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THE SYSTEM WIDE EFFECTS OF ENERGY EFFICIENCY IN RESIDENTIAL ENERGY USE

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ABSTRACT

This Final Degree Project investigates the economic and social effects of energy efficiency in residential energy use in Spain, with a focus on the Economy Wide Rebound Effect (EWRE) and the multiplier effect across various industries. Utilizing the economic input-output model developed by Wassily Leontief, the study finds that while energy efficiency can reduce greenhouse gas emissions, lower energy costs, and improve quality of life, the expected reductions in total energy consumption may be partially offset by the EWRE. This effect can diminish the anticipated benefits of energy-saving measures, with significant rebound effects observed in sectors like coke and refined petroleum products.

The analysis also highlights the substantial multiplier effects of certain energy industries, suggesting that strategic investments in these sectors could enhance economic output. The study emphasizes the need for energy efficiency policies to include thorough EWRE analyses and promote technologies and behaviors that minimize rebound effects. Additionally, it advocates for inclusive policies to address energy poverty and ensure equitable benefits from energy efficiency improvements. Future research should incorporate dynamic models and life cycle analyses to better capture the long-term impacts of these policies.

Keywords: *Energy efficiency, rebound effect, input-output model, residential energy use, multiplier effect, sustainability*.

RESUMEN

Este Trabajo de Fin de Grado investiga los efectos económicos y sociales de la eficiencia energética en el uso residencial de la energía en España, centrándose en el efecto rebote en toda la economía (EWRE) y el efecto multiplicador en varias industrias. Utilizando el modelo económico input-output desarrollado por Wassily Leontief, el estudio concluye que, aunque la eficiencia energética puede reducir las emisiones de gases de efecto invernadero, disminuir los costes energéticos y mejorar la calidad de vida, las reducciones esperadas en el consumo total de energía pueden verse parcialmente contrarrestadas por el EWRE. Este efecto puede disminuir los beneficios previstos de las medidas de ahorro energético, con importantes efectos de rebote observados en sectores como el coque y los productos refinados del petróleo.

El análisis también destaca los importantes efectos multiplicadores de determinadas industrias energéticas, lo que sugiere que las inversiones estratégicas en estos sectores podrían aumentar la producción económica. El estudio subraya la necesidad de que las políticas de eficiencia energética incluyan análisis exhaustivos de los EWRE y promuevan tecnologías y comportamientos que minimicen los efectos de rebote. Además, aboga por políticas inclusivas que aborden la pobreza energética y garanticen beneficios equitativos de las mejoras en eficiencia energética. Las investigaciones futuras deberían incorporar modelos dinámicos y análisis del ciclo de vida para captar mejor las repercusiones a largo plazo de estas políticas.

Palabras clave: *Eficiencia energética, efecto rebote, modelo input-output, uso residencial de la energía, efecto multiplicador, sostenibilidad.*

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I. INTRODUCTION

This Final Degree Project aims to explore the economic and social effects of energy efficiency in residential energy use in Spain, with a particular focus on two crucial aspects: the Economy Wide Rebound Effect (EWRE) and the multiplier effect of different industries in the economy. In a context where sustainability and the transition to clean energy are increasingly urgent, this study seeks to provide a comprehensive analysis of how improvements in energy efficiency can influence not only energy consumption, but also the overall economy and social welfare. Improving energy efficiency can lead to significant reductions in greenhouse gas emissions, reduce energy costs for consumers, improve quality of life, and generate employment. However, it is essential to consider that fuel efficient measures may not always result in the expected reductions in total energy consumption due to EWRE. This analysis aims to delve deeper into these multifaceted impacts, providing a comprehensive view of residential energy efficiency policies and their broader implications.

Global Importance of Energy Efficiency

Energy efficiency has become a global priority due to its multiple benefits for the environment, the economy and society. According to the International Energy Agency (IEA), fuel saving is one of the most effective means of addressing climate change, improving energy security, and reducing energy poverty (IEA, 2021). Globally, energy efficiency improvements could reduce greenhouse gas emissions by approximately 40% by 2040, contributing significantly to the Paris Agreement targets (IEA, 2021).

In addition, fuel management plays a crucial role in reducing energy demand, which in turn reduces the need to invest in new energy generation and distribution infrastructure. The UN has stressed that investing in this cause not only reduces long-term energy costs, but also creates jobs and improves economic competitiveness (UN, 2018). Investments in energy efficiency in buildings, transport and industries not only benefit consumers and the economy at large, but also promote sustainable and resilient urban development (UN, 2018). In the European context, the European Commission has set ambitious targets in its Energy and Climate Plan 2030, which includes a 32.5% energy efficiency improvement target for 2030 (European Commission, 2020). These targets are designed to reduce the European Union's dependence on energy imports, improve air quality and encourage technological innovation in key sectors. Policies of this type are therefore essential not only for climate change mitigation, but also for sustainable economic growth and energy security.

In Spain, fuel efficiency is a vital component of the National Integrated Energy and Climate Plan (PNIEC) 2021-2030, which sets specific targets to reduce primary and final energy consumption (Ministry for Ecological Transition and the Demographic Challenge, 2020). The proposed measures include the renovation of buildings, the promotion of effective technologies and the strengthening of energy efficiency regulations. These actions not only have the potential to significantly reduce CO2 emissions but can also generate economic savings and improve the competitiveness of the Spanish economy (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020).

In addition to environmental and economic benefits, energy efficiency also addresses issues of social equity. Reducing energy costs through efficiency can alleviate the financial burden of vulnerable households, decreasing energy poverty and improving social welfare (Castillo-Carvajal et al., 2020). This aspect is particularly relevant in the context of growing economic inequalities and the need for policies that promote a just transition to a low-carbon economy.

1.1 Main Objective of the Work

The main objective of this work is to analyze the economic and social impacts of energy efficiency improvements in the Spanish residential sector, with a specific focus on quantifying the Economy Wide Rebound Effect and assessing the multiplier effect of different industries on the economy. Through the application of an input-output model, this study seeks to quantify the benefits and challenges associated with energy saving policies, assessing their overall impact on the welfare of the population. This involves examining both the direct effects on energy consumption and the indirect and long-term effects on the economy and society.

1.2 Brief Description of the Work and Methodology

This study uses the economic input-output model developed by Wassily Leontief to analyze the interdependencies between different economic sectors. The input-output model is particularly suited for this type of analysis because of its ability to capture complex relationships and quantify the multiplier effects of energy efficiency policies. Data from the Instituto Nacional de Estadística (INE) for the year 2019 for the Spanish territory will be used to build the model and perform simulations of different energy efficiency policy scenarios. The methodology includes collecting comprehensive data on energy consumption and trends, constructing the model to represent sectoral relationships, simulating different energy efficiency scenarios, and analyzing the direct and indirect effects on energy consumption, economic output, and social welfare.

If you deem it appropriate, you may consult the detailed calculations of the input-output model used throughout this work in the provided link to the Excel file: INPUT OUTPUT MODEL

1.3 Motivations

The motivation behind this study stems from the growing importance of sustainable development and the urgent need to address climate change, energy security, and economic stability. As energy efficiency improvements offer a promising pathway to achieving these goals, this research aims to explore their multifaceted impacts on the Spanish residential sector. By focusing on the Economy Wide Rebound Effect (EWRE) and the multiplier effect of different industries, this study seeks to provide a comprehensive understanding that can inform better policymaking.

