Climate changes, energy and sustainable development are key issues nowadays in the global scientific and political agendas. These issues have important implications for development process and national policy in all regions of the planet. It is a very complicated task to predict how much the economy of country will grow and how much energy it will need in the near future. We have to note that this growth will strongly modulate CO2 emissions of any country and therefore it will be crucial to make a realistic estimate of the emissions. Also the different feedback-mechanisms, both in climatic and economic system make any predictions highly questionable beyond 5-10 years. However, it is critical to provide accurate information to policymakers in order to design appropriate energy policies for the near future. This book proposes a new methodology that can be useful to estimate CO2 emissions for a given country and to understand the driving forces that guide this process. It is easily transferable to other regions, and time periods. Also it is pedagogically useful for explaining to policymakers the possible ways to design a policy for reducing emissions in a medium term.

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CO2 emissions, energy and sustainable development in Ecuador 1980-2025

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Dedicated to people who believes that We must stand together...
[1]

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October 2014

Abstract

The energy consumption and the growth of the CO_2 emissions related with the growth of the economy represents a challenge requiring a deep analysis and the development of appropriated policies. Several analysis of future changes of the economy of particular countries rely on quantitative point forecasts for which is difficult to achieve a reasonable accuracy. In this dissertation a System Dynamics (SD) model, combined with the design of a set of scenarios, has been developed and applied to Ecuador within a medium term (up to 2025), allowing to estimate the Gross Domestic Product (GDP) and the CO_2 emissions, among other variables.

This research applied a combination of the so called decomposition analysis with a scenario analysis to identify and determine the driving forces of change of CO_2 emissions in Ecuador. A historical, from 1980 to 2010, and a forecast period, from 2011 to 2025, have been considered. Logarithmic Mean Divisia Index (LMDI) to carry out the decomposition analysis has been applied to both the historical and forecast periods, using in the latter case different plausible scenarios of development.

The historical analysis provides insights at both macro and sectoral level, allowing to establish the driving forces of the system: structure, scale, energy mix and, energy intensity. The macro decomposition was based on an extended Kaya identity while the sectoral decomposition tried to offer deeper insights of each productive sector. In addition, the formation of a GDP that depends on renewable energy, which introduces a feedback mechanism in the model, has been introduced to

build the model, which allows to generate a non-trivial evolution of the system.

The four considered scenarios show different emission trajectories, based on the different alternative development paths. In particular, special attention was paid to the effect of a reduction of the share of fossil energy, as well as of an improvement in the efficiency of the fossil energy use. The estimated values (for CO_2 emission and GDP, among others) are given in an aggregate way as well as in terms of sectoral contributions.

In a deeper analysis of the model outcome, we have studied the Environmental Kuznets Curve (EKC) hypothesis for Ecuador in a forthcoming period, 2011-2025 using the proposed scenarios. Our proposal goes a step further than previous contributions, and intends to see under which conditions a country could approach the fulfilment of this hypothesis in the medium term. The results do not support the fulfilment of the EKC, nevertheless, the estimations show that Ecuador could be on the way to achieving environmental stabilization in the near future. Indeed, our estimates show that Ecuador could be able to enter the area of environmental stability (second stage of the EKC) in the medium term (2019-2021). However, to achieve this goal it is essential to implement policies that allow the diversification of energy sources and to increase the energy efficiency in the productive sectors in order to get a more sustainable development.

The final conclusion of this work suggests that emissions can evolve with values higher or lower than the present ones and they will be determined not only by the evolution of the economic growth but also by the development path. Within the development path, economic growth interacts with governance, societal choices and other driving forces.

Resumen

El consumo de energía y el aumento de las emisiones de CO_2 relacionadas con el crecimiento económico suponen un desafío para el desarrollo sostenible que requiere un análisis profundo y el desarrollo de políticas apropiadas. Muchos de los análisis de los futuros cambios en la economía de países o de regiones concretas se basan en predicciones cuantitativas para las cuales es complicado garantizar una precisión adecuada. En la presente investigación, se ha construido un modelo utilizando para ello la técnica de Dinámica de Sistemas (DS) en base a un enfoque de escenarios que permiten realizar estimaciones, a medio plazo (hasta 2025), del Producto Interno Bruto (PIB) y de las emisiones de CO_2, entre otras variables, para el caso de Ecuador.

Esta investigación aplica una combinación del análisis de descomposición y del análisis de escenarios para identificar y analizar las fuerzas impulsoras que provocan el cambio de las emisiones de CO_2 en Ecuador. Se ha considerado para ello el periodo histórico de 1980 a 2010 y una proyección hasta el año 2025. Para el análisis de descomposición se usó el método de Indice de Divisia de la Media Logarítmica (IDML), aplicándolo tanto al periodo de datos (1980-2010) como al periodo de proyección (2011-2025), para el cual se emplearon diferentes escenarios que permitían explorar diferentes formas de desarrollo en Ecuador.

El análisis histórico da una visión a nivel macro a la vez que sectorial, permitiendo diferenciar diferentes fuentes de cambio: estructurales, de escala, de mix energetico, y de la intensidad energética. La descomposición a nivel macroeconómico se basa en una identidad Kaya extendida, mientras que el análisis sectorial intenta ofrecer una visión más

profunda de cada sector productivo. Además, se ha considerado en el modelo un enfoque de la formación del PIB que depende de la energía renovable, lo que introduce un mecanismo de retroalimentación en el modelo y nos permite generar una evolución no trivial del sistema.

Los cuatro escenarios que se consideran muestran diferentes patrones de evolución de las emisiones de CO_2, basados en los diferentes caminos de desarrollo alternativo considerados. En particular, se prestó especial atención al efecto de la reducción de la cuota de energía fósil, así como a la mejora en la eficiencia del uso de este tipo de energía. Los resultados se dan tanto en forma global para el país, como también referidos a cada una de los sectores productivos. Se observó que el efecto de la reducción de uso de energía fósil puede ser igual de efectivo que el aumento de su eficiencia de uso.

