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Research article

Exploring the rebound effect in Spain through a multisectoral framework

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ABSTRACT

This study estimates projected CO2 emissions based on energy efficiency improvements and the rebound effect. It analyzes the contribution of households, categorized by income deciles, and sectors to emissions, exploring various scenarios related to energy efficiency and the rebound effect. Using the social accounting matrix, the study examines how these scenarios influence emissions across income groups and offers insights into the relationship between energy efficiency, household income, and emissions. The results show that households in deciles VII and X are the largest emitters, and that improvements in energy efficiency in housing, manufacturing, and transportation lead to increased savings, which are spent across sectors based on household income, offsetting efficiency gains. Additionally, the rebound effect does not significantly impact the consumption income of most sectors. These findings provide important implications for policy development, particularly regarding sector-specific emissions and household income levels.

1. Introduction

Throughout history, human energy use has evolved significantly, transitioning from wood in the medieval periods to charcoal by the 1830s. Charcoal was later replaced with oil, nuclear energy, and natural gas in the 20th century (Dunphy et al., 2025). However, a significant portion of the world has yet to begin a transition to low-carbon energy sources. These regions continue to prioritize energy supply security and economic development over the reduction of greenhouse gas (GHG) emissions. Instead, they tend to focus on mitigating urban pollution (Eyl-Mazzega and Mathieu, 2020). Economic growth is accompanied by energy consumption, and there is evidence supporting causal or correlational links between the two (Soytas et al., 2007; Soytas and Sari, 2009; Odhiambo, 2012; Naranyan et al., 2016).

According to Soytas et al. (2007), the primary causes of global warming are GHG emissions, especially CO_2 emissions, which are associated with economic growth but lead to environmental degradation. Industrial activities, such as steel, cement, and chemical production, heavily rely on fossil fuels, leading to increased CO_2 emissions despite existing decarbonization targets (Sarma et al., 2024). Efforts to curb these emissions and their impacts on the environment have been initiated, including the Paris Agreement and the Tokyo Protocol, with primary goals of limiting the increase in the global average temperature to 1.5 °C above pre-industrial levels and reducing GHG emissions by 5% compared with 1990 levels, respectively (Leggett, 2020). However, measures undertaken to achieve the goals of the Paris Agreement and the Tokyo Protocol cannot be successful without an associated cost for CO_2 emissions that motivates the use of clean energy (Luciani, 2022).

According to the International Energy Agency (IEA), a high proportion of renewable energy is linked to low electricity prices and increased efficiency and electrification of heating, which has alleviated the economic consequences of transition to renewable energy for some consumers. Considering the high prices of other energy sources, policy responses are rapidly prioritizing clean, secure energy systems, and the benefits of improved energy efficiency are driving behavioral and technological changes aimed at reducing energy consumption in some countries (IEA, 2022). The International Renewable Energy Agency (2019) examines the current policy pathways and proposes a cleaner, more climate-resilient alternative, offering an ambitious energy transition to renewable energy sources and related technologies. This energy transition is expected to reduce total emissions by 70% compared with estimates of current plans. To achieve this, current investment estimates must be modified by doubling investment in renewable energy generation and quadrupling investment in energy efficiency. In addition, as

Abbreviations: GHG, Greenhouse Gas; IEA, International Energy Agency; SAM, Social Accounting Matrix; HBS, Household Budget Survey; LCS, Living Conditions Survey; EU, European Union.

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solar and wind energy and high-efficiency heat pumps gain popularity, investments in energy systems and infrastructure technology (e.g., transportation, industry, and buildings) will be essential. For example, Solà et al. (2021) note that current investment levels are insufficient owing to shortcomings in the market (including a lack of information), energy use, investment behavior, and other factors such as social norms. In addition to investment levels, some clean energy alternatives are becoming cheaper than carbon-intensive fuels even without the imposed costs, potentially justifying market-driven shifts; thus, policies for promoting clean energies may not be necessary (Luciani, 2022).

Notably, energy efficiency improvements can have a “rebound” effect, which is the difference between the expected and actual reduction in energy consumption attributable to efficiency improvements (Gillingham et al., 2024). This phenomenon, observed during resource utilization, clarifies the discrepancy between expected and actual environmental benefits resulting from energy efficiency measures (Vivanco et al., 2016). However, the rebound effect does not clarify whether efficiency gains derived from technical improvements affect economic costs or whether they are a result of efficient policies with significant economic costs (Berkhout et al., 2000). Quantifications of the rebound effect in some sectors, such as the housing sector, tend to estimate the real environmental benefits of efficiency measures in the sector (Shinde et al., 2021). Energy price and household income also play an important role in the rebound effect (Copiello and Gabrielli, 2017).

Although most emissions originate from industrial activities, residential buildings in the European Union account for 24% of total energy consumption (European Commission, 2016). Households’ energy-saving behavior and investments in retrofitting to improve energy efficiency are determined by their income level. That is, unlike middle- or high-income households, low-income households tend to prioritize energy conservation through daily activities rather than investments in retrofitting (Trotta, 2018), thereby contributing to greater energy poverty (Galvin, 2019). In addition, high-income households in residential buildings consume more energy for heating purposes because they have more heating appliances and more available space (Huo et al., 2021).

Spain is one of the European countries producing significant amounts of solar and wind energy (Dogan and Seker, 2016), which represent 20% of the national energy mix (Baroni, 2022). One of Spain’s goals for 2050 (Agenda España, 2025) is to become a carbon-neutral, sustainable, and climate change–resilient society. Despite uncertainties, a 90% reduction in GHG emissions by 2050 remains a critical objective. However, changes in consumption patterns may offset the efficiency gains brought about by technological developments in production processes. In other words, increased resource use and waste generation may cause a rebound effect. The latest United Nations report on the global context of buildings and construction (United Nations Environment Programme, 2022) reveals that while investments toward lowering the energy intensity of buildings have increased, total energy consumption and CO_2 emissions in the sector have risen above pre-pandemic levels. Specifically, energy demand in the construction sector has increased by 4% since 2020, the highest increase in the last 10 years. In other words, the Paris Agreement targets for decarbonization by 2050 are not being met in the buildings and construction sector.