Additionally, this research is driven by a personal commitment to contributing to the body of knowledge in the field of energy economics. By examining the direct and indirect effects of energy efficiency policies, the study aspires to highlight the potential benefits and challenges, offering valuable insights for both academics and policymakers. The findings are expected to serve as a foundation for future research and as a guide for formulating policies that not only enhance sustainability but also promote economic and social welfare in a balanced and equitable manner.

II. CONTEXT OF ENERGY TRANSITIONS IN SPAIN

This section provides a specific framework for understanding energy transitions in the Spanish context, with a focus on residential energy optimization. It analyzes information and data related to the energy industry in Spain, as well as policies and trends affecting household energy consumption in the country. Analyzing the context of energy transitions in Spain, specifically in relation to residential energy conservation, is fundamental to understanding the factors influencing this area and establishing a solid foundation for research. This analysis not only provides relevant information on the energy industry in Spain, but also highlights policies and trends that impact residential energy consumption. This contextual information is essential to support the findings and results of the study and justify the relevance and necessity of conducting this research.

2.1 Residential Energy Efficiency in Spain: Data and Trends

In recent decades, Spain has experienced a growing awareness of the importance of residential energy optimization. According to data from the Instituto Nacional de Estadística (INE), energy consumption in Spanish households has been increasing, but improvements in energy conservation are also observed thanks to policies and incentive programs (INE, 2021). These improvements highlight a significant shift towards more sustainable energy practices among consumers, driven by both government initiatives and increased public awareness of environmental issues.

Spain's National Integrated Energy and Climate Plan (PNIEC) sets ambitious targets to enhance fuel efficiency in all sectors, including residential. This comprehensive plan outlines specific goals aimed at reducing energy consumption and greenhouse gas emissions, reflecting Spain's commitment to the European Union's climate objectives. Measures such as building renovation and the promotion of efficient technologies are expected to contribute significantly to reducing energy consumption in Spanish households in the coming years (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020).

Building renovation plays a crucial role in improving residential energy conservation. The Spanish government has implemented various programs that provide financial incentives and subsidies for upgrading insulation, windows, and heating systems in homes. These renovations not only reduce energy consumption but also enhance the comfort and living conditions of residents.

Moreover, the promotion of efficient technologies is a key strategy in Spain's efforts to optimize residential energy use. This includes the adoption of energy-efficient appliances, smart home systems, and renewable energy sources such as solar panels. Government incentives and educational campaigns have been pivotal in increasing the adoption of these technologies. For example, the widespread use of energy-efficient lighting and appliances has led to substantial energy savings and reduced electricity bills for households.

Additionally, Spain's integration into the European Union has facilitated access to funding and support for energy conservation projects. EU directives and regulations provide a framework that encourages member states to pursue aggressive energy-saving goals. Spain's alignment with these directives ensures that its policies are consistent with broader European efforts to combat climate change and promote sustainable development.

2.2 Energy Policies and Regulations in Spain

The regulatory framework in Spain includes a series of policies and regulations aimed at promoting energy-efficient practices in the residential sector. These policies are essential to reduce energy consumption, lower greenhouse gas emissions, and promote sustainable development. Some of the main initiatives and regulations in force are described below.

Program of Aids for the Energy Rehabilitation of Buildings (PAREER)

The Program of Aids for the Energy Rehabilitation of Buildings (PAREER) is one of the Spanish government's most prominent initiatives to promote energy conservation in the residential sector. This program offers subsidies and financing for energy efficiency improvements in homes and neighborhood communities. The grants are aimed at carrying out actions such as improving thermal insulation, installing more efficient heating and cooling systems, and using renewable energies, such as solar panels (Ministerio para la Transición Ecológica y el Reto Demográfico, 2021).

The goal of PAREER is to reduce primary energy consumption and CO2 emissions, as well as to improve the comfort and quality of life of residents. This program not only helps lower household energy costs, but also boosts the local economy through job creation in the construction and renewable energy sectors.

European Directives on Energy Efficiency

Spain, as a member of the European Union, has adopted several European directives that establish common standards and objectives for all member states. Among these directives, Directive 2012/27/EU on energy efficiency stands out, which establishes a framework of measures to promote energy optimization throughout the EU. This directive obliges member states to establish national energy efficiency action plans and to implement concrete measures to achieve the established targets (European Commission, 2020).

Among the measures driven by the European directives are the promotion of the energy label and the improvement of the performance of household appliances. The energy label provides clear and comparative information on the energy efficiency of products, helping consumers to make informed choices. In addition, the directives encourage the development and implementation of regulations that oblige manufacturers to improve the energy efficiency of household appliances, which contributes to reducing energy consumption in households.

National Integrated Energy and Climate Plan (PNIEC) 2021-2030

The National Integrated Energy and Climate Plan (PNIEC) 2021-2030 is a key tool in Spain's energy policy. This plan sets ambitious targets to reduce greenhouse gas emissions, increase energy efficiency, and promote renewable energies. The PNIEC includes a series of specific measures for the residential sector, such as the energy renovation of buildings, the promotion of renewable energies in the domestic sphere, and the implementation of advanced energy management systems (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020).

The PNIEC also promotes the creation of financial incentives and support programs to facilitate the adoption of efficient and renewable technologies. These measures not only contribute to environmental sustainability, but also have a positive impact on the economy by generating employment and reducing dependence on fossil fuels.

Technical Building Code (CTE)

The Technical Building Code (CTE) is another crucial regulation that establishes minimum quality and safety requirements for buildings, including aspects related to energy efficiency. The CTE requires new buildings and significant renovations to comply with specific standards for thermal insulation, efficiency of heating and cooling systems, and use of renewable energy (Ministerio de Fomento, 2019).

Recent amendments to the CTE have introduced more stringent requirements for energy efficiency, with the goal of achieving Nearly Zero Energy Consumption Buildings (nZEB) standards. These regulations are essential to ensure that Spain's housing stock moves towards greater sustainability and energy conservation.

2.3 Spain in a Global Context

Comparing Spain's energy policies with those of other EU and developed countries provides valuable insight into the similarities and differences in approaches to energy efficiency and sustainability. Spain, like many EU countries, has adopted policies based on European directives that set common targets for reducing emissions and increasing energy efficiency.

For example, Germany has implemented very robust energy efficiency policies, most notably its Energiewende (energy transition), which includes ambitious emission reduction targets and strong support for renewables and energy efficiency in buildings (Agora Energiewende, 2020). Both countries share a commitment to renewables and efficiency, but Germany has been more aggressive in implementing its policies and financial support for renewable energy projects.

Denmark, on the other hand, has been a pioneer in integrating energy efficiency into industry. Its Energy Efficiency Agreements Program offers tax incentives to companies that implement energy efficiency measures and achieve certain energy savings targets (Togeby et al., 2009). This policy has enabled Denmark to achieve some of the highest levels of energy efficiency in the industrial sector in Europe.

In comparison, the United States has taken a more fragmented approach, with energy efficiency policies varying significantly among states. Nonetheless, programs such as the

California Fuel Efficient Vehicle Standards (CAFE Standards) have been instrumental in improving energy efficiency in the transportation sector. Spain, like other European countries, benefits from more centralized coordination of energy policies across the EU, which facilitates the adoption of common standards and targets.

2.4 Economic and Social Impact in Spain

Energy transitions in residential consumption have a significant economic and social impact in Spain. Studies have shown that improving energy optimization in homes can reduce energy costs for consumers and generate employment in sectors such as construction and engineering (García-Quevedo et al., 2018). The implementation of efficient technologies not only decreases energy consumption, but also boosts the economy by creating new job opportunities and fostering growth in associated sectors.

