable to household final consumption in physical units per capita reveal important differences among countries and the respective gases (Table 4). For illustrative purposes, the aggregated footprint in tons of CO<sub>2</sub>-equivalents is also presented. Appendix C provides the CO<sub>2</sub>-, CH<sub>4</sub>-, and N<sub>2</sub>O-footprints in physical units per capita and tons of CO<sub>2</sub>-equivalents of all demand categories (the national footprints). The CO<sub>2</sub>-footprints of household final consumption and all demand categories together (Appendix C) in developing countries (UMC and LMC/LIC) are much lower than in developed countries—in this example, Germany, which also finds its reflection in the amount of GHGs- footprints when all gases are converted to CO<sub>2</sub>-equivalents (Appendix C). At the same time, developing countries from different geographical regions (Europe and Central Asia, East Asia and Pacific, Sub-Saharan Africa, Middle East, and North Africa) outperform the developed countries regarding their CH<sub>4</sub>- and N<sub>2</sub>O-footprints per capita—a clear indication that more attention should be given to these gases when designing an environmental policy in non-HIC

Table 3 Structure of C(	D <sub>2</sub> -footprint by final	demand category in 2	2015, %. Source .	Authors' own calculatic	m using the EORA26 mod	el (Lenzen et al., 2015	•
Development level	Countries	Households	HSIdN	Governments	Gross fixed capital formation	Changes in inven- tories	Acquisitions less disposals of valu- ables
HIC	Germany	57.11	1.22	15.38	26.48	$-0.38^{a}$	0.19
UMC	Belarus <sup>b</sup>	65.69	1.01	12.28	20.97	0.05	°-1
LIC	Tajikistan	73.02	9.11	7.61	6.07	0.68	3.51
LMC	Myanmar	84.31	1.35	7.15	6.80	0.35	0.04
UMC	Thailand	48.37	2.77	9.85	22.95	12.41	3.64
LMC	Honduras	70.29	4.79	6.85	15.37	0.97	1.73
UMC	Peru	57.50	3.84	10.01	23.48	1.30	3.86
LMC	Morocco	67.63	3.07	9.66	17.81	-0.21	2.05
UMC	Jordan	70.72	6.41	9.10	10.97	0.41	2.40
LMC	Sri Lanka	70.01	5.29	5.89	15.17	0.44	3.19
LMC	Pakistan	84.56	1.03	4.92	8.11	0.79	0.59
LMC	Kenya	56.49	11.83	11.85	17.37	0.27	2.18
UMC	Namibia	52.92	11.61	13.91	15.65	0.23	5.67
<sup>a</sup> The negative values in that is, emissions from <sup>b</sup> Amendix A presents of	the "Changes in inv the production of the	ventories" category in is part of the gross ou rial on the FEIO mode	dicate that part o tput were saved	f the gross output "was	supplied by a drawdown	of existing inventory"	(Lenzen et al., 2015);
<sup>°</sup> The EEIO model base model, except for the "	d on the input-output acquisitions less disp	ut table from the Natio osals of valuables."	onal Statistical C	ommittee of the Repub	dic of Belarus includes the	same categories as th	e EORA26 EEMRIO

**Table 4**  $CO_2$ <sup>-</sup>,  $CH_4$ <sup>-</sup>, and  $N_2O$ -footprints of household final consumption in physical units per capita and tons of  $CO_2$ -equivalents in 2015. *Source* Authors' own calculation using the EORA26 model (Lenzen et al., 2015)