We aim to analyze the energy efficiency forecast for 2050 through household consumption and CO_2 emissions according to household income. For this purpose, we compare emission projections with and without the rebound effect (following Cansino et al., 2022). More specifically, using 2016—the year from which the social accounting matrix (SAM) has been available—as a reference, the most polluting production sectors are identified in both scenarios. Finally, we investigate whether the rebound effect impacts household incomes in the most polluting sectors (owing to different consumption patterns).

This study addresses key questions regarding the contribution of households, categorized by income deciles, and economic sectors to CO_2 emissions. It explores scenarios involving improvements in energy efficiency in specific sectors, examining the potential for a rebound effect in these scenarios. Additionally, the study investigates whether the rebound effect is associated with the emissions generated by individual household income groups and how this relationship varies across household income levels. In addition to expanding the literature on energy efficiency and household income, this work introduces an innovative use of the SAM to compare emission projections. Furthermore, it discusses the impact of the rebound effect on emissions according to household income, offering valuable insights into this critical issue.

The paper is divided into five sections: The second section provides a review of the literature. The third section outlines the methodology. The fourth section describes the proposed scenarios and presents their results. Finally, the fifth section presents a discussion of the results and the main conclusions.

2. Literature review

This section focuses on studies related to the rebound effect and its impact on energy efficiency. These studies are based on input–output models that analyze energy issues as a reflection of the effects of intersectoral relations within the production system. These effects are considered in this research.

The effectiveness of energy efficiency measures is closely linked to the rebound effect, as demonstrated by various studies worldwide. Thomas and Azevedo (2013) find that in the United States, the rebound effect tends to increase as incomes rise, although this relationship is influenced by regional energy prices, baseline energy consumption levels, and income variations. In China, Wang et al., (2016) report direct and indirect rebound effects of 46% and 56%, respectively, for long-term residential electricity use. Additionally, in rural China, Li et al., (2018) demonstrate that reduced transportation costs lead to increased household demand, particularly among wealthier households, who use transportation services more frequently. Shinde et al. (2022) explore two key areas related to the rebound effect and energy efficiency: the mechanism underlying this effect and policies aimed at mitigating it. Specifically, they quantify the environmental footprint of household-induced rebound effects resulting from reduced predicted expenditures using random forest regressions in Switzerland. Meanwhile, Chitnis et al. (2014) highlight the importance of considering the rebound effect in policy evaluations, estimating it for different household income groups in the United Kingdom (organized by quintiles). In Spain, Cansino et al., (2022) provide a novel approach by decomposing and measuring the direct, indirect, and economy-wide (broad) rebound effects while accounting for intersectoral relationships. To this end, they employ a combination of the Cobb–Douglas production function and structural decomposition techniques, applying this framework to data spanning from 2000 to 2014.

Chitnis and Sorrell (2015) estimate the overall rebound effects for households in the United Kingdom, finding substitution effects of 41%, 48%, and 78% for gas, electricity, and vehicle fuel use, respectively. Additionally, they reveal that improving the efficiency of certain energy services tends to generate larger positive direct rebound effects than indirect rebound effects, which are occasionally negative. The generated rebound effects decline over time (Chitnis et al., 2020). Meanwhile, (Hardadi et al., 2021) observe that high-income German households contribute more to pollution due to transportation, including international travel, whereas low-income households exhibit higher energy use for electricity and utilities. For low-income households, a rebound effect is observed in increased heating use. In Greece, (Gkatsikos et al., 2022) report that the country’s budget allocation for irrigation development would lead to a water rebound effect of 12.76% under the most realistic scenario. This is primarily attributed to water use for cotton, durum wheat, and other agricultural activities. In Norway, Bjelle et al., 2018 estimate that the implementation of energy efficiency measures in households could reduce GHG emissions by 58%. However, the rebound effect would offset these reductions by 24%–35%. They suggest mitigating this effect by reducing consumption of goods and services with high fossil fuel intensity (e.g., vehicles, clothing, and certain manufactured products) and redirecting income toward services with low GHG intensity. Similarly, Nässén and Holmberg (2009) find that in Sweden, the rebound effect for energy services (including direct energy use, heating, and transport) ranges between 10% and 20%, with the effect increasing as income levels rise.

In Spain, a study reviewing measures to mitigate climate change proposed policy recommendations to avoid the rebound effect, such as offering tax benefits to companies that reduce energy intensity (Cansino et al., 2016). Freire-González (2011) quantified the direct and indirect static rebound effects on household energy consumption following improvements in energy efficiency. Additionally, Cansino et al. (2016) were the first to decompose the rebound effect resulting from energy efficiency improvements using structural decomposition analysis. Freire-González et al. (2017) argue that the rebound effect would remain below 100% if energy savings are proportionally redistributed as income across all economic sectors. A study has also estimated the direct and indirect cross-rebound effects for the Spanish economy, capturing variations in the use of other natural resources (Freire-González and Vivanco, 2017). Meanwhile, to establish effective policies and minimize rebound effects in household electricity use, Sarasa and Turner (2021) recommend improving energy efficiency while using nonrenewable electricity and achieving more competitive renewable electricity production.

However, most of these studies use emission models to explore consumption patterns and explain energy efficiency–related emissions and their actual projections (including the rebound effect). To the best of our knowledge, SAM has not been used for this purpose. SAM incorporates not only the changes in intersectoral relations of production but also those in some institutions, such as labor and capital.

3. Materials and methods

This section outlines the fundamentals of the Social Accounting Matrix (SAM) framework, supplementing the discussion with relevant references. Additionally, the methodology employed is presented and explained.

3.1. Social accounting matrix

To conduct impact analysis, understanding the flows of production value (interactions involving supply and demand between production sectors and institutions) and household consumption differentiated by income is crucial. In this study, this information is obtained from an SAM that presents the structure of the economy for a given period of time (usually 1 year). The SAM requires a multisectoral framework illustrating exchanges and transfers among all involved economic agents.

SAM is used to evaluate the potential impact of changes in exogenous shocks. In addition, depending on the level of decomposition of the accounts included, an SAM can describe household income distribution while considering socioeconomic characteristics such as division by income level for analyses of unemployment, poverty, social development, social integration and gender issues, and environmental problems. In this regard, an SAM presents an economy's structural interdependence at the macroeconomic level using comprises input–output tables complemented by transfers between institutional sectors.