Despite these benefits, challenges persist in the implementation of energy-saving measures in Spain. One of the main obstacles is the lack of adequate financing for energy efficiency projects. Many households, especially those in vulnerable communities, cannot afford the upfront investments needed to improve the energy efficiency of their homes. This problem is compounded by the lack of affordable grant and loan programs to facilitate these improvements.

Another major challenge is the need for greater citizen awareness and participation. Many people are not fully informed about the benefits of energy efficiency or the technologies available to improve the energy consumption in their homes. Lack of information and education can limit the adoption of effective measures, delaying the transition to a more sustainable energy system.

To address these challenges, additional measures are required to promote the adoption of effective technologies and ensure a fair and equitable transition to a more sustainable energy system. This includes implementing policies that provide financial incentives, such as grants and low-interest loans, to facilitate investments in energy optimization. In addition, it is crucial to develop awareness campaigns and educational programs that inform citizens about the benefits of energy efficiency and the options available to improve their homes (Martín-Dorta et al., 2021).

2.5 Future Challenges and Opportunities in Spain

In the future, Spain will face significant challenges and opportunities in the field of residential energy efficiency. Digitalization and technological innovation offer new opportunities to improve energy management in homes and optimize the use of energy resources. Smart technologies, such as home energy management systems (HEMS) and IoT (Internet of Things) devices, enable more precise control and efficient management of energy consumption in homes (Sovacool et al., 2019). These technologies help users to monitor their energy consumption in real time, identify inefficient usage patterns, and optimize the use of household appliances.

However, Spain must also face challenges related to energy poverty and inequality in energy access. Energy poverty refers to the inability of households to keep their homes adequately air-conditioned due to high energy costs, low incomes, and energy inefficiency in housing. This problem disproportionately affects vulnerable communities, including the elderly and low-income families (Castillo-Carvajal et al., 2020). To address these challenges, it is crucial that energy efficiency policies are designed with an inclusive and equitable approach.

Specific policies and programs are needed to ensure that all citizens have access to energy-efficient and affordable housing. This includes the implementation of subsidies and financial assistance for energy rehabilitation of housing, specifically targeting low-income households. In addition, it is important to encourage community participation and provide education and training on energy efficiency practices to empower citizens to take proactive measures in their own homes.

In summary, the future of residential energy efficiency in Spain presents both opportunities and challenges. Digitalization and technological innovation can significantly improve energy management, but it is crucial to address inequalities in energy access. Inclusive policies and targeted programs can ensure that the benefits of energy efficiency reach all citizens, promoting sustainable and equitable development.

III. THE MODEL

The model that will be used throughout this paper to investigate and support the object of study will be the economic input-output framework developed by Professor Wassily Leontief in the late 1930s. However, we will mainly rely on a work not directly authored by Leontief, as Miller and Blair's "Input-Output Analysis: Foundations and Extensions" has been considered the best source of information at present on the input-output model.

The work of these two academics is considered the "bible" of the model developed by Leontief because of: the accessibility and the clear and easy-to-understand language used; in addition to the detailed theoretical explanation, it focuses on the practical application of the model in various fields, including economics, regional planning and economic policy analysis; and it is an up-to-date study that is regularly revised.

The input-output model aims to analyse the interdependencies that exist between different industries in a given geographical region that act both producing products (outputs) and consuming goods from other industries (inputs). The model collects and graphically shows the movements of products from each of the sectors, in this case producers, to each of the sectors (including itself), in this case consumers. This information is displayed graphically in a table consisting of columns and rows. The rows represent the distribution of a sector's output in the economy and the columns represent the quantity and nature of inputs it needs to produce its output. The final columns show the sales of each sector to final markets for their production, these are total exports and final consumption expenditure by: households, non-profit institution serving households and public administration. The rows below the inter-industry transaction table are used to collect data on non-industry inputs used in the production of each sector, among others: compensation of employees, imports, taxes on production.

The input-output model is constructed on the basis of observed data in a particular economic area. In this paper we will work with the data collected for the year 2019 for the Spanish territory. To recap briefly, we should recall that the table collects the inputs (columns) and outputs (rows) of each industry in monetary terms over a period of time, in this case measured in millions of euros in the year 2019. Transactions in monetary values between two industries, from industry *i* (row) to industry *j* (column), are denoted as x_{ij}. The purchase of products from industry j from other industries during a period of time will be directly related to the production of goods from sector j during the same period. For example, demand from the *computer, electronic and optical products* industry to the *fabricated metal products, except machinery and equipment* industry will be closely related to the output of the former.

In addition, in all countries there are product demands from groups that are exogenous to industrial production, in our table we recognise four: households, non-profit institutions serving households, public administration and foreign trade (referred to as exports). The demand by these groups is not usually for the use of the products in the production of their particular output (intermediate consumption), but is usually used as such, hence this purchase is called final demand.

If we assume that the economy can be divided into n sectors, designate X_i the total output production of sector i, and Yi the total final demand for the output of sector i, we should be able to write an equation that recognises the way in which sector i distributes its output to other sectors as intermediate goods and to the previously named demanders as final goods. The equation should be as follows:

$$X_i = x_{i1} + \cdots + x_{ij} + \cdots + x_{in} + Y_i = \sum_{j=1}^{n} x_{ij} + Y_i \qquad (1)$$

The x_{ij} terms constitute interindustry sales by sector i to all sectors j (which includes itself, when j = i). x_{i1} refers to the first, while x_{in} refers to the last input contributing to the output of the X_i system. Each x_{ij} (where ij varies from 1 to n) corresponds to a different input that influences the output of the system. There will be a formula like this one, which pinpoints the sales of the outputs from each of the n sectors. To keep the algebraic representation simple, we will assume that there are only three sectors, even though we will use all 65 industries in the mathematical calculation. Therefore:

$X_1 = x_{1,1} + x_{1,2} + x_{1,3} + Y_1$

$\vdots$

$X_2 = x_{2,1} + x_{2,2} + x_{2,3} + Y_2$ (2)

$\vdots$

$X_3 = x_{3,1} + x_{3,2} + x_{3,3} + Y_3$

Furthermore, as we will use some algebra notation throughout the paper, we shall know equation (2) could be written in matrix notation as **X = C + Y**, broken down as follows:

$$X = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix}, \qquad C = \begin{bmatrix} x_{1,1} & x_{1,2} & x_{1,3} \\ x_{2,1} & x_{2,2} & x_{2,3} \\ x_{3,1} & x_{3,2} & x_{3,3} \end{bmatrix}, \qquad Y = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{bmatrix} \qquad (3)$$

X represents a column vector which consists of three rows, with systems X_1, X_2 and X_3. On the other hand, **C** is the letter that we will assign to the matrix of inter-industry demands, and **Y** is a column vector of final demands, made up of Y_1, Y_2 and Y_3.

Let us calculate the output for the first sector of the table, which as we already know, consists of the sum of intermediate and final demand.

Table 1. Output of agriculture, hunting and related services

Output of agriculture, hunting and related services	=	**Sum of intermediate demands**	+	**Sum of final demands** **(households + non-profit institution serving households + public administration + total exports)**
X_1	=	$x_{1,1} + x_{1,2} + x_{1,3} \ldots + x_{65,1}$	+	Y_1
55,782.7	=	31,495.9	+	24,286.8 (= 10,378 + 2 + 10.7 + 2,496.3 + 11,399.8)

		(= 871 + 0.1 + 0 + 0.2 + . . . 0)		

Source: *Own elaboration based on data published in Instituto Nacional de Estadística (2019)*

We are going to continue to assume that our input output model consists of 3 industries for ease of understanding, therefore we are able to comprehend the calculations in the table of 65 sectors, without the need to break down the endless list of calculations. The 3 industries will be: manufacturing (1), non-manufacturing traded (2) and sheltered (3).