En un análisis más profundo de los resultados del modelo, se ha estudiado la hipótesis de la Curva de Kuznets Ambiental (CKA), utilizando para ello los mismos escenarios referidos anteriormente. Nuestra propuesta va un paso más allá de las contribuciones anteriores presentes en la literatura revisada, y tiene la intención de ver en qué condiciones un país podría acercarse al cumplimiento de esta hipótesis en el medio plazo. Los resultados no apoyan el cumplimiento de la CKA, sin embargo, las estimaciones muestran que Ecuador podría estar en el camino de lograr la estabilización de las emisiones de CO_2 (en relación al crecimiento del PIB) en un futuro relativamente cercano. De hecho, nuestras estimaciones muestran que Ecuador podría entrar en el ámbito de la estabilidad ambiental (segunda etapa de la CKA) en torno a 2019-2021. Sin embargo, para lograr dicho objetivo, es necesario implementar políticas que permitan la diversificación de las fuentes de energía y aumentar la eficiencia energética en los sectores productivos con el fin de conseguir un desarrollo más sostenible.

La conclusión final de este trabajo sugiere que las emisiones de CO_2 pueden evolucionar a lo largo de diferentes trayectorias, con niveles de emisiones superiores o inferiores a los actuales, que vendrán determinados no sólo por la evolución del crecimiento económico, sino también por la vía de desarrollo seleccionada. En el camino hacia el desarrollo, el crecimiento económico interactúa con la gobernanza, las opciones sociales y las otras fuerzas impulsoras.

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ACRONYMS

ADF	Augmented Dickey-Fuller
AGE	Applied General Equilibrium
AR	Auto-Regression
BAU	Business As Usual
bbl	Oil Barrel
BEC	Banco Central del Ecuador, Ecuadorian Central Bank
BUSD	Billion United State Dollar
CGE	Computable General Equilibrium
CO	Carbon Monoxide
COE	Compensation of Employees
CSP	Concentrated Solar Power
DA	Decomposition Analysis
EEA	European Environment Agency
EFOM	Energy Flow Optimization Model
EKC	Environmental Kuznets Curve
EU	European Union
FDI	Foreign Direct Investment
FTP	Feed-in Tariff Policies
gCO$_2$e	Grams of Carbon Dioxide Equivalent
GDI	Gross Domestic Income
GDP	Gross Domestic Product
GED	Global Environmental Degradation

GIGO	Garbage Input Garbage Output
GLS	Generalized Least Squares
GMI	Gross Mixed Income
GNP	Gross National Product
GOS	Gross Operating Surplus
GHG	Greenhouse Gas Gases
HDI	Human Development Index
HP	Hodrick and Prescott
ICTs	Information and Communication Technologies
IDA	Index Decomposition Analysis
IEA	International Energy Agency
IPAT	Human Impact, Population, Affluence, Technology
IPCC	Intergovernmental Panel on Climate Change
ISIC	International Standard Industrial Classification of All Economic Activities
kWh	kilowatt hour
LPG	Liquefied Petroleum Gas
LEAP	Long range Energy Alternatives Planning
LMDI	Logarithmic mean Divisia index
MA	Moving Average
MAPE	Mean Absolute Percentage Error
MB	Marginal Benefit
MC	Marginal Cost

MARKAL	Market Allocation
MEDEE	Model for Long-Term Energy Demand Evaluation
NAFTA	North American Free Trade Agreement
NOx	Nitrogen Oxides
PP	Phillip-Perron
PPP	Purchasing power parity
PSM	Productive Sectors Matrix
PV	Photovoltaics
REN21	Renewable Energy Policy for the 21st Century
RGSR	Renewables Global Status Report
RPS	Renewable Portfolio Standards
SD	System Dynamics
SDA	Structural Decomposition Analysis
SEM	Structural Equation Modeling
$S_{P\&M}$	Subsidies on Production and Imports
SOx	Sulfur Oxides
SRRES	Special Report on Renewable Energy Sources
SUR	Seemingly Unrelated Regression
TB	Trade Balance
$T_{P\&M}$	Taxes on Production and Import
UK	United Kingdom
US	United States

• USD	United States Dollar-2005-PPP
• WB	World Bank
• WEC	World Energy Council

The beginning is the most important
part of the work.
Plato

CHAPTER

1

Introduction

1.1 The challenges of sustainable development and energy

Climate change, energy and sustainable development is nowadays a key issue in the global scientific and political agendas. These issues have important implications for the development process and national policy in all regions of the planet. Through Kyoto Protocol, most industrialized nations have committed to reduce their emissions. In particular, *The climate and energy package* in European Union (EU) which is a set of binding legislation aims to ensure that the region meets its ambitious climate and energy targets for 2020[1] [9] and most recently, in May 2014, the United States (U.S.) Global Change Research Program released the *Third National Climate Assessment* (Melillo, 2014) [10], the authoritative and comprehensive report on climate change and its impacts in U.S. where Obama's administration showed its concern on climate change and on its effects.

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[1] These targets, known as the ”20-20-20” targets, set three key objectives for 2020:
i) A 20% reduction in EU greenhouse gas (GHG) emissions from 1990 levels;
ii) Raising the share of EU energy consumption produced from renewable resources to 20%;
iii) A 20% improvement in the EU's energy efficiency [9].

1. INTRODUCTION

Political debates and policy decisions with respect to energy and emissions involve a wide spectrum of fields and competences. National planning and policy processes, including: national development policy, sustainable development, environment, energy, climate and technology in fields such as spatial development, economic development, societal well-being and public education are relevant. Many of this spheres require an enhancement of its knowledge.

The United Nations Conference on Environment and Development, also known as the Earth Summits held in Stockholm (Sweden) in 1972, Rio de Janeiro (Brazil) in 1992 and Johannesburg (South Africa) in September 2002. In 2012, the United Nations Conference on Sustainable Development was also held in Rio (commonly called Rio+20 or Rio Earth Summit 2012). These meetings had a very outstanding outcome and guidance on arrangements for the signatory states in activities related with the environment.