To mention a few studies that accomplish the combination of the methodology of accounting multipliers to analyze environmental aspects, Park and Lee (2013) developed an Environmental Social Accounting Matrix (e-SAM) to analyze the connections between productive activities, fossil energy consumption, and CO2 emissions in Korea. Their findings highlighted a strong direct effect from the electricity industry, but only a small indirect effect. Additionally, the study revealed that the service industry accounts for 50% of the gross effect of fossil fuel consumption, emphasizing the need for industry-specific energy policies.

In Scotland, (Xu et al., 2013) analyzed rural and urban households, comparing income levels and energy requirements to identify variations in fuel types and consumption patterns across locations. Their findings highlight the need for tailored policies to address the high energy demands associated with final consumption goods. In Mexico, (Chapa and Ortega, 2017) analyzed the impact of the carbon tax on individuals living in poverty, categorized by geographic area. Their findings identified three sectors most affected by the carbon tax: coke, refined petroleum, and nuclear fuel. Additionally, they observed indirect effects on air and land transport, as these sectors rely on inputs from the aforementioned industries. In Indonesia, Hartono and Resosudarmo, 2008 quantified the impact of energy policies aimed at reducing energy use and improving efficiency, with a focus on different household groups. Their findings revealed that improvements in energy efficiency are positively correlated with increased income for most households.

For Spain, Duarte et al., (2010) investigated household consumption and pollution in Spain, identifying a connection between income inequality, consumption patterns, and CO2 emissions using a SAM. Accordingly, Duarte et al. (2012) employed econometric methods and a SAM approach to quantify the final volume of emissions, characterizing Spanish households based on income, population density, social class, the educational level of the household head, and whether the household was urban or rural. Their findings concluded that income is the primary determinant of consumption patterns. Moreover, Duarte et al. (2017) investigated the responsibilities of Spanish households in greenhouse gas (GHG) emissions. Their findings reveal a relationship between income and pollution generation. The wealthiest regions in the country—Madrid, as well as the Northeast and East regions—exhibit higher emissions due to increased levels of consumption. On other aspect, Manresa and Sancho (2004) analyzed CO2 emissions in Catalonia to estimate sectoral energy intensities using a Social Accounting Matrix (SAM) and Leontief multipliers. They estimated that 20 million metric tons of emissions were associated with productive activities, while 7 million metric tons were linked to domestic final demand. The authors recommended the adoption of energy-saving technologies to reduce emissions and pollution.

For the case of this article, the database is taken from Beltran et al. (2024), which follows the guidelines of the European System of Integrated Accounts (2010). This SAM framework represents the structural composition of an individual economy. It highlights the interconnected links among economic agents by means of the resource flows stemming from economic transactions. The SAM is structured with rows and columns that display receipts and payments. This matrix records the circular flow of income. The database includes the accounts of the entire economy and institutional sectors (current and accrual accounts), as well as a supply and use table. This matrix is considered foundational because it decomposes households by income level in addition to showing the remuneration of employees and how their skills are used in different sectors of the economy, given the goal of this study to identify the emissions of each household. This analysis extends to assess labor supply from different socioeconomic groups. It follows the accounting that allocates primary income to households. This table was compiled using the National Classification of Economic Activities sectoral classification into 63 production sectors (Annex 1). The structure of the SAM is shown in Table 1.

As mentioned before, this structure reflects the relationships between intermediate and aggregate demand and value added in the economy, decomposed by different attributes (i.e., gender, occupational level, and household income). For the purposes of this study, microdata from the Household Budget Survey (2016) and the Living Conditions Survey (2016) were used to consider the SAM structure, decomposed by income level.

Table 1
Social accounting matrix for Spain (base year 2016).[12]

	Homogeneous Branches (1 … 63)	Factors of Production (64) Labour (65) Capital	Institutional Sectors (66) Households (68) Employers' social contributions (69) Net taxes on products (70) Other net taxes on production (71) Income Tax (IRPF) (72) Social Contributions to employees (73) Public Administration	(67) Savings/ Investment	(74) Rest of the World
Homogeneous Branches (1 … 63)	I/O MATRIX (Intermediate Demand)	Final Demand			
Factors of Production (64) Labour	Added Value/Indirect Taxes/ Imports Payments	Closure Matrix			
(65) Capital					
Institutional Sectors (66) Households					
(68) Employers' social contributions					
(69) Net taxes on products					
(70) Other net taxes on production					
(71) Income Tax (IRPF)					
(72) Social Contributions to employees					
(73) Public Administration					
(67) Savings/Investment					
(74) Rest of the World					

Source: Spain's SAM 2016 Beltran et al. (2024).[1] based on the Input–Output Framework 2016 published by the National Institute of Statistics [2] and Mainar-Causapé et al. (2018).

3.2. Methodological considerations

To obtain the CO_2 emissions of household consumption as a function of income, linear multiplier models using a national-level SAM for the year 2016 are employed. In this case, the study uses a demand model expressed in physical units, that is, CO_2 emissions measured in tons (Miller and Blair, 2022). To this end, we will use the CO_2 emissions for each sector from the input-output tables, obtained from the Air Emission Accounts provided by the National Institute of Statistics (NIE, 2022).

The basis for the analysis of linear multipliers is the matrix of technical coefficients, which presents the expenditure trend for each account in the matrix. According to Stone (1962, 1978) and Pyatt and Round (1979), endogenous and exogenous accounts should be identified, considering that endogenous accounts show a dependence between expenditures and income while exogenous accounts show expenditures independent of variations in income. The 63 sectors of economic activity and the factors of production (capital and labor) are considered as endogenous accounts.

Following Pyatt and Round (1979) and Campoy-Muñoz et al. (2017) in notation, the subscript m signifies endogenous accounts, whereas k represents exogenous accounts. In addition, the SAM includes the total income that rows i receive from columns j; meanwhile, the columns present the aggregate income in column j and how it is divided among different accounts i. Each component Y_{ij} of the matrix denotes the bilateral flow between accounts i and j. The average expenditure coefficients—$a_{ij} = Y_{ij}/Y_j$, $i,j = 1,..,n$.—show the payments to account i per unit of j's income. With this definition, the following expression is obtained:

$$Y_i = \sum_{j=1}^{n} (Y_{ij} / Y_j) Y_j = \sum_{j=1}^{m} a_{ij} Y_j + \sum_{j=m+1}^{m+k} a_{ij} Y_j;\ n = m + k, \quad (1)$$

where Y_i denotes the aggregated income from endogenous and exogenous accounts.