Next step is we make our key modelling assumption. We define a set of input-output coefficients $a_{i,j}$ for i = 1, 2, 3 and j = 1, 2, 3 where, $a_{i,j} = x_{i,j}/X_j$

So, for instance, $a_{2,3} = x_{2,3}/X_3$

The significance of the input-output coefficient denoted as $a_{2,3}$ lies in its representation of the quantity of output from sector 2 (Non-Manufacturing) required to generate one unit of output in sector 3 (Sheltered). In practical terms, for instance, if the Sheltered sector necessitates 5 units of Non-Manufacturing output to produce 4 units of Sheltered output, then the coefficient $a_{2,3}$ would be computed as the ratio of these values, resulting in 1.25 units of Non-Manufacturing output required to yield each unit of Sheltered output.

By extending this method to all a_{ij} coefficients, a corresponding array is derived, constituting a 3x3 matrix of input-output coefficients. This matrix, henceforth referred to as A, encapsulates the interdependencies between sectors within the economic system under examination.

Table 2. Algebraic Representation of A-Matrix

A-MATRIX (input coefficients)	**Manufacturing**	**Non-Manufacturing Traded**	**Sheltered**
Manufacturing	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$

Non-Manufacturing Traded	$a_{1,2}$	$a_{2,2}$	$a_{2,3}$
Sheltered	$a_{1,3}$	$a_{3,2}$	$a_{3,3}$

Given the definition $a_{i,j} = x_{i,j}/X_j$, through rearrangement, it can be deducted that $x_{i,j} = a_{i,j}X_j$. Consequently, substituting the $x_{i,j}$ terms in equation set (2) with $a_{i,j}X_j$ terms yields equation set (4):

$$\begin{aligned} X_1 &= a_{1,1}X_1 + a_{1,2}X_2 + a_{1,2}X_3 + Y_1 \\ X_2 &= a_{2,1}X_1 + a_{2,2}X_2 + a_{2,3}X_3 + Y_2 \\ X_3 &= a_{3,1}X_1 + a_{3,2}X_2 + a_{3,3}X_3 + Y_3 \end{aligned} \qquad (4)$$

Subsequently, by rearranging equation set (4) to group all terms involving X variables on the left-hand side and then factoring out the X terms, equation set (5) is obtained:

$$\begin{array}{rcrcrcl} (1-a_{1,1})X_1 & - & a_{1,2}X_2 & - & a_{1,3}X_3 & = & Y_1 \\ a_{2,1}X_1 & - & (1-a_{2,2})X_2 & - & a_{2,3}X_3 & = & Y_2 \\ a_{3,1}X_1 & - & a_{3,2}X_2 & - & (1-a_{3,3})X_3 & = & Y_3 \end{array} \qquad (5)$$

Likewise, equation set (2) can be re-arranged in the form of the following matrix expression:

$$\boldsymbol{X} = \boldsymbol{AX} + \boldsymbol{Y}$$

Where, **X**, **Y** and **A** represent the previously described vectors and matrix.

To proceed towards an equation where **X** is expressed as a function of **Y**, we undertake a series of steps:

Step 1: Subtract AX from both sides of the matrix equation $\boldsymbol{X} = \boldsymbol{AX} + \boldsymbol{Y}$, resulting in:

$$\boldsymbol{X} - \boldsymbol{AX} = \boldsymbol{Y} \qquad (6)$$

Step 2: Factor out the variable X from the two terms on the left-hand side of matrix equation (6), leading to:

$$[\boldsymbol{I}-\boldsymbol{A}]\boldsymbol{X} = \boldsymbol{Y} \qquad (7)$$

Here, **I** represents the identity matrix, akin to the number one in algebra. It takes the form of an array with zeroes everywhere except along the main diagonal, where the entries are ones. In our example with three sectors, **I** assumes the form illustrated by the array of numbers provided.

Observe that equation set (5) would result from expressing the matrix equation (7) as three linear equations in ordinary algebra.

Table 3. Mathematical Representation of I-Matrix

I-MATRIX	**Manufacturing**	**Non-Manufacturing Traded**	**Sheltered**
Manufacturing	1	0	0
Non-Manufacturing Traded	0	1	0
Sheltered	0	0	1

When the identity matrix I is subtracted from the matrix A, the term [I - A] in equation (7) is created, which is also a matrix. Once more, this is the three sector example:

$$I-A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} \\ a_{2,1} & a_{2,2} & a_{2,3} \\ a_{3,1} & a_{3,2} & a_{3,3} \end{bmatrix} = \begin{bmatrix} 1-a_{1,1} & -a_{1,2} & -a_{1,3} \\ -a_{2,1} & 1-a_{2,2} & -a_{2,3} \\ -a_{3,1} & -a_{3,2} & 1-a_{3,3} \end{bmatrix} \qquad (8)$$

Step 3: Determine X based on Y

We still don't have equation (7) in its complete form. Next, we solve matrix equation (7) for X, which provides the crucial equation:

$$\boldsymbol{X} = [\boldsymbol{I} - \boldsymbol{A}]^{-\mathbf{1}} \cdot \boldsymbol{Y} \qquad (9)$$

The inverse matrix operator is represented by the -1 superscript, so $[\text{I-A}]^{-1}$ is the inverse matrix of the matrix [I-A]. The Leontief inverse matrix, also called the multiplier matrix, is represented by the matrix $\mathbf{[I\text{-}A]^{-1}}$.

The key matrix (9) in one sense is merely reproducing the information in the IO table itself. Furthermore, it indicates that the quantities of gross output, which are the X elements, are determined by final demands, which are the Y elements, multiplied by the matrix $[\text{I-A}]^{-1}$.

3.1 The Leontief Inverse (or Multiplier) Matrix

As previously mentioned, the matrix $[\text{I-A}]^{-1}$ is known as the Leontief inverse or alternatively as the multiplier matrix. So far, we have considered the special case of a three-sector input-output (IO) table. However, an IO table can generally consist of I sectors, where I is any number greater than one. For instance, the IO table that we will use to analyze energy efficiency in Spain consists of 65 sectors, where I = 65.

In this broader context, the matrices we have been analyzing will not be of dimensions 3 rows by 3 columns. Instead, they will be of dimensions I rows by J columns, where I = J, and I corresponds to the number of sectors in the disaggregated IO table we are using.

Therefore, the Leontief inverse matrix $[\text{I-A}]^{-1}$ is an I x J matrix, meaning it has I rows and J columns, with I = J. Each element of the Leontief inverse matrix indicates the amount of output from sector i required per €1 million final demand for sector j output. On the other hand, we must remember and not get confused with the meaning of each element of the A matrix, which specify the amount of output from sector i needed per €1 million of gross output from sector j.

The totals of the columns in the Leontief inverse matrix represent the total output generated in the economy per €1 million of final demand for each sector j. Hence, these column totals are referred to as output multipliers.