Countries	CO <sub>2</sub> -footprint (tons per capita)	CH <sub>4</sub> -footprint (tons per capita)	N <sub>2</sub> O-footprint (tons per capita)	Aggregate footprint of $CO_2$ , $CH_4$ , and $N_2O$ emissions (in tons of $CO_2$ -equivalents per capita)
Germany	5.81	0.0319	0.0013	7.04
Belarus	3.05	0.0335	0.0023	4.59
Tajikistan	0.50	0.0213	0.0011	1.38
Myanmar	0.35	0.0474	0.0011	1.97
Thailand	2.05	0.0221	0.0005	2.81
Honduras	0.86	0.0192	0.0007	1.58
Peru	1.45	0.0220	0.0009	2.31
Morocco	1.11	0.0158	0.0017	2.00
Jordan	2.12	0.0147	0.0004	2.65
Sri Lanka	0.96	0.0122	0.0004	1.41
Pakistan	0.71	0.0257	0.0007	1.63
Kenya	0.31	0.0172	0.0006	0.94
Namibia	2.04	0.0693	0.0025	4.65

\*As it has been mentioned in our definition of 'footprint', these results include embodied emissions and do not include direct emissions from household consumption.

countries. The data from the World Bank's Carbon Pricing Dashboard (World Bank, 2020b) show that only four developing countries in 2015 (Bulgaria (UMC), Kazakhstan (UMC), Mexico (UMC), and Ukraine (LMC)) had some sort of GHG emissions legislation. From the aforementioned countries, only Bulgaria as a member of the European Union implemented regulations for  $CO_2$  and  $N_2O$  emissions; the legislation for all other economies concerned only  $CO_2$  emissions.

Our findings about the importance to bring  $CH_4$  emissions into a policy discourse are in line with the United Nations Environment Programme and Climate and Clean Air Coalition (2021) which suggests that climate change could be mitigated at decadal time scales by methane emissions reductions. Fernández-Amador et al. (2020) as well point out that although being important for global warming, methane has been to a large extent absent from economic and political debates and not targeted by environmental policies.

Figures 2 and 3 present the aggregated footprint for  $CO_2$ ,  $CH_4$ , and  $N_2O$  emissions of household consumption per capita in monetary values at 3% and 1.4% discount rates, respectively. At a 3% discount rate, Tajikistan, Myanmar, Honduras, Pakistan, Kenya, and Namibia exhibit a higher share of  $CH_4$  than  $CO_2$  in the aggregated footprint of household consumption. In this scenario, the contribution of  $CH_4$  to the footprint in Myanmar is the largest, at 72.22%. In contrast, it is the lowest in Germany, at 19.95%. It is difficult to compare our results with other research findings directly, as the majority of research does not disaggregate the GHG emissions footprint into separate gases. Nevertheless, literature on spatial distribution of  $CH_4$  emissions can be used to back up our findings. According to Stavert et al. (2021), a steady decline is observed in  $CH_4$ emissions in Europe between 2000 and 2017 but Southeast Asia and South Asia are among the top emitting regions. Reductions in European  $CH_4$  emissions could be linked



**Fig.2** Aggregated footprint of household consumption per capita in 2015 valued at 3% discount rate in USD per capita. *Source* Authors' own calculation using the EORA26 model (Lenzen et al., 2015)



**Fig.3** Aggregated footprint of household consumption per capita in 2015 valued at 1.4% discount rate in USD per capita. *Source* Authors' own calculation using the EORA26 model (Lenzen et al., 2015)

to decreases in emissions from livestock driven by the EU common agricultural policy (CAP) reforms (EUROSTAT, 2017) and in emissions from solid waste due to the EU Landfill Directive 1999/31/EC (EUROSTAT, 2014).

Among the countries being analyzed at a 3% discount rate, the share of  $N_2O$  is the highest in Morocco (31.37%) and Tajikistan (26.53%). The relative contribution of CH<sub>4</sub> and  $N_2O$  to the aggregated footprint is observed to also diminish as the discount rate decreases. Nevertheless, even at a 1.4% discount rate in Tajikistan (41.24%), Myanmar (65.92%), and Kenya (49.01%), the share of CH<sub>4</sub> is still larger than that of CO<sub>2</sub>. Germany, Namibia, and Belarus are the leaders in the aggregated footprint for CO<sub>2</sub>, CH<sub>4</sub>, and  $N_2O$  of household consumption per capita in all scenarios. At the 3% discount rate, Germany takes first place, followed by Namibia and Belarus. At the 1.4% discount rate, Belarus surpasses Namibia, but Germany remains in the lead. At the 3% discount rate, Kenya and Sri Lanka demonstrate the lowest aggregated footprint, but it is Kenya and Tajikistan at the 1.4% discount rate. Depending on the scenario, the footprint in Kenya is from 5.48 (at 3%) to 7.93 (at 1.4%) times lower than the largest footprint in the given scenario.