As mentioned previously, the subscripts m and k specify the categorization of SAM accounts into endogenous and exogenous groups, resulting in a division of the total coefficient matrix nxn into different sub-matrices: A_{mm}, A_{mk}, A_{km}, and A_{kk}. Matrix A is the matrix of technical coefficients describing the average trend to spend, obtained by dividing each element of the corresponding column by the total of that column, indicating the income from endogenous and exogenous accounts: Y_m and Y_k. Sub-matrix A_{mm} represents the coefficients of the endogenous accounts. Sub-matrix A_{mk} shows the distribution of income flows from exogenous to endogenous accounts, whereas sub-matrix A_{km} denotes the distribution of income flows from endogenous to exogenous accounts. Finally, sub-matrix A_{kk} represents the coefficients of the exogenous accounts. In this case, only the aggregated income of the endogenous accounts is considered, that is, sub-matrices A_{mm} and A_{mk}. Meanwhile, the exogenous demand components are described by $A_{mk} Y_k = X_m$. The total revenues of the endogenous accounts of the system are defined as follows:

$$Y_m = A_{mm} Y_m + A_{mk} Y_k \quad (2)$$

This expression can be rewritten as follows:

$$Y_m = (I - A_{mm})^{-1} A_{mk} Y_k \quad (3)$$

where I is the identity matrix and $(I - A_{mm})^{-1} = M$, corresponding to the matrix of linear multipliers. Equation (3) captures the change of Y_m with any exogenous shock $A_{mk} Y_k = X_k$. Expression (3) can be simplified as follows:

$$Y_m = M X_k \quad (4)$$

In addition to production impacts, this system facilitates the computation of the impact of various macroeconomic variables and their expression in physical units, such as GHG emissions. To this end, the model described earlier is employed to evaluate how changes in household consumption affect GHG emissions. Changes in household consumption, reflected by X_k, cause variations in the level of economic activity of the production sectors (ΔY_m), resulting in fluctuations in GHG emissions owing to the economic activities necessary to meet household demand. This modeling is achieved by premultiplying the inverse matrix M by a vector of unit coefficients of atmospheric emissions diagonalizing $E_n = diag(E_i / Y_i)$, where E_i denotes the GHG emissions of sector *i*, and Y_i is the total production of sector *i*. Meanwhile, E_n signifies the atmospheric emissions generated by each sector per unit produced. Thus, the environmental effects of changes in household consumption can be obtained as follows.

$$EMI_n = E_n(I - A_{mm})^{-1} A_{mk} Y_k \Rightarrow dEMI_n = E_n M dX_k \quad (5)$$

The different scenarios are described below, along with the sources used for the modeling.

4. Results

4.1. Scenario descriptions

In this section we collect all the results derived from the different scenarios established.

4.1.1. Scenario 1: household emissions

The first scenario is crucial because it serves as a reference for the following scenarios and makes it possible to achieve the study objectives. This scenario involves estimating the CO2 emissions of Spanish households in 2016 based on the SAM for that year, applying the mentioned methodology to households according to their income.

4.1.2. Scenario 2: forecast of emissions based on reduced household consumption due to energy efficiency improvements

The second scenario models the reduction in CO_2 emissions due to energy efficiency improvements in 2050. According to the European Commission, the consumption footprint is primarily produced in five major areas: food, mobility, housing, household goods, and household appliances (Ministry of Consumer Affairs, 2022).

In Spain, the areas with the largest footprint are food (52.1%), mobility (17.1%), and housing (16.2%%). Therefore, this scenario defines an improvement in the consumption efficiency of the three most representative sectors: manufacturing (which includes the food sector), transportation (which coincides with mobility), and electricity (the sector that primarily captures housing expenditures in terms of carbon footprint).

To model these changes in consumption, we use information gathered by the Net Zero by 2050 report (Bouckaert et al., 2021), which predicts a 14% reduction in energy consumption (heating and cooling), 25% reduction in transportation, and 34% reduction in manufacturing.

4.1.3. Scenario 3: forecast of emissions based on reduced household consumption due to energy efficiency improvements, including the rebound effect

The final scenario is built on the previous one because emissions are estimated based on the consumption decrease in the three sectors with the largest footprint. Here, reduced spending on these goods leads to savings that are allocated to the consumption of other goods or the same ones.

To distribute these savings, we use the calculation of the rebound effect used by Cansino et al. (2022), who estimate an increase in consumption after the achievement of energy efficiency for 14 sectors of production (Annex 2). These percentages are applied to the total savings obtained (resulting from reduced expenditure) and the 63 production sectors available in our SAM. For this purpose, they are aggregated to the 14 industries under consideration and then distributed to other industries (again decomposed to 63) in accordance with the consumption pattern.

Therefore, this scenario presents emissions forecasts based on energy efficiency improvements while assuming that there will be a rebound effect, that is, an increase in household consumption due to improved efficiency.

4.2. Findings

This section presents the outcomes derived from the three proposed scenarios and the CO_2 footprint of households according to income variations.

As shown in Table 2, the footprint of all households decreases by 15.90% from Scenario 1 to Scenario 2. However, if the reduction in consumption due to energy efficiency improvements is allocated to the consumption of other goods (i.e., if we include the rebound effect), the reduction is lower, at 7.26%. Regarding these reductions, there are no differences between different deciles of households. However, if we focus on the footprint of each scenario, we find that the footprint is larger from decile V onward, with the households in deciles VII and X being the main contributors. In addition, for low-income households, decile III represents the smallest footprint.

To determine the extent to which production sectors are responsible for emissions, the sectors generating the largest household footprint were selected (Annexes 3, 4, and 5). In particular, 11 sectors are responsible for approximately 90% of the footprint in all scenarios (Table 3).