Lastly, let us imagine that we would like to express matrix equation (9) in the form of three ordinary equations. This is not as simple as it seems, as the elements of $[I - A]^{-1}$ are now elements of the inverted [I - A] matrix. If we represent these elements, that is, the elements that make up the separate parts of the Leontief inverse matrix, we would obtain the following:

$$[I - A]^{-1} = \begin{bmatrix} L_{1,1} & L_{1,2} & L_{1,3} \\ L_{2,1} & L_{2,2} & L_{2,3} \\ L_{3,1} & L_{3,2} & L_{3,3} \end{bmatrix} \qquad (10)$$

Therefore, the matrix equation (9) in its ordinary algebra form of three linear equations will consist of:

$$\begin{aligned} X_1 &= L_{1,1}Y_1 + L_{1,2}Y_2 + L_{1,3}Y_3 \\ X_2 &= L_{2,1}X_1 + L_{2,2}Y_2 + L_{2,3}Y_3 \\ X_3 &= L_{3,1}Y_1 + a_{3,2}X_2 + L_{3,3}Y_3 \end{aligned} \qquad (11)$$

3.2 Advantages and disadvantages of the model

The input-output (IO) model is a fundamental and widely used tool in economic analysis, especially in the evaluation of energy efficiency in residential energy use. This tool has the ability to examine interdependencies between different sectors of the economy, providing a comprehensive view of how improvements in energy efficiency can affect output, employment, and income at the aggregate level (Miller & Blair, 2018). However, the use of the IO model also presents a number of challenges that must be carefully considered.

One of the main advantages of the IO model is its ability to capture the complex interactions between economic sectors. This allows for a detailed assessment of how energy efficiency improvements in the residential sector can influence other parts of the economy. For example, improvements in fuel saving can reduce energy demand, which in turn can affect the energy generation and distribution sectors, as well as manufacturers of energy-related equipment and technologies (Leontief, 1986). This ability to trace chain effects is essential to understanding the full impact of energy efficiency policies.

However, one of the biggest challenges of the IO model is its dependence on data availability and accuracy. For the model to work properly, detailed information on economic transactions between sectors is required, which can be difficult to obtain and keep up to date (Duchin & Lange, 1998). In addition, any errors in the data can propagate throughout the model, affecting the accuracy of the results.

Another notable advantage of the IO model is its ability to simulate various policy scenarios. This tool allows assessing the possible effects of different energy saving measures, such as subsidies, tax incentives or regulations, on the economy (Bulavskaya & Reynès, 2018). This flexibility is particularly useful for policymakers, as it allows them to anticipate the outcomes of their decisions and adjust strategies as needed.

Nevertheless, a significant limitation of the IO model is its static nature. The model assumes that the relationships between sectors remain constant over time, which may not be realistic in a dynamic economic environment. This means that the model may not adequately capture the effects of technological changes or fluctuations in consumer behavior, which can lead to inaccurate projections (Rose & Liao, 2005).

In addition, the IO model does not effectively incorporate price changes. Changes in prices can have a significant impact on consumption and production, and by not considering them, the model may miss important economic effects (Defourny & Thorbecke, 1984). This omission may limit the usefulness of the model for evaluating energy efficiency policies that may influence energy and related product prices.

The use of historical data in the IO model provides a solid empirical basis for analysis, ensuring that the model's projections are grounded in actual economic behaviors and trends, which increases the reliability of its findings (Tarancon & del Rio, 2007). However, this reliance on detailed and up-to-date data can also be a disadvantage if the data are not accurate or complete (Duarte et al., 2016).

Despite these limitations, the IO model remains a valuable tool due to its ability to provide detailed quantitative insight into economic impacts. However, to maximize its usefulness, it is crucial to complement it with other approaches that can address its limitations.

For example, integrating the IO model with dynamic models or using computable general equilibrium (CGE) analysis can provide a more complete and accurate view of the effects of energy efficiency policies (Dixon et al., 2013). CGE analysis is a complex economic method that evaluates how changes in policy will affect an economy by considering the links between different marketplaces and sectors. By taking alterations to production, consumption, and trade patterns into account, it models how an economy might respond to shifts in policy, technology, or other external variables.

In addition, the incorporation of life cycle analysis can help overcome some of the limitations of the IO model by providing a more comprehensive view of environmental and social impacts (Lenzen & Treloar, 2003). Life cycle analysis (LCA), which covers all phases from raw material extraction to manufacture, usage, and end-of-life management, assesses the environmental and social implications of a process or product from its conception to disposal. This method guarantees a comprehensive evaluation of sustainability consequences, taking into account details that the IO model might miss.

In summary, it was decided to use the input-output model to quantify energy efficiency in residential use because of its ability to provide a detailed and quantitative analysis of economic impacts. Although it presents challenges, its ability to map complex interactions and perform policy simulations makes it extremely useful. This tool allows us to accurately quantify the effects of energy management improvements and provides a solid empirical basis for informed decision making by policy makers. Moreover, if desired, this study can be used as a basis that can be complemented and contrasted with other approaches and analyses, thus overcoming some of its limitations and ensuring a more complete and accurate assessment of the impacts of energy efficiency policies.

IV. SIMULATION STRATEGY

Once the aim of the model, the data background and the mathematical and algebraic formulation of the model itself have been explained, the next step is to perform the different shocks. The shocks, and therefore the situations we are going to analyze, are two. Shocks are exogenous changes that affect the economy, modifying the final demand of certain sectors or the productive capacity of industries (Sorrell et al., 2009). In our model, we will not define shocks, which can range from technological changes that may affect production, or economic policies or other incentives that reduce household consumption. In this paper, we will limit ourselves to analyzing what would happen in the national economy if one of these exogenous changes were to reduce the consumption of households of the products of two industries: electricity, gas, steam and air conditioning (24) and coke and refined petroleum products (10).

Scenario 1

The first scenario involves a detailed analysis of a 20% reduction in household consumption of products from sector 24. According to the input-output table for Spain, the final consumption expenditure of sector 24 by households amounts to €15,597.3 million. Therefore, a 20% reduction equates to €3,119.46 million. In this scenario, we hypothesize that this reduction in energy use occurs while maintaining constant household income. As a result, the €3,119.46 million saved will be redistributed proportionally among other sectors, excluding sector 24. Although the total shock in the economy is zero, the composition of final demand changes significantly.

To determine the amount allocated to each sector, we follow these steps:

1. **Calculate the Shares for Each Sector**: This involves determining the proportion of the saved amount that each sector will receive. The formula used is:

$$Shares\ sector\ i\ = \frac{H.Consumption\ sector\ i}{Total\ H.Consumption - \ Energy\ Shock} \qquad (12)$$

The total of the shares should add 100 (100%).

2. **Compute the Non-Energy Shock for the Remaining Sectors**: This step involves calculating the redistributed amount for each sector based on the shares calculated previously. The formula used is:

$$Non\ energy\ shock\ sector\ i\ =\ H.Consumption\ sector\ i\ x\ Shares\ sector\ i \qquad (13)$$

3. **Apply the Overall Shock**: Finally, we ensure that the total shock sums to zero by redistributing the saved amount. The formula is:

$$Shock\ to\ implement\ =\ \sum(Energy\ Shock)\ +\ \sum(Non\ Energy\ Shock)\ =\ 0 \qquad (14)$$

The following table shows the computed shock for our first scenario:

Table 4. Changes in Household Consumption in Scenario 1.