The Rio Declaration on Environment and Development 1992 (UN, 1992) [11] establish that: *Human beings are at the centre of concerns for sustainable development* (Principle 1). *States have the sovereign right to exploit their own resources pursuant to their own environmental and developmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction* (Principle 2). *In order to achieve sustainable development, environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it* (Principle 4). *To achieve sustainable development and a higher quality of life for all people, States should reduce and eliminate unsustainable patterns of production and consumption and promote appropriate demographic policies* (Principle 8). *States shall facilitate and encourage public awareness and participation by making information widely available* (Principle 10). *States shall enact effective environmental legislation* (Principle 11). *Environmental impact assessment, as a national instrument, shall be undertaken by States* (Principle 17) and that *indigenous people, their communities and other local communities, have a vital role in environmental management and development because of their knowledge and traditional practices. States should recognize and duly support their identity, culture and interests and enable their effective participation in the achievement of sustainable development* (Principle 22).

On the other hand, one of the most interesting definitions of *Sustainable Development* refers to *the development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (Principle 3).

A key factor of economic development in countries and the transition from subsistence agricultural economies to modern industrial societies which are oriented to services, is to have an adequate supply of *affordable energy*. Energy is essential to enhance the social and economic welfare and, in most cases, it is essential to attract industrial and commercial wealth. It is a condition, *sine qua non*. to support poverty alleviation, generalize social protection and raise living standards. Note that no matter how essential energy[1] can be for the development, energy is just a medium, it is not the *final goal*, while the *final goal* of sustainable development is to achieve good health, a high standard of living, sustainable energy and a clean environment.

As already mentioned, energy consumption is one of the greatest measures of progress and well-being of a society. The concept of *energy crisis* appears when the energy sources of the society are depleted. An economic model as the present, whose operation depends on continued growth, also requires an equally growing demand for energy. Since fossil energy sources are finite, it is inevitable that at some point the demand can not be supplied and all the system will collapse unless new sources of energy would be discovered or new techniques are developed, as would be the case of renewable energy.

The energy obtained from virtually inexhaustible natural sources is called renewable energy, because this kind of sources contain a vast amount of energy, and also they are able to be regenerated by natural means in relatively short times.

The potential of renewable energy has a great capacity to help meet global energy demand. Furthermore, this type of clean energy has a rapid growth due to the remarkable technical advances that have taken place in recent years and of society.

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[1] It is worthy to note that there are no form of energy: coal, solar, nuclear, wind or any other type, that is inherently good or bad, and each is valid only to the extent that meets the purpose for which it was created.

The commitment to promote this type of development and the rational use of energy, involves setting goals at national and regional levels and define a policy according with these goals.

1.2 Trends in technology of renewable energy

Climate change, peak oil and energy security are the trends that are setting the pace of the global energy transition. New types of technologies are required to supply the growing energy demand and thus stop the historical dependence on fossil fuels. Faced with this challenge, the technologies related to renewable energy are receiving strong incentives and stimuli, leading to a global development. Some of these technologies has become competitive alternatives to traditional energy generation and start having a display and commercial use.

Indeed, the last three decades of investment in renewable energy sources have allowed cost reductions close to 40% in technologies related to biomass, 70% in geothermal and 90% in wind, solar photovoltaic and solar thermal (Arent et at. 2011) [2]. Therefore, it is important to interpret the state of the global trends in development and dissemination of technologies of renewable energy.

This section is intended to show the level of technological development of the main renewable energy technologies. Note that these technologies should be in an advanced stage of its development (deployment and marketing) to have the potential to be used in developing countries such as Ecuador.

1.2.1 Wind energy

Wind power is one of the more mature renewable energy sources in the world and the fastest growing in the last three decades (IEA, 2011a [12], WEC, 2010 [13]). This development has focused on wind turbines on land (onshore) with the three-bladed rotors model. The overall trend of the average cost [1] of wind power shows a marked reduction in the last years and in 2025 is projected to be less than 5

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[1] Average costs refer to the total incurred for the operation of a power plant. These include the costs of investment, operation, maintenance and financing. They are expressed in terms of the energy produced by the power plant during its life cycle (*e.g.* US/kWh) (Wiser et al, 2011) [14].

USD-cents/kWh (see Figure 1.1) (Arent et al., 2011) [2]. Although wind energy is a technology already being marketed and widespread disseminated, it is expected that there would be incremental advances and improvements in its design, more efficient use of materials, reliability and energy capture, reduction of operating and maintenance costs and longer life of the components.

Technological advances may lead to further cost reductions, facilitating its deployment and adoption in developing countries. Wind power prices are competitive compared to traditional energy systems based on fossil fuel. (Wiser et al, 2011 [14]; Arent et al. 2011 [2]). It is estimated that the average cost of onshore turbine technologies will be reduced between 10% and 30% for 2020 and ranges between 15% and 35% by 2030, regardless of cost reductions and incentive policies to facilitate the adoption of these systems (*e.g.* feed in tariff-FIT [1]) (Wiser et al., 2011) [14].

The technological development of other kind of wind energy such as wind turbines (offshore) and even floating turbines at sea are already a reality in developed countries (especially in Europe) (Wiser et al., 2011) [14]. The costs of these technologies are still higher than onshore turbines, since this kind of technology have a lower level of overall development. However, future reductions are also expected in the average costs of these technologies, ranging between 10% and 40% by 2020 and 20% to 45% by 2030 (Wiser et al., 2011) [14].

1.2.2 **Solar energy**

There is a wide range of solar energy technologies for use in heating, lighting, electricity, among others. These technologies have varying degrees of maturity and development. Since the 2000s the fastest growing of renewable energy are solar photovoltaic modules (Arvizu et al., 2011) [16].

Among solar technologies, the most competitive prices compared to traditional energy sources are solar thermal systems for heating and water heating. Others whit are at the stage of deployment and use, at an increasing rate, are photovoltaic (PV) systems for electricity generation. Most installations of photovoltaic systems

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[1] FIT is a policy mechanism designed to accelerate investment in renewable energy technologies. It achieves this by offering long-term contracts to renewable energy producers, typically based on the cost of generation of each technology (Couture, 2011) [15].

correspond to panels on roofs of houses and, connected to the grid of the city (Arvizu et al., 2011) [16]. Note that a trend of decentralized solar energy systems is also starting to be developed.