The first six sectors in the three scenarios account for approximately 75% of the emissions. Hence, it is relevant and rational to scrutinize the emissions from these sectors. Energy represents the largest contributor to household footprint, followed by transportation, petroleum products, agricultural products, other non-metallic mineral products, and air transportation.

Considering the 11 most polluting sectors, the rate of change between Scenarios 1 and 2 is calculated to identify differences between households in the different deciles (Table 4).

Of the most polluting sectors, households in the highest decile (VIII onward) are the ones that reduce their footprint the least. This is mainly due to the use of agricultural products (1), other non-metallic mineral products (14), food products (5), and petroleum products (10). However, no significant difference is found between the deciles for each of the sectors.

If we consider the results of the variation rate between Scenarios 1 and 3, which includes the rebound effect and implies higher consumption, the reduction in the footprint of all these sectors is lower, as expected (Table 5).

Specifically, there is a reduction of 7% or 8% in the footprint of all these sectors, with the greatest reduction in deciles I and II. In this case, the decrease in agricultural products (1), other non-metallic mineral

Table 2
CO_2 emissions of the different scenarios in millions of tons and income variations (in percentages).

Households	Scen. 1	Scen. 2	Scen. 3	Scen. 1–Scen. 2	Scen. 1–Scen. 3
I	8022.76	6677.39	7372.65	−16.77%	−8.10%
II	8307.28	6948.63	7681.12	−16.35%	−7.54%
III	**7438.50**	**6276.48**	**6888.46**	−15.62%	−7.39%
IV	8735.74	7344.49	8090.06	−15.93%	−7.39%
V	9329.89	7818.15	8635.85	−16.20%	−7.44%
VI	8963.48	7537.42	8371.88	−15.91%	−6.60%
VII	**11,984.68**	**10,008.00**	**11,128.18**	−16.49%	−7.15%
VIII	9778.02	8246.47	9050.16	−15.66%	−7.44%
IX	9474.70	7991.09	8778.08	−15.66%	−7.35%
X	**11,664.18**	**9953.84**	**10,900.99**	−14.66%	−6.54%
Total	93,699.24	78,801.96	86,897.43	−15.90%	−7.26%

Source: Compiled by the authors.

Table 3
Representation of CO_2 emissions by the most polluting sectors.

Número	Sector	Scen. 1	Scen. 2	Scen. 3
24	Electricity, gas, steam, and air conditioning	40.25%	41.74%	41.86%
31	Land transportation services and pipeline transportation services	10.37%	9.94%	10.13%
10	Coke and refined petroleum products	9.12%	7.82%	7.78%
1	Products of agriculture, hunting, and related services	6.61%	6.48%	6.27%
14	Other non-metallic mineral products	5.04%	5.02%	5.00%
33	Air transportation services	4.94%	4.89%	5.03%
11	Chemicals and chemical products	3.92%	3.55%	3.52%
5	Food products, beverages, and tobacco products	3.73%	3.18%	3.14%
3	Fish and other fishing products, aquaculture products, and support services to fishing	2.50%	2.97%	2.81%
8	Paper and paper products	1.92%	1.69%	1.67%
36	Accommodation and food services	1.87%	2.24%	2.28%
Total		90.26%	89.53%	89.49%

Source: Compiled by the authors

products (14), and food products (5) is observed from decile VII onward, whereas the footprint of air transportation declines for the first three deciles. Furthermore, accommodation services and fishing products stand out as the only sectors that increase their footprint in all deciles.

Regardless of this finding, the difference between the deciles for each of the sectors continues to be small. Therefore, to determine whether variations in CO_2 emissions according to household income impact the rebound effect, we perform an analysis with low-income households as the reference. In other words, the increases from deciles II to X, with respect to decile I, are calculated and analyzed in the following section.

4.3. Rebound effect on Spanish household income

Annexes 6, 7, and 8 show variations in CO_2 emissions for each decile (from II to X) with respect to decile I for the three scenarios. As we aim to confirm whether the rebound effect impacts the footprint of households with different incomes, it is necessary to focus on Scenarios 2 and 3, wherein the former does not include the rebound effect and the latter does. As this difference causes the abovementioned variations, it is calculated for each of the selected sectors (the largest polluters), with the results presented in Table 6.

When analyzing the most polluting sectors, an increase of 1% in deciles VI and VII and a decrease of 1% in deciles III, VIII, and X are observed. The other deciles do not show any significant difference. This finding implies that in Spanish households, the rebound effect persists independent of household income levels. As household income rises, the household's consumption, and thereby its footprint, increases. However, the proportion of the CO_2 footprint tends to stay similar regardless of the presence of the rebound effect. Therefore, it can be confirmed that the variation in emissions in all income brackets does not affect the lower income bracket when there is a rebound effect.

When considering each sector, some exceptions emerge that contradict the above findings. In the case of land transportation (31), if a low-income household is positioned in decile VII or higher, the rebound effect leads to a reduction of 4%–5% in the carbon footprint. The same is true for accommodation services (36) when positioned in decile VIII, with an 11% reduction when positioned in decile X. Finally, in air transportation services (33), there are differences from decile VII to deciles IV and V and from decile V onward.

5. Discussion and conclusions

Many authors and institutions have found it valuable to analyze emissions resulting from household consumption to demonstrate that

Table 4
Variation in the CO_2 emissions of the sectors between Scenarios 1 and 2 (in percentages).

Number	I	II	III	IV	V	VI	VII	VIII	IX	X
24	−14%	−13%	−13%	−13%	−13%	−13%	−13%	−13%	−13%	−12%
31	−20%	−20%	−19%	−20%	−21%	−20%	−21%	−21%	−21%	−20%
10	−29%	−28%	−28%	−28%	−28%	−27%	−27%	−27%	−27%	−26%
1	−18%	−18%	−16%	−17%	−18%	−18%	−19%	−15%	−15%	−13%
14	−17%	−16%	−15%	−15%	−16%	−16%	−16%	−14%	−14%	−13%
33	−18%	−18%	−18%	−19%	−19%	−18%	−19%	−20%	−19%	−17%
11	−25%	−25%	−23%	−23%	−24%	−23%	−24%	−24%	−24%	−25%
5	−29%	−27%	−26%	−26%	−27%	−27%	−27%	−24%	−25%	−22%
3	−1%	−1%	−1%	−1%	−1%	−1%	−1%	−1%	−1%	−1%
36	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
8	−27%	−26%	−25%	−24%	−25%	−24%	−25%	−24%	−25%	−25%
Total	−17%	−17%	−16%	−17%	−17%	−16%	−17%	−16%	−16%	−15%

Source: Compiled by the authors

Table 5
Variation in the CO_2 emissions of the sectors between Scenarios 1 and 3 (in percentages).