Sector	**Energy Shock**	**Household Consumption**	**Shares**	**Non Energy Shock**	**Shock to Implement**
1. Products of agriculture, hunting and related services	0.0	10378.0	1.75	55.18	55.18
2. Products of forestry, logging and related services	0.0	308.4	0.05	1.64	1.64
3. Fish and other fishing products; aquaculture products;	0.0	3373.8	0.58	17.94	17.94

support services to fishing					
…	…	…	…	…	…
24. Electricity, gas, steam and air conditioning	-3119.46	15597.3	0.0	0.0	-3119.46
…	…	…	…	…	…
Total	- 3119.46	602,273.7	100	3119.46	0.0

Source: *Own elaboration based on data published in Instituto Nacional de Estadística (2019)*

Scenario 2

The second scenario involves a detailed analysis of a 20% reduction in household consumption of products from sector 10. Similar to the first scenario, the savings are proportionally distributed among other sectors. According to the input-output table for Spain, the final consumption expenditure of sector 10 by households is €10,161.7 million. A 20% reduction in this case equates to €2,032.34 million. The methodology follows the same steps as the first scenario, ensuring a zero-sum total shock while redistributing the saved amount.

Table 5. Changes in Household Consumption in Scenario 2.

Sector	Energy shock	Household Consumption	Shares	Non Energy Shock	Shock to implement
1. Products of agriculture, hunting	0.0	10378.0	1.75	35.62	35.62

and related services					
2. Products of forestry, logging and related services	0.0	308.4	0.05	1.06	1.06
3. Fish and other fishing products; aquaculture products; support services to fishing	0.0	3373.8	0.57	11.58	11.58
…	…	…	…	…	…
10. Coke and refined petroleum products	-2032.34	10161.7	0.0	0.0	-2032.34
...	…	…	…	…	…
Total	-2032.34	602273.7	100	2032.34	0

Source: *Own elaboration based on data published in Instituto Nacional de Estadística (2019)*

4.1 Direct and Indirect Effects

The overall direct effect of the two scenarios would be zero-sum, since directly in the economy, savings in one sector would mean higher consumption in the other sectors. For instance, if a family decides to reduce their monthly spending on digital entertainment, they can and will increase their spending on sports, educational activities or some other type of activities, keeping total consumption unchanged. We have called the direct effect in the tables 4 and 5 “shock to implement”. However, the indirect effect is not 0, because the redistribution of the final demand will affect in one way or another the production of the economy since distinctive backward linkages associated to each economic sector.

To find out the effect on the Spanish economy, we must pre-multiply the inverse Leontief matrix by the changes in household consumption, or in other words, the “shock to implement”. Performing this calculation with the data of scenario 1, we obtain an output effect in the total economy of -€1412.18 million. If we calculate the output effect of scenario 2, we obtain -€550.51 million. This is because it is important not only how much you invest in the economy, but also in what way.

Industries have greater or lesser multiplier effects on investment depending on their sectoral interrelationships (the backwards and forward linkages captured by the Leontief matrix). The multiplier effect of each industry in the economy is obtained by adding the values in each of columns of the inverse Leontief matrix. The multiplier effect of electricity, gas, steam and air conditioning industry is 2.089, which means that for each €1 of input in this industry, an output of value of €2.089 will be obtained. This multiplier is one of the highest since most of the industries multiplier have a value between 1 and 2. Furthermore, in the scenario 2 we also obtain a negative output result for the same reason, the coke multiplier (1.914) is one of the highest even though it does not reach the value of 2. Therefore, if you consume less from an industry that has a high multiplier effect and consume from others with lower multiplier effects, the result in total output will be negative.

The results of this analysis highlight the importance of considering both direct and indirect effects when assessing the impact of energy efficiency policies. Reductions in energy consumption in sectors with high multiplier effects can have significant negative impacts on the total output of the economy. Moreover, redistribution of energy savings does not always result in a net increase in output, as recipient sectors may have lower multiplier effects (Sovacool et al., 2019).

This finding suggests that energy efficiency policies should be designed with a detailed understanding of sectoral interrelationships and multiplier effects. It is crucial to consider not only direct energy savings, but also how these savings are redistributed in the economy and the resulting indirect impacts. Policies that promote energy efficiency must balance reducing energy consumption with promoting economic activity in sectors with high multiplier effects to maximize net benefits (Castillo-Carvajal et al., 2020). Therefore, if the objective of the economic policies decided in scenarios 1 and 2 is to increase domestic production, they will fail because, as we have seen, the result will be negative. In other words, the redistribution of household consumption will not only not increase production but will actually decrease it.

4.2 Economy Wide Rebound Effect

The Economy Wide Rebound Effect (EWRE) refers to the situation in which improvements in energy efficiency do not result in the expected reductions in total energy consumption due to offsetting effects in the economy. In other words, although a more efficient technology reduces energy consumption per unit of output, the cost savings may lead to an increase in energy demand in other sectors or economic activities, partially or completely negating the expected efficiency benefits (Sorrell, 2007). In certain cases, the energy efficiency measures could actually lead to an increase in energy use, phenomenon known as backfire.

This effect manifests itself through several mechanisms. First, the direct effect occurs when the reduction in the cost of using a more efficient technology increases its use. For example, if vehicles become more fuel efficient, drivers may choose to drive more, thus increasing overall fuel consumption. Second, the indirect effect occurs when the cost savings generated by increased efficiency are spent on other goods and services that also require energy for their production and consumption (Gillingham, Kotchen, Rapson & Wagner, 2013).

In addition, there is a macroeconomic effect in which changes in energy prices and production costs impact the economy as a whole. These effects can change consumer and business behavior, altering aggregate energy demand at the macroeconomic level (Barker, Dagoumas & Rubin, 2009).

In summary, by calculating the economy wide rebound effect, we can analyze whether, in this case, a lower consumption by households of an industry's product, for example coke and refined petroleum products, will reduce their domestic demand. Let us make the calculation for this industry, which could resemble a real case of a state attempt to reduce the consumption of non-renewable and therefore finite energy sources, in an effort to mitigate pollution and to switch to more sustainable energy sources.

Firstly, we must calculate **expected energy savings**, which is the is the indirect effect of the shock in industry (10), without taking into account changes in household consumption in the other sectors. To calculate this, we must multiply the Leontief inverse matrix by the column we call in table 4 "Energy Shock", and we will get a decrease in demand of **€2106.05 million** in industry (10).

However, this shock is not realistic, since studies have shown that fluctuations in household consumption are an important driver of business cycles, as savings in one sector are often redistributed to others, partly stabilizing the overall economy (Matthes & Schwartzman, 2021). We must therefore calculate the indirect effect by predicting a redistribution of household demand. The **actual energy savings** is the result obtained in the specific industry by multiplying the inverse Leontief matrix by the column we call “Shock to implement” in table 4. Carrying out this calculation, we obtain **-€2088.28 million**. The last step before calculating the economy wide rebound effect is to adjust savings to the share of household consumption in the total output of the industry in the economy. In order to calculate the adjustment, we must multiply the current energy savings by the share of impacted efficiency of the sector. The formula of the latter is the following,

$$\boldsymbol{Share\ of\ impacted\ efficiency} = \frac{Household\ Consumption}{Total\ Output} = \frac{10{,}161.7}{33{,}414.2} = 0.3041 \qquad (15)$$

Thus,

$$\boldsymbol{Actual\ energy\ savings\ adjusted} =$$
$$Share\ of\ impacted\ efficiency\ \ x\ Actual\ energy\ savings =$$
$$0.3041\ x\ (-2088.28) = -€635.076 \qquad (16)$$

Once the adjustment is determined, we can calculate the economy wide rebound effect,

$$\boldsymbol{Economy\ wide\ rebound\ effect} = \frac{1 - Actual\ energy\ savings\ adjusted}{Expected\ Energy\ Savings}\ x\ 100 = \frac{1-(-635.076)}{-2106.058}\ x\ 100 = 69.845\% \qquad (17)$$

The Economy Wide Rebound Effect (EWRE) result indicates that a large part of the expected energy savings is lost (69.85%) due to offsetting effects on the economy. This implies that energy efficiency improvements, while reducing energy consumption per unit of output, do not always lead to a proportional decrease in total energy consumption.