Other technological options are developing solar power generation systems based on concentrated solar power (CSP) used in some power plants. Designs include dyes sensitized to capture solar energy and solar cells from organic materials. Also, they are developing solar technologies for producing fuels such as hydrogen or hydrocarbons and to store a greater amount of energy in efficient carriers (Arvizu et al., 2011) [16].

Advances in solar thermal technologies for heating show developments enabling longer life of the systems, lower installation costs and higher temperatures. The trend is that these systems may be essential components of all the roofs of houses and buildings. In addition, recent designs in storage and conversion of heat and cold allow use the walls of buildings as active systems of air conditioning and heating (Arvizu et al., 2011) [16].

In PV panel technologies, future developments aimed at improving the performance (efficiency) and environmental and sustainability profiles in the manufacture of the modules. Advances aim to improve not only the panel that captures energy but the entire system (power inverter, battery, control and network) to convert that energy into electricity according to the standards used in end use appliances in houses.

The technological evolution during last four decades in solar energy has allowed a cost reductions of nearly 80% in PV systems. Indeed, since the PV systems reach further deployment in the market, their costs are projected to continue to decline rapidly. Based on these trends of technological development and the increase in the world market, it is projected the average cost of PV systems to be reduced by more than 50% and may reach an average of 7.3 USD-cents/kWh in 2020 (Arvizu et al., 2011) [16].

1.2.3 Bioenergy

Bioenergy production is an option to diversify the energy sources in the world (Kammen, 2004) [17] due to its large energy efficiency, clean and cost-competitive.

Commercial available technologies are: heating and electricity generation through combustion of biofuels. Biofuels come from oil crops, such as biodiesel, and sugars and starches, such as ethanol (Chum et al., 2011) [18].

There are also small-scale systems that use bioenergy to provide heat for cooking, anaerobic digestion systems for treating solid waste and produce methane gas for burning (heating, cooking) and gasifiers.

These technologies use a wide range of agricultural products. Most existing bioenergy systems are mainly based on wood and agricultural residues for the production of heat and electricity, and agricultural crops for the production of liquid biofuels. The energy performance of these systems vary due to the conversion technology and material used (crop residues, pulp). Charcoal is one of the most frequent uses of bioenergy in developing countries, especially in rural areas, however, production can be improved with cleaner and more efficient furnaces (Chum et al., 2011) [18].

Another technology still in development status and still holding high costs is second-generation biofuel. These are manufactured from non-food biomass which crops require less both water and land for its production, or from agricultural and forest residues. It is under investigation and in its early stages of production, biofuels based inedible lignocellulosic biomass, including crop residues and wood production (such as rice husk, corn husk or sawdust), inedible plant crops in which whole plant is used (such as switchgrass) and vegetable oils crops that do not compete for land use (such as biodiesel from microalgae) (Carriquiri et al., 2011) [19]. Biomass is the only renewable energy where can be obtained liquid high energy density fuels to replace fossil fuels in transport by land, air and maritime (Chum et al., 2011) [18].

Trends in bioenergy costs are varied and depend on the prices of agricultural raw materials and on applied technology for conversion and energy use. Hence, the main factors affecting costs are the costs of bioenergy crop production, transportation to processing centers (these two may represent between 20% and 50% of the total average cost) and technical specificities the used technology (Chum et al. 2011) [18].

The cost projections for bioenergy are subject of uncertainty. However, based on the trends of improvement and maturity of the technology, can be estimated a cost reduction close to 40% for the production of ethanol from sugarcane in countries like Brazil and 20% for corn ethanol in U.S. by 2020. Second-generation biofuels based on lignocellulosic materials also have the potential to reduce its cost production in medium term, which could compete with the prices of gasoline and diesel from a barrel of oil at USD 60- 70/bbl[1] (0.38 to 0.44 USD per liter of ethanol) by 2030 (Chum et al., 2011) [18].

1.2.4 Wave and tidal energy

This type of technology is still at an embryonic stage and is not commercially available yet. The industry dedicated to the development of this technology is focused in the design and evaluation of prototypes for harnessing wave and tidal energy (REN 21, 2011 [20] and Lewis et al, 2011 [21]). The only exception is the use of tidal energy through dams, similar to hydroelectric dams design, located in the sea estuaries (Lewis et al., 2011) [21].

Prototypes so far do not converge to a unique design as in the case of wind turbines where the consensus has resulted in a three-bladed model. Due to this fact, there are several options for energy use and a unique design is not likely in this technology. The investment cost and the average cost of electric generation is not yet competitive (between 12 and 22 USD/ kWh) compared to other renewable energy sources, even worse when compared with traditional sources (Lewis et al., 2011) [21].

1.2.5 Geothermal energy

Geothermal is one of the most promising alternatives for energy supply in the long term. A technological option is the use of high temperature fluids to generate electricity through turbines. To this end, there are two alternatives: use the natural hot spring pools or enhanced geothermal systems with the use of artificial fluids (Goldstein et al, 2011) [22].

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[1] An oil barrel (abbreviated as bbl) is a unit of volume whose definition has not been universally standardized. In the U.S. and Canada, an oil barrel is defined as 42 U.S. gallons, which is about 159 liters or 35 imperial gallons, and it can also be defined in those units, depending on the context.

Thermal water reservoir is a mature and reliable technology (it has over 100 years of operation). Enhanced geothermal systems are still in demonstration phase. Geothermal energy has a great potential to generate electricity due to the high levels of efficiency that can be achieved (load factor[1]). This feature is an advantage over other renewables such as solar, wind and hydroelectric, because these technologies, by their variable and intermittent nature, have a fickle electricity production based on the availability of the source that use. Indeed, the global average load factor of geothermal systems for power generation is 74.5%. The new geothermal plants reach higher ground factors 90% (Goldstein et al., 2011) [22].

The power plants based on geothermal reservoirs of hot springs have high initial investment costs, because it is necessary to explore and drill similarly to those of the oil industry wells. However, operating costs are low and do not use fuels. Therefore, the average cost of electricity from these systems is competitive. Depending on the level of utilization of the resource, the range is between 0.03 and 0.17 USD/kWh. The cost of enhanced geothermal systems is still greater than this traditional source (Goldstein et al., 2011) [22].