Number	I	II	III	IV	V	VI	VII	VIII	IX	X
24	−4%	−4%	−4%	−3%	−3%	−2%	−2%	−3%	−3%	−2%
31	−10%	−11%	−9%	−12%	−12%	−11%	−13%	−13%	−13%	−12%
10	−22%	−21%	−22%	−21%	−20%	−19%	−19%	−21%	−20%	−20%
1	−13%	−12%	−10%	−11%	−12%	−12%	−12%	−8%	−9%	−6%
33	−6%	−8%	−7%	−10%	−10%	−8%	−10%	−12%	−11%	−10%
14	−9%	−8%	−7%	−7%	−7%	−7%	−7%	−6%	−6%	−5%
11	−18%	−18%	−16%	−16%	−16%	−15%	−16%	−17%	−17%	−19%
5	−23%	−20%	−19%	−19%	−20%	−20%	−20%	−16%	−17%	−13%
3	3%	4%	3%	4%	4%	4%	4%	4%	3%	4%
36	12%	11%	11%	11%	10%	11%	12%	10%	10%	8%
8	−20%	−20%	−18%	−17%	−18%	−16%	−17%	−18%	−19%	−20%
Total	−8%	−8%	−7%	−7%	−7%	−7%	−7%	−7%	−7%	−7%

Source: Compiled by the authors

Table 6
Difference between variations in CO_2 emissions with respect to Decile I in Scenarios 2 and 3 (in percentages).

Sector	II	III	IV	V	VI	VII	VIII	IX	X
24	1%	−1%	0%	1%	1%	2%	0%	0%	0%
31	−1%	0%	−2%	−2%	−1%	**−4%**	**−5%**	**−4%**	**−5%**
10	0%	−1%	0%	1%	1%	2%	0%	0%	−1%
1	1%	0%	1%	1%	1%	2%	1%	1%	1%
33	−1%	0%	**−3%**	**−3%**	−1%	**−5%**	**−6%**	**−5%**	**−8%**
14	0%	−1%	0%	0%	0%	1%	0%	0%	−2%
11	0%	0%	0%	0%	1%	2%	0%	0%	−1%
5	1%	1%	1%	0%	0%	1%	2%	1%	3%
3	0%	0%	0%	1%	1%	2%	0%	0%	0%
36	−1%	−2%	−2%	−3%	−2%	−1%	**−5%**	**−5%**	**−11%**
8	0%	0%	1%	0%	1%	1%	0%	−1%	−3%
Total	0%	−1%	0%	0%	1%	1%	−1%	0%	−1%

Source: Compiled by the authors based on their own preparation of Annexes 7 and 8.

energy efficiency improvements can achieve reduced consumption, at least in the most polluting sectors (Ke and Cai, 2023). This study finds that households with the highest income are the biggest consumers and the largest polluters, with those in deciles VII and X particularly prominent, in both scenarios (with or without the rebound effect). This was confirmed by Zang et al. (2017), who stated that the increase in direct carbon emissions is primarily attributable to the growth in per capita income of households. Similarly, Weizhen Ren et al. (2024) argue that an increase in household income initially leads to a decrease in resource efficiency, although it begins to improve once income exceeds a specific threshold.

Fortunately, the increase in household consumption following reduced expenditures due to energy efficiency improvements (including the rebound effect) leads to overall emission reductions, as this effect is reallocated to economic sectors (Freire-González et al., 2017). However, this reduction amounts to only 7.26%, indicating that the targets proposed by official institutions for combating and mitigating climate change remain distant. The scenarios investigated in this study show that in the absence of the rebound effect, the reduction in emissions doubles, reaching 15.80% (compared with a reduction of 7.26% with the rebound effect). The Agenda España (2025) had already confirmed that the reduction would not be as expected, due to factors such as, for example, the efficiency gains in automobile technology (engines, fuels, and parts) may be offset by increased use of more powerful and heavier cars. Similarly, modern irrigation systems have increased water consumption in certain regions of the country.

This limited reduction is primarily attributable to the most polluting sectors, namely, electricity, land transportation services, petroleum products, agricultural products, other non-metallic mineral products, and air transportation services (United Nations Framework Convention on Climate Change, 2021; IEA, 2024). These sectors account for approximately 75% of household emissions and as Sorrell et al. (2020) point out, rebound effects are notable in actions that influence these sectors, smaller in those affecting heating and electricity, more significant in transport fuels, and more pronounced in those that impact food consumption.

Regarding the rebound effect in household consumption and income, the reduction in emissions from agricultural products, other non-metallic mineral products, and food decreases from decile VII onward, whereas the reduction in emissions from air transportation is smaller in the first three deciles. However, emissions from accommodation services and fishery products increase consistently across all deciles.

After considering households with the lowest income (decile I) as the reference and calculating variations in emissions in the other deciles, we can conclude that the rebound effect is not affected by income in Spanish households. In other words, if a household's income increases, its consumption will increase and the household's footprint will be larger; however, the proportion of the CO_2 footprint will be similar with or without the rebound effect. In terms of production sectors, there are certain exceptions, such as land transportation, where if a household with a lower income is in decile VII or higher, the rebound effect will reduce its footprint share by 4%–5%. This is also true for accommodation services if the households are in deciles VIII and IX (5%) and in decile X (11%). The last exception is air transportation services, where there are differences from decile VII onward (5%–8%).

These results will be valuable in identifying residential carbon footprints as a function of income and making energy efficiency projections for 2050. Furthermore, the results are presented in two scenarios—one that includes the rebound effect and one that does not. Thus, the study demonstrates that the rebound effect does not impact the income of Spanish people in most sectors.