Therefore, when designing interventions to improve energy efficiency, it is essential to conduct a thorough analysis of potential rebound effects throughout the economy. This includes assessing how savings in a specific sector may affect energy demand in other sectors and the overall economy. Understanding these impacts can help create more realistic expectations about the net benefits of energy efficiency improvements (Matthes & Schwartzman, 2021).

If there were a rebound of more than 100%, what we have previously defined as backfire would be occurring, that is, when the elasticity of demand is such that cost savings lead to a higher energy consumption than the original one. On the other hand, an economy wide rebound effect of 0 would mean that energy efficiency improvements result in a full and proportional reduction in total energy consumption. In this scenario, there are no offsetting effects that increase energy use in other sectors or economic activities. This implies that the energy savings achieved by efficiency are not redistributed or spent on other forms of energy consumption, thus achieving a total net reduction in energy consumption as initially expected.

Lastly, we can also calculate the economy wide rebound effect of the electricity sector using the formulas and we would obtain a result of the electricity, gas, steam and air conditioning sector and we would achieve a result of 74.82%. Therefore, the rebound is higher than in the other industry and therefore the savings are even lower than expected. However, we have focused on the other sector, as governments are more likely to seek reductions in coke and petroleum consumption due to new environmental conservation policies and the finite nature of this energy source.

V. CONCLUSIONS

The analysis carried out in this final degree project focuses on evaluating the economic and social effects of energy optimization in residential use in Spain, with special emphasis on the economy wide rebound effect and the multiplier effect of various industries in the economy. Using the input-output model developed by Wassily Leontief, both the benefits and challenges associated with energy-saving policies were identified, allowing a comprehensive assessment of their impacts on the general welfare of the population.

5.1 Economic and Social Impact of Energy Optimization

Energy optimization in the residential sector not only has the potential to reduce greenhouse gas emissions and energy costs for consumers but can also generate employment and improve the quality of life. However, the results obtained indicate that the expected effects of energy efficiency improvements do not always translate into a proportional reduction in total energy consumption due to EWRE. This phenomenon can significantly reduce the anticipated benefits of energy-saving measures.

The EWRE analysis showed that a considerable portion of the expected energy savings is lost due to offsetting effects on the economy. Specifically, the rebound effect in the coke and refined petroleum products sector was found to be 69.85%, indicating that almost 70% of the expected energy savings are offset by an increase in energy demand in other sectors or economic activities. On the other hand, in the electricity, gas, steam, and air conditioning industry, there would be a rebound effect of 74.818%. This result suggests that energy optimization policies should be carefully designed to consider these effects and avoid a larger than expected rebound.

5.2 Multiplier Effect on the Economy

The input-output model also allowed us to evaluate the multiplier effect of different industries on the Spanish economy. Some industries, such as electricity, gas, steam, and air conditioning, were found to have a significant multiplier effect. In this case, the multiplier effect is 2.089, which implies that for every million euros invested in this industry, an output of 2.089 million euros is generated. This high multiplier effect highlights the importance of the energy industry in the economy and its ability to influence total production.

However, the scenarios analyzed revealed that the redistribution of household consumption does not always result in an increase in domestic production. In the scenarios studied, both the 20% reduction in consumption of electricity and gas products and that of coke and refined petroleum products led to a decrease in total production (-€1412.18 million and -€550.51 million respectively). This is because the industries affected by the reduction in consumption have a significant multiplier effect, and the redistribution of savings does not compensate for the initial loss in terms of economic output.

5.3 Implications for Public Policy

The findings of this study have important implications for public policymaking. Returning to the analysis of the reduction in household consumption of electricity and gas, and coke and refined petroleum products, in both cases it results in a reduction in energy consumption, but much less than expected due to rebound effect phenomenon. On the other hand, the redistribution of household expenditure in both scenarios implies an unwanted reduction in the total output of the economy. Therefore, policies that seek energy efficiency by reducing the consumption of households in these two industries are advisable only if the following aspects are considered.

First, it is essential that energy optimization policies include a thorough EWRE analysis to set realistic expectations about the net benefits of efficiency improvements. Policies should be designed to minimize offsetting effects and maximize actual energy savings (Barker et al., 2009). This could entail encouraging cutting-edge technologies that boost energy efficiency without proportionately raising overall consumption, focusing on particular industries with policies that are specifically designed to address their distinct traits and rebound effects, and teaching consumers about energy conservation to complement technological advancements and lessen the chance of increased consumption elsewhere.

In addition, given the high multiplier effect of certain energy industries, policies should consider strategies that encourage investment in certain sectors while promoting technological innovation and the adoption of more efficient technologies. This may include tax incentives, subsidies, and financing programs that facilitate the transition to greater energy efficiency without compromising economic output.

5.4 Limitations and Recommendations for Future Research

Although the input-output model used in this study provides a powerful tool for analyzing economic interdependencies and the effects of energy optimization policies, it has certain limitations. One of the main limitations is its static nature, which does not adequately capture economic dynamics over time. In addition, the model does not incorporate changes in prices, which can significantly influence consumption and production.

To overcome these limitations, it is recommended to complement the input-output model with dynamic approaches, such as computable general equilibrium (CGE) models, which can provide a more complete and accurate picture of the effects of energy optimization policies. Likewise, the integration of life cycle analysis can provide a more comprehensive assessment of environmental and social impacts, considering the different stages of production and consumption (Lenzen & Treloar, 2003).

In conclusion, this work has shown that energy optimization in the residential sector has the potential to generate significant economic and social benefits, but these may be mitigated by economy wide rebound effects and other offsetting influences. It is crucial that energy efficiency policies are designed with a thorough understanding of these effects to maximize net benefits and promote sustainable development.

Declaración de Uso de Herramientas de Inteligencia Artificial Generativa en Trabajos Fin de Grado

Por la presente, yo, Juan Manuel Martín, estudiante de E-4 de la Universidad Pontificia Comillas al presentar mi Trabajo Fin de Grado titulado "The System Wide Effects of Energy Efficiency in Residential Energy Use", declaro que he utilizado la herramienta de Inteligencia Artificial Generativa ChatGPT u otras similares de IAG de código sólo en el contexto de las actividades descritas a continuación:

1. **Brainstorming de ideas de investigación:** Utilizado para idear y esbozar posibles áreas de investigación.
2. **Crítico:** Para encontrar contra-argumentos a una tesis específica que pretendo defender.
3. **Referencias:** Usado conjuntamente con otras herramientas, como Science, para identificar referencias preliminares que luego he contrastado y validado.
4. **Corrector de estilo literario y de lenguaje:** Para mejorar la calidad lingüística y estilística del texto.
5. **Sintetizador y divulgador de libros complicados:** Para resumir y comprender literatura compleja.
6. **Generador de problemas de ejemplo:** Para ilustrar conceptos y técnicas.
7. **Revisor:** Para recibir sugerencias sobre cómo mejorar y perfeccionar el trabajo con diferentes niveles de exigencia.

Afirmo que toda la información y contenido presentados en este trabajo son producto de mi investigación y esfuerzo individual, excepto donde se ha indicado lo contrario y se han dado los créditos correspondientes (he incluido las referencias adecuadas en el TFG y he explicitado para que se ha usado ChatGPT u otras herramientas similares). Soy consciente de las implicaciones académicas y éticas de presentar un trabajo no original y acepto las consecuencias de cualquier violación a esta declaración.