Attention should be paid to the fact that the footprint of household consumption converted to  $CO_2$ -equivalents and estimated at the  $CO_2$  rate either underestimates or overestimates the true value of social costs calculated on the basis of the separate rates for  $CO_2$ ,  $CH_4$ , and  $N_2O$ . At the 3% discount rate, the  $CO_2$ -equivalent footprint underestimates the impact from 1.15 (in Germany) to 1.69 (in Myanmar) times. The 1.4% discount rate represents the scenario in which the difference between two estimations is at its minimum and for which the true impact is lower (1.99–9.37%) than that estimated with the help of  $CO_2$ -equivalents. When estimating the social costs of emissions embodied in household consumption and other final demand categories, separately valuing different GHGs is important.

The research findings from the developed countries (Spangenberg & Lorek, 2002; Tukker & Jansen, 2006) show that building/housing, mobility, and food are the most resourceintensive areas of household consumption. Table 5 provides the aggregated footprint for  $CO_2$ ,  $CH_4$ , and  $N_2O$  of the household consumption per capita in monetary values (at the 1.4% discount rate) in the aforementioned areas and in the "Textiles and Wearing Apparel" and "Agriculture" sectors. Appendix D contains more detailed information on the embodied emissions of household consumption in different sectors at the 1.4% and 3% discount rates for each country being analyzed. The results show that not only building/housing (which can be connected to the "Electricity, Gas and Water" category) and food and mobility (which can be represented by the "Transport" category), but also clothing (which can be represented by the "Textiles and Wearing Apparel" category) and agriculture belong to the sectors with a substantial household consumption impact. In this regard, clothing and agriculture should also be added to the spheres in which consumers can make a difference and could be stimulated to act more sustainably. It is especially important for developing countries, in which agriculture is one of the key sectors. According to Stavert et al. (2021),  $CH_4$  emissions in East Asia and Pacific and in Latin America come mostly from agriculture and waste sectors and wetlands; in South Asia, the majority of these emissions are of agriculture and waste origin.

The highest variation in the aggregated footprints is observed in the "Electricity, Gas and Water" category, from 2.44 USD per capita in Kenya to 533.82 USD per capita in Belarus at the 1.4% discount rate. The reason for this variation is that the electricity mix options among the countries under analysis are very diverse. Belarus and Namibia exhibit the largest aggregated footprint in this category. Except for Germany, Thailand, Peru, and Kenya, the impact from "Electricity, Gas and Water" outperforms all other

1.4%	Electricity	', gas and water	Food and	beverages	Transport		Textiles an	d wearing apparel	Agricultu	ą
	Total	% of Import	Total	% of Import	Total	% of Import	Total	% of Import	Total	% of Import
Germany	53.85	0.59	233.53	32.57	79.93	21.05	214.71	88.23	45.05	62.78
Belarus <sup>a</sup>	533.82	I	147.33	I	30.34	I	24.51	I	41.33	I
Tajikistan	184.02	1.68	14.96	21.41	9.82	59.34	9.84	76.40	1.06	43.88
Myanmar	404.65	0.00	19.26	0.00	3.98	0.01	2.87	0.06	1.93	0.02
Thailand	22.34	0.21	125.04	5.85	59.58	13.97	96.18	11.35	17.58	5.31
Honduras	225.31	0.09	27.68	14.88	9.37	40.26	10.46	70.75	3.00	21.12
Peru	9.14	0.19	129.59	3.45	44.19	7.99	46.76	7.38	29.96	2.72
Morocco	325.29	0.01	30.73	5.18	8.02	19.11	14.01	61.60	3.52	9.42
Jordan	426.33	0.03	48.75	16.60	15.53	42.22	44.47	88.90	6.16	22.68
Sri Lanka	241.09	0.02	20.20	19.10	7.28	35.36	13.06	76.81	3.24	12.69
Pakistan	240.18	0.00	21.51	1.22	6.11	7.25	5.47	18.89	1.66	4.63
Kenya	2.44	0.83	47.64	3.10	48.20	15.71	8.03	25.77	47.65	1.92
Namibia	527.31	0.08	75.48	26.86	38.60	42.94	45.97	80.66	9.48	46.63