Meanwhile, the footprint of households in different sectors presented in the SAM reveals that the decomposition into 63 production sectors is relevant because it can be used to identify and analyze the footprint of the 11 most polluting sectors. These sectors, in turn, can be addressed by developing energy efficiency policies that propose different interventions for different households based on their incomes. These findings could be extended by considering other factors—household consumption and associated CO_2 emissions are not only related to income but also to the type of housing and home ownership, and rural or urban location (Druckman and Jackson, 2008; Zhang et al., 2015; Trotta, 2018).

The Net Zero by 2050 report acknowledges that it considers savings decisions and the rebound effect after energy efficiency improvements for household consumption in only three production sectors. Although there are limitations in the model used—for example, the modeling in the SAM table assumes a linear and fixed structure of intersectoral relationships—the SAM can effectively capture the interdependencies of the economic system and emissions and offer a way to decompose households by income and production sectors. However, this paper represents the initial attempt to analyze the rebound effect through a basic general equilibrium approach (as it employs a linear model). Nevertheless, one of the key limitations is the absence of the structural complexity that, for instance, a more specialized dynamic model could provide. We suggest that future research should incorporate the underlying dynamics through which the rebound effect would play a more significant role in modeling.

Annex 1
Productive sectors of the MRIO

Number	Sector
1	Products of agriculture, hunting and related services
2	Products of forestry, logging and related services
3	Fish and other fishing products; aquaculture products; support services to fishing
4	Mining and quarrying
5	Food products; beverages; tobacco products
6	Textiles; wearing apparel; leather and related products
7	Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials
8	Paper and paper products
9	Printing and recording services
10	Coke and refined petroleum products
11	Chemicals and chemical products
12	Basic pharmaceutical products and pharmaceutical preparations
13	Rubber and plastics products
14	Other non-metallic mineral products
15	Basic metals
16	Fabricated metal products, except machinery and equipment
17	Computer, electronic and optical products
18	Electrical equipment
19	Machinery and equipment
20	Motor vehicles, trailers and semi-trailers
21	Other transport equipment
22	Furniture; other manufactured goods
23	Repair and installation services of machinery and equipment
24	Electricity, gas, steam and air conditioning
25	Natural water; water treatment and supply services
26	Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery
27	Constructions and construction Works
28	Wholesale and retail trade and repair services of motor vehicles and motorcycles
29	Wholesale trade services, except of motor vehicles and motorcycles
30	Retail trade services, except of motor vehicles and motorcycles
31	Land transport services and transport services via pipelines
32	Water transport services
33	Air transport services
34	Warehousing and support services for transportation
35	Postal and courier services
36	Accommodation and food services
37	Publishing services
38	Motion picture, video and television programme production services, sound recording and music publishing;
39	Telecommunications services
40	Computer programming, consultancy and related services; information services
41	Financial services, except insurance and pension funding
42	Insurance, reinsurance and pension funding services, except compulsory social security
43	Services auxiliary to financial services and insurance services
44	Real estate services
45	Imputed rents of owner-occupied dwellings
46	Legal and accounting services; services of head offices; management consulting services
47	Architectural and engineering services; technical testing and analysis services
48	Scientific research and development services
49	Advertising and market research services
50	Other professional, scientific and technical services; veterinary services
51	Rental and leasing services
52	Employment services
53	Travel agency, tour operator and other reservation services and related services
54	Security and investigation services; services to buildings and landscape; office administrative, office
55	Public administration and defence services; compulsory social security services
56	Education services
57	Human health services
58	Residential care services; social work services without accommodation
59	Creative, arts and entertainment services; library, archive, museum and other cultural services; gambling and betting services
60	Sporting services and amusement and recreation services
61	Services furnished by membership organisations
62	Repair services of computers and personal and household goods
63	Other personal services

Source: Eurostat: European Classification of Economic Activities. NACE Rev. 2 (Adapted to the Classification of Products per Activity: CPA).

Annex 2
Increase in domestic consumption due to energy efficiency improvements (M €).

SECTORES	RAMAS	HOGARES	%
1–3	Agriculture, forestry and fishing	2,6	1,20%
4	Mining and quarrying	0	0,00%
5	Food, beverages and tobacco	14,3	6,58%
6	Textile and leather	1,3	0,60%
7–9	Paper, pulp and printing	0,7	0,32%
10–14	Chemical and petrochemical; non-metallic minerals	6,4	2,94%
15–16	Basic metals & fabricated metal products	0,5	0,23%
17–19	Machinery	0,7	0,32%
20–21	Transport equipment	1,3	0,60%
22–23	Other industries	0,8	0,37%
27	Construction	2,4	1,10%
24–26	Energy sector	9,3	4,28%
31–34	Transport and storage	6,2	2,85%
28-30 y 35 -63	Commercial, services and public services	171	78,66%
TOTAL		217,4	100,00%

Source: Compiled by the authors based on Cansio, Ordóñez y Prieto (2022).

Annex 3
CO_2 emissions from households in the different deciles in SCENARIO 1 (in million tons).

Sector	I	II	III	IV	V	VI	VII	VIII	IX	X
24	3229	3218	3088	3361	3489	3331	4304	3658	3454	4142
31	832	918	729	1052	1128	1030	1592	1274	1213	1473
10	731	706	690	739	750	694	912	798	743	848
1	530	528	458	529	604	645	774	543	568	625
14	404	426	379	443	488	479	624	493	481	594
33	396	439	332	525	540	489	806	641	611	790
11	315	350	268	310	350	323	447	367	386	552
5	299	303	248	300	358	396	487	294	300	314
3	201	189	180	192	204	203	229	210	230	264
8	154	173	129	152	174	164	226	178	190	277
36	150	220	213	259	292	343	406	334	318	436
Total	**7241**	**7470**	**6713**	**7861**	**8377**	**8098**	**10,807**	**8790**	**8494**	**10,315**
Sector	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
Resto	781	837	725	875	953	866	1178	988	981	1350
Total	**8023**	**8307**	**7439**	**8736**	**9330**	**8963**	**11,985**	**9778**	**9475**	**11,664**

Note.
24 - Electricity, gas, steam and air conditioning.
31 - Land transport services and transport services via pipelines.
10 - Coke and refined petroleum products.
1 - Products of agriculture, hunting and related services.
14 - Other non-metallic mineral products.
33 - Air transport services.
11 - Chemicals and chemical products.
5 - Food products; beverages; tobacco products.
3 - Fish and other fishing products.
8 - Paper and paper products.
36 - Accommodation and food services.