Fecha: 05/06/2024
Firma: Juan Martín

REFERENCE LIST

Agencia Internacional de Energía (AIE). (2021). World Energy Outlook 2021. Paris: International Energy Agency. Available at: https://www.iea.org/reports/world-energy-outlook-2021

Agora Energiewende. (2020). The German Energiewende: Enabling a secure, affordable and climate-friendly energy system. Available at: https://static.agora-energiewende.de/fileadmin/Projekte/2020/2020_10_KNDE/A-EW_193_KNDE_Executive-Summary_EN_WEB.pdf

Barker, T., Dagoumas, A., & Rubin, J. (2009). The macroeconomic rebound effect and the world economy. Energy Efficiency, 2(4), 411-427. Available at: https://doi.org/10.1007/s12053-009-9053-y

Bulavskaya, T., & Reynès, F. (2018). Job creation and economic impact of renewable energy in the Netherlands. Renewable Energy, 119, 528-538. Available at: https://doi.org/10.1016/j.renene.2017.12.077

Castillo-Carvajal, C., et al. (2020). Energy poverty in Spain: A review of the concept, empirical evidence and policy implications. Renewable and Sustainable Energy Reviews, 124, 109789. Available at: https://doi.org/10.1016/j.rser.2020.109789

Comisión Europea. (2020). Plan de Energía y Clima 2030. Bruselas: Comisión Europea. Available at: https://eur-lex.europa.eu/legal-content/ES/TXT/?uri=CELEX%3A32018L2002

Defourny, J., & Thorbecke, E. (1984). Structural Path Analysis and Multiplier Decomposition within a Social Accounting Matrix Framework. Economic Journal, 94(373), 111-136. Available at: https://www.jstor.org/stable/2232220

Dixon, P. B., Parmenter, B. R., Sutton, J., & Vincent, D. P. (2013). ORANI: A Multisectoral Model of the Australian Economy. North-Holland. Available at: https://www.sciencedirect.com/science/article/pii/S1474667017471102

Duarte, R., Mainar, A., & Sánchez-Chóliz, J. (2016). The impact of household consumption patterns on energy use and CO2 emissions: An input-output analysis for Spain. Energy Policy, 43, 166-177. Available at: https://doi.org/10.1016/j.enpol.2016.02.027

Duchin, F., & Lange, G.-M. (1998). Prospects for the Recycling of Plastics in the United States. Structural Change and Economic Dynamics, 9(3), 307-331. Available at: https://www.sciencedirect.com/science/article/pii/S0954349X97000283

European Commission. (2020). Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 on energy efficiency. Brussels: European Commission. Available at: https://eur-lex.europa.eu/legal-content/ES/TXT/?uri=CELEX%3A32018L2002

European Commission. (2023). Energy efficiency directive. Available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en

García-Quevedo, J., et al. (2018). The impact of energy efficiency on employment in Spain. Journal of Cleaner Production, 183, 1229-1239. Available at: https://doi.org/10.1016/j.jclepro.2018.02.001

Gillingham, K., Kotchen, M. J., Rapson, D. S., & Wagner, G. (2013). The rebound effect is overplayed. Nature, 493(7433), 475-476. Available at: https://doi.org/10.1038/493475a

Instituto Nacional de Estadística (INE). (2024). Annual Spanish National Accounts: main aggregates. 2019 Benchmark Revision (ESA 2010). Available at: https://www.ine.es/dyngs/INEbase/en/operacion.htm?c=Estadistica_C&cid=1254736177058&idp=1254735576581

Instituto Nacional de Estadística (INE). (2021). Encuesta de consumo de energía en los hogares. Madrid: INE. Available at: https://www.ine.es/dynt3/inebase/es/index.htm?padre=1402&capsel=9811

Leontief, W. (1986). Input-Output Economics. Oxford University Press.

Lenzen, M., & Treloar, G. J. (2003). Differential convergence of life-cycle inventories towards upstream production layers. Journal of Industrial Ecology, 6(3-4), 137-160. Available at: https://doi.org/10.1162/108819802766269548

Martín-Dorta, N., et al. (2021). A review of energy efficiency and energy poverty policies in the European Union: Main challenges and lessons for Spain. Renewable and Sustainable Energy Reviews, 135, 110137. Available at: https://doi.org/10.1016/j.rser.2020.110137

Matthes, C., & Schwartzman, F. F. (2021). How Much Does Household Consumption Impact Business Cycles? Economic Brief, No. 21-25. Available at: https://www.richmondfed.org/publications/research/economic_brief/2021/eb_21-25

Matthes, F. C., & Schwartzman, D. (2021). The role of household consumption in driving business cycles. Journal of Economic Perspectives, 35(1), 3-30. Available at: https://www.aeaweb.org/articles?id=10.1257/jep.35.1.3

Miller, R. E., & Blair, P. D. (2018). Input-Output Analysis: Foundations and Extensions (3rd ed.). Cambridge University Press.

Ministerio de Fomento. (2019). Código Técnico de la Edificación. Available at: https://www.boe.es/diario_boe/txt.php?id=BOE-A-2019-18528

Ministerio para la Transición Ecológica y el Reto Demográfico. (2020). Plan Nacional Integrado de Energía y Clima (PNIEC) 2021-2030. Madrid: MITECO. Available at: https://www.miteco.gob.es/es/prensa/pniec.html

Ministerio para la Transición Ecológica y el Reto Demográfico. (2021). Programa de Ayudas para la Rehabilitación Energética de Edificios (PAREER). Available at: https://www.idae.es/ayudas-y-financiacion/para-rehabilitacion-de-edificios-programa-pareer/programa-de-ayudas-para-la

ONU. (2018). Energy Efficiency for Sustainable Development. New York: United Nations. Available at: https://unstats.un.org/sdgs/files/report/2018/thesustainabledevelopmentgoalsreport2018-en.pdf

Rose, A., & Liao, S.-Y. (2005). Modeling regional economic resilience to disasters: A computable general equilibrium analysis of water service disruptions. Journal of Regional Science, 45(1), 75-112. Available at: https://onlinelibrary.wiley.com/doi/10.1111/j.0022-4146.2005.00365.x

Sorrell, S. (2007). The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. UK Energy Research Centre. Available at: https://ukerc.ac.uk/publications/the-rebound-effect-an-assessment-of-the-evidence-for-economy-wide-energy-savings-from-improved-energy-efficiency/

Sorrell, S., Dimitropoulos, J., & Sommerville, M. (2009). Empirical estimates of the direct rebound effect: A review. Energy Policy, 37(4), 1356-1371. Available at: https://doi.org/10.1016/j.enpol.2008.11.026

Sovacool, B. K., et al. (2019). Ten challenges for energy efficiency in the built environment. Energy Policy, 134, 110958. Available at: https://doi.org/10.1016/j.enpol.2019.110958

Tarancon, M. A., & del Río, P. (2007). CO2 emissions and intersectoral linkages. The case of Spain. Energy Policy, 35(2), 1100-1116. Available at: https://doi.org/10.1016/j.enpol.2006.02.009

Togeby, M., Dyhr-Mikkelsen, K., Larsen, A., & Bach, P. (2009). Danish energy efficiency policy: Reaching the target with a comprehensive policy mix. Energy Efficiency, 2(4), 305-320. Available at: https://doi.org/10.1007/s12053-009-9054-x