Technological advances point to improve the reliability and energy recovery as well as increase the life cycle of plants. Therefore, research and development in the exploration of hidden geothermal resources is required. This type of geothermal resource is characterized by not showing water reservoirs, so they are exploited by improved systems. As a result of technological improvements, it is expected that the average cost of generation from geothermal water reservoirs decrease by 7% in 2020 (Goldstein et al., 2011) [22].

1.3 Integration of renewable energies in energy systems

The analysis of the potential of renewable energy for changing the energy matrix is done on the basis of treating them as energy systems rather than from the perspective of technical and economic parameters of each technology (Kriegler, 2011)

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[1] In electrical engineering the load factor is defined as the average load divided by the peak load in a specified time period.

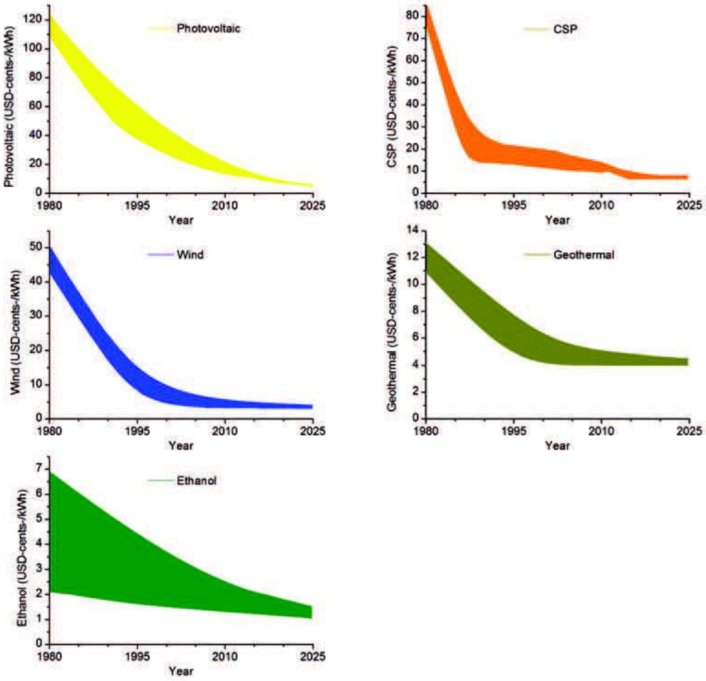

Figure 1.1: Historical trends and projected price of renewable energy based on Arent et al, 2011 [2] data.

[23].

In order to minimize the risks inside an energy system and to have greater reliability in the provision of energy is needed: diversification of energy sources, flexibility and complementarity between adopted technologies, extent of energy infrastructure (interconnection, transmission and distribution), the use of energy storage technologies and mainly of institutional and market mechanisms to improve security and energy supply (Sims et al., 2011) [24]. It is needed well-diversified energy sources to face the challenge of replacing fossil fuels as a primary energy source worldwide, in Latin America and in Ecuador.

According to IPCC (2011) [25], in the best case, about 77% of the world energy matrix can be supplied from the use of renewable resources. Some countries are exploring the possibility of having an energy matrix based 100% on renewable energy sources. Such is the case in Denmark, where by 2030 is aiming to achieve 50% and 100% by 2050. The energy matrix of each country should be based on the resources with the greatest potential in each nation (Lund and Mathiesen, 2009) [26].

Planning for an energy system based 100% on renewable energy sources is physically possible in allocation terms of energy resources. Some authors describe three scenarios regarding the reorganization of the energy systems around the replacement of fossil fuels worldwide. The first is the extensive use of bioenergy to supply the non-electric energy demand (*e.g.,* transportation fuels), in particular the use of biofuels. In this scenario, the biggest challenge is how to organize a sustainable coexistence between agriculture for food, conservation of ecosystems and bioenergy production. The second generation biofuels can make a significant contribution in reducing pressure, using waste water and marginal land, but their development still requires competitive costs (Kriegler, 2011) [23].

The second scenario suggests the production of fuels and energy storage with renewable technologies (other than biomass) . The limitations of renewable energy sources, *e.g.*, intermittency, geographic dispersion and electrical use are removed when used for the production of fuels such as hydrogen. The challenges for this scenario are the massive changes in energy infrastructure in order to use hydrogen at large-scale. However, there are criticisms about cost and efficiency of hydrogen as fuel and energy storage, but certainly this type of energy can be transported to end-uses (*e.g.,* fuel cells in cars) (Kriegler, 2011) [23].

The third scenario considers electrify transport and heating. This scenario requires technologies such as hybrid electric vehicles (plug in), among others, and may be feasible since there is already infrastructure to provide electric energy to end users. Extra advantage is the high efficiency of electric engines. However, it is required to improve battery technology for electric vehicles and the electric transmission grid to incorporate decentralized generation (Kriegler, 2011) [23].

Another challenge is to incorporate decentralized generation systems to the energy matrix. Traditionally, electrical systems were designed to transport energy from large scale power plants (hydroelectric, thermoelectric and nuclear) with high voltages to local distribution networks, with lower voltages. However, due to the disperse distribution of renewable energy sources, energy transition to a greener matrices requires that the grid transmission manage several medium and small generators connected to distribution systems (Bayod-Rújula, 2009) [27].

With the increasing demand of energy and the necessity of decarbonised energy systems, the world is beginning to understand that diversified and decentralized systems make a energy matrix more robust. This robustness has several advantages: lower concentration in few sources, lower risk of natural disasters and climate change effects and greater diversification of energy sources (Ebinger and Vergara, 2011 [28]; Bouffard and Kirschen, 2008 [29]; Nair and Zhang, 2009 [30]).

Decentralized energy systems involves challenges for transmission infrastructure. The management of electricity distribution networks by information, communication and control infrastructure is required, in order to manage the increasing complexity of having several generators connected to the system. In this sense, there are new concepts and perspectives as micro grids, virtual power plants (Bayod-Rújula, 2009) [27] and smart grid (Lindley, 2010) [31].