**Table 5** Aggregated  $CO_2$ ,  $CH_4$ , and  $N_2O$  footprint of household consumption valued at the 1.4% discount rate in various sectors (in USD per capita) in 2015. Source Authors' own calculation using the FOR 3.56 model (*Tenzen et al.* 2015).



**Fig. 4** Sectors with the highest social costs of aggregated emissions per 1 USD of output (in USD per 1 USD of output) at the 1.4% discount rate in 2015. Blue represents  $CO_2$ , red—CH<sub>4</sub>, green—N<sub>2</sub>O. *Source:* Authors' own calculation using the EORA26 model (Lenzen et al., 2015) and the data from National Statistical Committee of the Republic of Belarus (2020)

categories. The significant diversity in the aggregated footprint values for "Electricity, Gas and Water" among the countries and the fact that the footprint is relatively small for Germany point out the existence of possibilities to bring it down substantially.

In the "Textiles and Wearing Apparel" category, the largest share of the imported footprint is observed. In HIC and UMC nations, the aggregated footprint for this sector is larger than in LMC/LIC countries across all geographical regions (except for Sri Lanka). The situation is similar for "Food and Beverages" but within each separate geographical region; every presented UMC country exhibits a larger aggregated footprint in the "Food and Beverages" sector than an LMC (or LIC) nation in the same region (except for South Asia). This finding indicates that countries tend to exert a stronger environmental impact in the clothing and food sectors as their development levels increase. From a policy perspective, this moment should not be missed to promote more sustainable consumption in these two areas.

At the 3% discount rate in Myanmar, Pakistan, and Kenya in all of the represented sectors, in Tajikistan and Honduras in "Electricity, Gas and Water," "Food and Beverages," and "Agriculture," and in Namibia in "Electricity, Gas and Water" and "Food and Beverages" (Appendix D), the  $CH_4$  content in the aggregated footprint for  $CO_2$ ,  $CH_4$ , and  $N_2O$  of the household consumption is larger than  $CO_2$ . This finding again implies that with respect to policies, much more attention should be given to the  $CH_4$ -footprint and its reduction in LMC and LIC countries.

Figure 4 represents the sectors (five for each country being analyzed) with the highest social cost of aggregated  $CO_2$ ,  $CH_4$ , and  $N_2O$  emissions across the value chain to produce 1 USD of output to final consumers at the 1.4% discount rate. Appendix E presents the values for the 3% discount rate. The analysis of these sectors indicates the level of technological efficiency of the respective economies.