Annex 4
CO_2 emissions from households in the different deciles in SCENARIO 2 (in million tons).

Sector	I	II	III	IV	V	VI	VII	VIII	IX	X
24	2787	2791	2688	2926	3032	2901	3739	3195	3014	3648
31	664	733	589	838	896	822	1259	1012	964	1183
10	522	509	493	534	543	504	664	578	541	625
1	432	434	383	439	495	526	626	461	483	545
14	335	357	321	375	412	404	525	423	412	517
33	327	359	273	427	436	400	653	515	494	653
11	237	263	206	238	267	248	340	281	292	413
5	212	220	183	221	262	291	356	223	226	245
3	199	187	178	190	201	200	226	208	228	262
36	150	219	213	258	291	343	406	333	318	435
8	113	128	97	115	131	125	170	135	142	207
Total	**5978**	**6200**	**5624**	**6562**	**6966**	**6765**	**8963**	**7365**	**7114**	**8733**
Sector	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
Resto	699	749	652	783	852	773	1045	882	877	1221
Total	**6677**	**6949**	**6276**	**7344**	**7818**	**7537**	**10,008**	**8246**	**7991**	**9954**

Annex 5
CO_2 emissions from households in different deciles in SCENARIO 3 (in million tons).

Sector	I	II	III	IV	V	VI	VII	VIII	IX	X
24	3086	3105	2950	3244	3382	3258	4216	3538	3350	4054
31	747	820	661	926	992	919	1389	1105	1056	1293
10	573	558	538	587	600	559	738	634	593	682
1	462	467	411	473	533	565	678	498	519	589
33	371	404	309	473	484	450	722	563	541	713
14	369	393	351	412	453	446	581	463	451	562
11	259	287	224	261	293	274	376	307	319	448
5	231	241	201	243	286	317	390	247	249	273
3	207	196	186	199	212	210	240	218	238	274
36	168	244	236	286	322	382	454	367	349	471
8	123	139	106	126	143	137	187	147	154	222
Total	**6598**	**6855**	**6173**	**7230**	**7699**	**7516**	**9970**	**8087**	**7820**	**9581**
Sector	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
Resto	775	826	715	860	937	855	1158	963	958	1320
Total	**7373**	**7681**	**6888**	**8090**	**8636**	**8372**	**11,128**	**9050**	**8778**	**10,901**

Annex 6
Variation of CO_2 emissions of the deciles with respect to DECIL I in SCENARIO 1.

Sector	II	III	IV	V	VI	VII	VIII	IX	X
24	2%	−17%	0%	20%	33%	63%	−2%	0%	5%
31	−6%	−11%	−4%	1%	1%	14%	5%	15%	31%
10	5%	−6%	10%	21%	19%	54%	22%	19%	47%
1	0%	−4%	4%	8%	3%	33%	13%	7%	28%
14	11%	−15%	−2%	11%	3%	42%	17%	23%	75%
33	13%	−16%	−1%	13%	7%	47%	16%	23%	80%
11	11%	−16%	32%	36%	23%	103%	62%	54%	99%
5	−3%	−6%	1%	3%	−5%	25%	9%	2%	16%
3	10%	−12%	26%	36%	24%	91%	53%	46%	77%
8	0%	−14%	0%	14%	22%	46%	2%	7%	18%
36	47%	42%	73%	95%	129%	171%	123%	112%	191%
Total	**3%**	**−7%**	**9%**	**16%**	**12%**	**49%**	**21%**	**17%**	**42%**

Annex 7
Variation of CO_2 emissions of the deciles with respect to DECIL I in scenario 2.

Sector	II	III	IV	V	VI	VII	VIII	IX	X
24	0%	−4%	5%	9%	4%	34%	15%	8%	31%
31	10%	−11%	26%	35%	24%	90%	53%	45%	78%
10	−3%	−6%	2%	4%	−4%	27%	11%	3%	20%
1	0%	−11%	1%	15%	22%	45%	7%	12%	26%
14	7%	−4%	12%	23%	21%	57%	26%	23%	54%
33	10%	−16%	31%	34%	22%	100%	58%	51%	100%
11	11%	−13%	0%	12%	5%	43%	18%	23%	74%
5	4%	−14%	4%	23%	37%	68%	5%	6%	15%
3	−6%	−10%	−4%	1%	1%	14%	5%	15%	32%
36	47%	42%	73%	95%	129%	171%	123%	113%	191%
8	13%	−14%	2%	16%	10%	50%	19%	25%	83%
Total	**4%**	**−6%**	**10%**	**17%**	**13%**	**50%**	**23%**	**19%**	**46%**

Variation of CO_2 emissions of the deciles with respect to DECIL I in scenario 3.

Sector	II	III	IV	V	VI	VII	VIII	IX	X
24	1%	−4%	5%	10%	6%	37%	15%	9%	31%
31	10%	−12%	24%	33%	23%	86%	48%	41%	73%
10	−3%	−6%	2%	5%	−2%	29%	11%	3%	19%
1	1%	−11%	2%	15%	22%	47%	8%	12%	27%
33	9%	−17%	27%	31%	21%	95%	52%	46%	92%
14	6%	−5%	12%	23%	21%	58%	26%	22%	53%
11	11%	−14%	1%	13%	6%	45%	18%	23%	73%
5	4%	−13%	5%	24%	37%	69%	7%	8%	18%
3	−5%	−11%	−4%	2%	1%	16%	5%	15%	32%
36	45%	40%	70%	92%	127%	170%	118%	108%	180%
8	13%	−14%	2%	16%	11%	52%	19%	25%	80%
Total	**4%**	**−6%**	**10%**	**17%**	**14%**	**51%**	**23%**	**19%**	**45%**

(*continued on next column*)

Annex 7 (*continued*)

CRediT authorship contribution statement

Miguel Á. Martínez-García: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Supervision. **Manuel Alejandro Cardenete:** Validation, Supervision. **M. Carmen Delgado:** Validation, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Miguel A. Martinez-Garcia reports a relationship with Rey Juan Carlos University that includes: employment and non-financial support. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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