Smart grid is a concept that involves electrical transmission systems that incorporate the new information and communication technologies (ICTs) with transmission lines and distribution channels (Nair and Zhang, 2009) [30]. The purpose of smart grids is to optimize the operation of the electricity market and create a reliable and affordable transmission. This system would allows multiple options for managing electricity demand in order to reduce the peaks, to have greater efficiency and to interconnect between communities and households to exchange information and energy flows (Lindley, 2010) [31].

1.4 Methodological issues and exploration of future changes

The understanding of future changes in energy and emissions for both policy and reporting in the areas under study start from official data sources such as the World Bank, the International Energy Agency, Central Banks and Institutes of Statistics and Census of a given country or region. To carry out projections of energy use and emissions can be problematic, due to inertia in infrastructure, technology and even culture of each country or region. Note that short term decisions can have long term consequences. They can embed a long term development path that limits or prevents emission reductions and hence an environmental protection. According to Van't Klooster and Van Asselt (2006) [32], studies on the future of a system is complex, as many relations *that may seem to have been continuously developed in retrospect, often follow a non-linear model in future.* Those authors propose that it may be legitimate to hold different and often conflicting perspectives on how the future can reveal. Armstrong (2001) [33] discusses two key sources of uncertainty in forecasting in general. These are overconfidence in forecast due to uncertainty in the causal variables in an econometric model and assumptions about relationships that may not hold over the forecast horizon. Agnolucci et al. (2009) [34] suggest that the past is not necessarily a good guide to the future in the context of energy and emissions. The predictability of energy and emissions and the accuracy of the predictions have been questioned even in the short term.

It is often not possible to make an assessment and ex-post forecast on energy or emissions with high accuracy. Linderoth (2002) [35] among others, described large forecast errors in determining future energy consumption in countries member of IEA. These sometimes conceal the sum of considerable positive and negative forecast errors in the sectors, particularly in industry and transport. This author indicates that the underestimate of transport can have particular consequences for emission reduction policy. Winebrake and Sakva (2005) [36] found a low mean percentage error for total energy consumption concealing an average 5.9% overestimate for the industry sector and 4.5% underestimate for the transport sector in U.S.. O'Neill and Desai (2005) [37] noted that the errors occur not only in absolute values and sectoral consumption, but in GDP growth rates, energy intensity improvement and in fuel mix. This reduces the potential accuracy of forecast of GHG emissions and, as they are an input into policy processes, has potential further consequences. Errors can occur even on short time-scales. Linderoth (2002) [35] concluded that large forecast error can occur even when the forecast year is close to the review year.

Pilavachi et al. (2008) [38] state that the *Energy 2000* study of the European Community in 1985 underestimated consumptions of oil and gas and overestimated solid fuels and renewable energy in 2000 of most of the EU countries. The author found a substantial forecast error over the EU and outlined three areas of uncertainty: $i)$ unanticipated *strong* political decisions, $ii)$ unanticipated energy requirements and $iii)$ data definition and availability. In this context, the potential significance of such *overestimations/underestimations* is not just in meeting targets in environmental protection but also in cost effectiveness and cost benefit analysis of measures to meet targets.

On the short and medium term there is a clear benefit in using sectorally disaggregated scenarios. These can show variation in absolute totals of energy consumption and emissions. They can also illustrate potential divergent trends in, for example, sectoral contribution, economic growth rates and energy intensity change. de Jouvenel (2000) [39] stated that simulation models based on observations of the past are favoured by economists, econometrists, statisticians and forecasters. In addition, the accuracy or scientific quality of forecasts is not guaranteed where results may be arbitrary and subjective because can be subject to the GIGO effect (Garbage In Garbage Out). This method has long been opposed to the scenario method, which is more developed and used by futurists for one simple reason: better a rough but fair estimations than a refined yet incorrect forecast (de Jouvenel, 2000) [39]. In addition, technological and economic realities are implicitly embedded in energy modelling apparatus while results are often promoted as *objective* (Nielsen and Karlsson, 2007) [40]. Middtun and Baumgartner (1986) [41] termed this combination of modelling and politics as *the scientific negotiation of energy futures*. It increases the need for not only reproducible results and published models, but transparent assumptions and dynamics in studies related to energy and emissions modelling.

Note that, even in a short period, uncertainty in emissions projections can arise. This uncertainty is a challenge to probabilistic and predictive methodologies and suggests that scenarios are useful to delimit uncertainty. While forecasts are useful, it can also give an illusion of certainty. The continual revision of the CO_2 and energy projections for different countries and regions by the most of authors illustrates some of the methodological difficulties encountered by forecasting.

1.5 Data sources and data pre-processing

Data sources and statistics collected by an officially recognized national body are usually the most appropriate and accessible data. In some countries, however, those charged with the task of compiling inventory information may not have ready access to the entire range of data available within their country and may wish to use data specially provided by their country to the international organizations. In regard to this dissertation two main types of data sources will be distinguished, on one hand, population and economic activity and on the other, energy and fuels.

1.5.1 Population and economic activity data

Currently, there are two main international sources about population and economic activity statistics: the World Bank (WB), and the International Monetary Found (IMF). Both international organizations collect population and economic statistics from the national administrations of their member countries through systems of questionnaires.

In the case of WB, this database presents population and other demographic estimates and projections from 1960 to 2050. They are disaggregated by age-group and gender and cover approximately 200 economies.

Economic data here covers measures of economic growth, such as gross domestic product (GDP) and gross national income (GNI). It also includes indicators representing factors known to be relevant to economic growth, such as capital stock, employment, investment, savings, consumption, government spending, imports, and exports.

1.5.2 Energy and fuel data

The main international sources related to energy and fuel statistics are: the International Energy Agency (IEA), the United Nations (UN) and in particular in Latin-America the Latin American Energy Organization (OLADE). All this organizations collect energy data from the national administrations of their member countries through systems of questionnaires, thus, data gathered are *official*.