In Belarus, Tajikistan, Myanmar, Honduras, Morocco, Jordan, Sri Lanka, Pakistan, and Namibia, the social costs of the emissions from the "Electricity, Gas and Water" sector exceed its output already at the 3% discount rate. Moreover, "Electricity, Gas and Water" is the only sector for which the social costs of the aggregated emissions surpass the outcome at the 1.4% discount rate in all of the aforementioned countries (ranging from 5.03 USD in Sri Lanka to 37.03 USD per 1 USD of output in Myanmar). Therefore, this sector should be given central importance when developing GHG emissions reduction industrial policies in the given countries. In this regard, there is a lot of potential in applying renewable energy on a large scale (Le et al., 2022). It is worth emphasizing that in Tajikistan, Myanmar, Honduras, Pakistan, and Namibia, the share of  $CH_4$  in the social costs of the aggregated emissions from "Electricity, Gas and Water" is higher than the share of  $CO_2$ at the 3% discount rate. In Tajikistan, Myanmar, and Namibia, this share continues to be higher even at the 1.4% discount rate, implying that developing countries' energy policies should be much more oriented to decreasing  $CH_4$  emissions. Germany, Thailand, Peru, and Kenya do not exhibit problems with the technological efficiency of the "Electricity, Gas and Water" sector.

Other sectors should also be considered when designing the environmental policy; however, because the social costs of their emissions exceed 40 cents at the 1.4% discount rate (i.e., 40% of their output value), the measures are not that urgent in comparison with "Electricity, Gas and Water." The most common of these sectors for the countries being analyzed are "Recycling"<sup>2</sup> (the social costs of its emissions surpass or are close to 40 cents per 1 USD of the output in Belarus, Myanmar, Honduras, Morocco, Pakistan, and Namibia), "Metal Products" (the social costs of its emissions surpass or are close to 40 cents per 1 USD of the output in Belarus, Tajikistan, Myanmar, Honduras, Morocco, Pakistan, and Kenya), "Petroleum, Chemical and Non-Metallic Mineral Products" (the social costs of its emissions surpass or are close to 40 cents per 1 USD of the output in Myanmar, Honduras, Morocco, Pakistan, Kenya, and Namibia). In the "Metal Products" sector at the 1.4% discount rate in Tajikistan, Myanmar, and Kenya (out of all of the countries with social costs of emissions that surpass or are close to 40 cents per 1 USD of the output), the social costs of cmissions that surpass or are close to 40 cents per 1 USD of the output), the social costs of CH<sub>4</sub> emissions per 1 USD of output are higher than of CO<sub>2</sub>.

Among all of the countries under analysis, Germany demonstrates the highest technological efficiency regarding GHG emissions. At the 1.4% discount rate, the social costs of the GHG emissions from the sectors with the highest social cost of aggregated CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions across the value chain do not exceed 0.15 USD per 1 USD of output. Germany is followed by Peru for which the costs do not exceed 0.26 USD per 1 USD of output, Jordan—with the highest costs of 0.28 USD (except for the "Electricity, Gas and Water" sector), and Sri Lanka—with the highest costs of 0.30 USD (except for the "Electricity, Gas and Water" sector) at the 1.4% discount rate.

Germany is ahead of the other countries in terms of technological efficiency. Its environmental regulations for air pollutants are also some of the strictest on the continent. At the same time, its aggregated footprint for  $CO_2$ ,  $CH_4$ , and  $N_2O$  of household consumption per capita in monetary values at the 3% and 1.4% discount rates is the largest among

<sup>&</sup>lt;sup>2</sup> In Belarus, this sector is represented under the "Public, social and personal services" category.

all countries under analysis. This finding brings us to the most important conclusion of this study: technological efficiency and environmental regulations alone are not sufficient for sustainable consumption, and more focus should be placed on the change in consumers' behavior needed to achieve it. Greenford et al. (2020) has also arrived to the similar conclusion in their research showing that technological efficiency and shifting economic activity to services will not be of great help to reduce environmental impacts and for that prevailing patterns of consumption should be addressed.