Many countries have long time series about energy statistics that can be used to derive time series about GHG emissions. However, in many cases statistical practices (including definitions of fuels, of fuel use by sectors) will have changed over time and recalculations of the energy data in the latest set of definitions is not always feasible. In compiling time series about emissions from fuel combustion, these changes might give rise to time series inconsistencies, which should be dealt using the methods provided in Time Series Consistency Chapter 5 of Volume 1 of the 2006 IPCC Guidelines [42].

1.5.3 Data pre-processing

Data pre-processing is an important step in the data analysis and model building. The phrase *GIGO* is particularly applicable in these kind projects. Data-gathering methods are often loosely controlled, resulting in out-of-range values (*e.g.*, negative values in population data), impossible data combinations (e.g., Sex: Male, Pregnant: Yes), missing values, etc. Analyzing data that has not been carefully screened for such problems can produce misleading results. Thus, the representation and quality of data is first and foremost before running an analysis (Pyle, D., 1999) [43].

When there is much irrelevant and redundant information present or noisy and unreliable data, the knowledge discovery during the training phase is more difficult. Data preparation and filtering steps can take considerable amount of processing time. Data pre- processing includes cleaning, normalization, transformation, filtering, feature extraction and selection, etc. The product of data pre- processing is the input to analysis and model building phases. Kotsiantis et al. (2006) [44] present a well-known algorithm for each step of data pre-processing.

In modelling and forecasting works, to remove the effect of seasonal, cyclical and irregular components from observed data and work only with the trend part is important. Therefore, decomposition methods in time series to determine the trends, are required. The Hodrick- Pescott (HP) filter is a method to extract the trend component of a time series, proposed in 1980 by Robert J. Hodrick and Edward C. Prescott (Hodrick and Prescott (1980)) [45]. It decomposes the observed series into two components: $i)$ the trend component and $ii)$ the cyclical component. The sensitivity setting of the trend to short-term fluctuations is obtained by modifying a multiplier called λ. It is currently one of the most widely used techniques in research on business cycles to calculate the trend of the time series, as it gives more consistent results with the observed data than other methods.

According to Hodrick and Prescott (1980) [45], HP filter has its origin in the method of *Whittaker-Henderson Type A*, which was first used by actuaries to smooth life tables, but also has been useful in studies of astronomy and ballistics. Kydland and Prescott (1990) justify the use of this filter for its linearity, being well defined without subjective elements, independent of the series to which it applies and easy to replicate to find *the trend that one could draw freehand* (Kydland, E, and Prescott E, 1990) [46].

The reasoning for the methodology uses ideas related to the decomposition of time series. Let y_t, for $t = 1, 2, ..., T$, denote the time series variable. The series y_t, is made up of a trend component, denoted by τ, and a cyclical component, denoted by c, such that $y_t = \tau_t + c_t$. Given an adequately chosen, positive value of λ, there is a trend component that will solve the following equation:

$$min\left(\sum_{t=1}^{T}(y_t - \tau_t)^2 + \lambda\sum_{t=2}^{T-1}[(\tau_{t+1} - \tau_t) - (\tau_t - \tau_{t-1})]^2\right) \tag{1.1}$$

The first term of Equation 1.1 is the sum of the squared deviations $d_t = y_t - \tau_t$ which penalizes the cyclical component. The second term, which is multiple by λ corresponds to the sum of the squares of the trend component's second differences.

This second term penalizes variations in the growth rate of the trend component. The larger the value of λ, the higher is the penalty. Hodrick and Prescott suggest 1600 as a value of λ for quarterly data under the assumption of disturbances having effects during at least 8 years or more permanent. For monthly series is usually used $\lambda = 14400$ and for annual series a value of $\lambda = 100$ is recommended.

1.6 Decomposition of the driving forces of change

It is well known that humans have dramatically altered the global environment, but there is a limited understanding of the driving forces of these impacts. The absence of a refined set of analysis tools is cited as a fundamental limitation (York et al., 2003) [47]. Analysis methodologies and tools have been developed in the field of analysis of decomposition, including sustainability framework known as the IPAT[1] (Commoner, 1972 [48] and Ehrlich and Holdren, 1972 [49]). The decomposition of changes in an aggregate environmental impact and of its driving forces has become popular to unravel the relationship of society and economy with the environment.

The specific application in energy consumption and CO_2 emissions is the so called *Kaya identity* (Kaya, 1990) [50]. The Kaya identity is a linking expression of factors that determine the level of human impact on environment, in the form of CO_2 emissions. It states that total emission level can be expressed as the product of four inputs: population, GDP per capita, energy use per unit of GDP, carbon emissions per unit of energy consumed. The Kaya identity[2] plays a core role in the development of future emissions scenarios in the IPCC Special Report on Emissions Scenarios [51]. The scenarios set out a range of assumed conditions for future development of each of the four inputs. Population growth projections are available independently from demographic research; GDP per capita trends are available from economic statistics and econometrics; similarly for energy intensity

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[1] Human Impact (I) on the environment equals the product of P= Population, A= Affluence, T= Technology. This describes how our growing population, affluence, and technology contribute toward our environmental impact.

[2] Note that, a limitation of this equation is that it does not account for $i)$ the direct release of carbon dioxide by deforestation through burning $ii)$ the loss of the carbon sink due to that deforestation.

and emission levels. The projected carbon emissions can drive carbon cycle and climate models to predict future CO_2 concentration and climate change.

Some similar conceptual bases can be found in the field of index decomposition analysis (IDA). In particular, with the advent of the global oil crisis in 1973 and 1974, special attention was given to the use of energy in industry among policy-makers because energy in industrial constituted most of the primary energy demand in most countries. Therefore, researchers focused on the mechanisms of change in industrial energy use. This new area of research emerged to quantify the impact of a structural change in industrial production on the total energy demand. These initial studies showed a significant impact of structural changes on the trends of energy demand. The need to identify and quantify its impact became an imperative for policy-making. This line of research was expanded considerably in the methodology and in its application, *it is now a widely accepted tool for the formulation of national policies on energy and environment analysis* (Ang, 2004) [52]. It is particularly useful to provide the analysis of contributing factors, such as structural changes and changes in energy intensity. Steenhof et al., (2006) [53] manifested that decomposition of a predefined set of factors helps to understand the progression of the driving forces, the consequences of the processes occurring and the political dimensions associated with these processes. Steenhof et al., (2006) [53] also proposed that this would allow a rationalisation for possible progression into the future.