# 4 Conclusions

This paper provides insights into the environmental impact of  $CO_2$ ,  $CH_4$ , and  $N_2O$  embodied emissions of household consumption and their social costs from 12 UMC and LMC/ LIC countries in six different geographical regions benchmarked with Germany. Its main contribution is the analysis of GHGs separately rather than aggregated across the economic development spectrum. The GHGs specific analysis allows for the consideration of their peculiarities and, thus, more precisely estimating their social costs and as a result developing a more targeted and multidirectional environmental policy which in the short term should tackle emissions such as CH<sub>4</sub> with a near-term impact and should be oriented in the long term on emissions with larger effects over long periods (such as  $CO_2$  and  $N_2O$ ). In addition, the study also identifies those sectors where the social costs of aggregated  $CO_2$ ,  $CH_4$  and  $N_2O$  emissions across the value chain make up a substantial share of the industries' output, thus, indicating the level of technological efficiency of the respective economies and the spheres where more stringent environmental regulation in relation to industries should be in place. The overall conclusion of the study suggest that to reach sustainable development alongside with technological efficiency and environment regulation behavior change in the population should be addressed.

LIC/LMC economies tend to have a higher share of household consumption in the national CO<sub>2</sub>-footprint structure (67.63–84.56%) than HIC and UMC nations (48.37–65.69%). This comparison is also applicable for the national CH<sub>4</sub>-footprint and N<sub>2</sub>O-footprint structure. In this regard, environmental policies in LIC/LMC economies should be, first of all, oriented toward the population's behavioral change. This finding also implies the possibility that when more infrastructure starts to be developed in LIC/LMC countries, it could be from the very beginning done with the application of sustainable technologies.

Developing economies in contrast to the developed ones have much lower  $CO_2$ -footprints of household final consumption but exert a higher pressure on the environment with respect to  $CH_{4^-}$  and  $N_2O$ -footprints per capita. That highlights the necessity to focus environmental policies in developing countries on tackling  $CH_4$  and  $N_2O$  on a first-priority basis.

In developing countries, areas of high impact consumer behaviors, in addition to housing/building, food, and mobility (these areas were defined on the basis of the research on developed countries), also include clothing and agriculture. Effective GHG emission reduction policies should stimulate consumers to act sustainably in these areas, which will contribute to achieving SDG 12. The findings also show that the aggregated footprint of the  $CO_2$ ,  $CH_4$ , and  $N_2O$  emissions of household consumption per capita in UMC countries is higher for the "Textiles and Wearing Apparel" and "Food and Beverages" sectors than in LMC/LIC countries of the same geographical region (except for South Asia). Therefore, when these LMC/LIC countries increase their development levels, their environmental impact in the clothing and food sectors will possibly grow. From a policy perspective, this moment should not be missed to promote more sustainable consumption in these two areas.

The "Electricity, Gas and Water" sector exhibits social costs of the  $CO_2$ ,  $CH_4$ , and  $N_2O$  emissions that surpass its output already at the 3% discount rate in nine out of 13 countries being analyzed, bringing attention to the urgent necessity to increase this sector's technological efficiency regarding GHGs in the respective economies. The other sectors that have problems with the level of technological efficiency and that should be under more stringent environmental regulations across the value chain include "Recycling," "Metal Products," "Petroleum, Chemical and Non-Metallic Mineral Products."

# 5 Limitations and future research frontiers

The limitations of this study mostly stem from those inherent to the EEIO analysis. One of the biggest limitations of the EEIO approach is based on its homogeneity assumption, i.e., that each sector in the economy produces a single, homogenous item of goods or service (Kitzes, 2013). Thus, a product sold from a given industry to another industry or to its final consumers is assumed to be the same and carry an identical environmental impact (Kitzes, 2013). An EEIO table with a larger degree of sectors' disaggregation can contribute to improving the precision of the results regarding this assumption.

Greater effort should be made to achieve a sector-wise balance (a sector's input  $\approx$  a sector's output) for countries in global EEMRIO models and to improve the convergence of the results among different models. Better allocation of territorial emissions among the sectors will help raise the precision of the footprints of all final demand categories.

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**Data Availability** The dataset analyzed during the current study for all the countries except Belarus is available in https://worldmrio.com/eora26/. The dataset generated during the current study for Belarus is available from the corresponding author on a reasonable request.

# Declarations

**Conflict of interest** The authors have no conflict of interest to declare that are relevant to the content of this article.

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