The scope of the IDA was expanded beyond the analysis of industrial energy demand, now being used in the analysis, at country level, of fields such as energy or environment[1].

The need for *political views* [2] of the IDA has mainly focused on historical analysis of the driving forces. While decomposition techniques such as IPAT can be used to predict future changes in the driving forces of a given system (Waggoner and Ausubel, 2002) [54], IDA is on the cusp of a new scenario analysis techniques

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[1] Energy efficiency measures are required by several international and national policies as the EU directive 2006/32/EC and while these can be executed using tools like IDA and LMDI (Logarithmic Mean Divisia Index) techniques (Ang, 2004) [52].

[2] The development of policy, reporting and monitoring of progress depends on the right as the index decomposition analysis analytical tools.

and forecasting. For defining areas of future research in IDA, Ang and Zhang (2000) [55] suggests its use in projecting energy demand and emissions in short and medium term. Sun (2001) [56] used a complete decomposition method to forecast GHG emissions in the EU-15 up to 2010. Sorrell et al. (2009) [57] recommended more research in the use of the decomposition framework for scenario development. Although both, IDA in energy and emissions, as well as scenario analysis in the context of energy emissions are often based on the framework of Kaya, the combination of these approaches has often not applied. In this line some studies have combined these approaches; Kwon (2005) [58], Steenhof et al. (2006) [53], Steenhof (2007) [59] and Agnolucci et al. (2009) [34].

Agnolucci et al. (2009) [34] used a retrospective approach to scenarios and projection ratios decomposition. This approach was used to generate a predefined result in 2050 to discuss how relationships can be altered to achieve future goals through public policy. Kwon (2005) [58] used scenario analysis to quantify future CO_2 emissions from car travel in the United Kingdom (UK) until 2030 using the IPAT framework. This author built a Business as usual (BAU) scenario and alternatives scenarios to make assumptions about the forecast of each of the factors of the identity used. Steenhof (2007) [59] uses the IDA approach of Laspeyre to build baselines for the electricity sector in China by 2020. This author uses a BAU, conservative and optimistic scenarios with the analysis of time series decomposition (every two years instead of at the beginning and end of year). Steenhof et al. (2006) [53] also combines the decomposition analysis and the use of scenarios to project the burden of GHG in the short term (up to 2012) in Canada. Decomposition analysis was performed on the historical pattern to understand impact of the driving forces, while the scenario analysis provided the means to manipulate these forces in the future. Again BAU scenarios, optimistic and pessimistic have been employed.

In the research present in this dissertation about income growth, energy use and CO_2 emissions for Ecuador in medium term (up to 2025), the specific combination of techniques such as IDA (specifically LMDI approach), the use of exploratory scenarios and the Kaya identity (Kaya, 1993) [50] is trying to help to fill the gap in the regional literature in this topic. This study joins the study of the driving forces of change across both analysis decomposition and scenario analysis.

1.7 Background of scenario analysis

Scenario analysis has a wide history in a large number of sectors and disciplines (Van Notten et al, 2003) [60]. It is an approach to deal with uncertainty that may exist in organizations and governments (Nielsen and Karlsson, 2007) [40]. This type of analysis has been increasingly applied in the field of energy and environment, due to difficulties in providing accurate forecasts (Silberglitt et al., 2003) [61], and to the need for tools to imagining, discuss, and create future scenarios equally plausible. Specifically in the analysis of environmental settings including energy and emissions, there are two currents that could be described respectively as $i)$ *inquiry-driven* and $ii)$ *strategy-driven* (Alcamo et al., 2009) [62]. Inquiry-driven scenario analysis is conducted to meet the needs of the scientific community through expanding the knowledge and as an input to policy analysis. Strategy-driven scenario analysis is mainly due to the business community for corporate planning. The scientific credibility about scenarios theory has been increased due to the wide spectrum of opportunities for study and analysis that this technique offered in different fields.

The scenario analysis allows having a structured view of the future of development in areas such as driving forces, trends, themes, events and the logic of cause and effect. The objective of the scenario-based analysis is not prediction, but the construction and articulation of several different futures and the paths leading to them (Borjeson et al, 2006) [63]. In particular, climate change depends in part on the evolution of humans factors such as anthropogenic GHG emissions, population, economy, etc. Given the uncertainty of future development, the scenarios have been used in the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC, 2000) [51] as the most suitable tool for exploring the future evolution of global emissions of GHG by the year 2100.

To study the evolution of complex systems where elements with behaviour not fully understood exists, the use of scenarios could be compulsory. The scenarios are not predictions or forecasts, but they are used to explore the equally plausible images of future developments (Nakicenovic et al, 2000) [64]. Besides, scenarios have been used as tools to link qualitative and quantitative arguments in modelling.

The scenarios are also used by intergovernmental bodies such as the IEA and the European Environment Agency (EEA).

Certain works based on the use of scenarios have tended to focus on the long term in a world of great uncertainty (Nielsen and Karlsson, 2007) [40]. However, as indicated above, even in the short and medium-term, the application of the scenario methodology has scientific credibility and potential usefulness in policy development. In this dissertation a set of plausible scenarios for the evolution of CO_2 emissions and energy consumption in Ecuador in a medium term (2025) are carry out. These scenarios explore the evolution of the driving forces, both qualitatively and quantitatively. The delimitation of uncertainty in response to questions related to forecast accuracy provides insights into the driving forces of change and explores the potential contribution of different sectors to the total change of emissions.

1.8 Background of analysis models

The economics and environmental models can be divided in two general groups according to their structure: i) *top-down* and ii) *bottom-up* models (Great Britain. Department of Energy. Economics and Statistics Division, 1978) [65].

The top-down analysis method is based on a macroeconomic approach and considers the price of the energy and the elasticity as the main economic indicators to model the relationship between energy consumption and energy production. The top-down method is mainly applicable to the analysis of macroeconomics and to research on development of energy policies. However, this approach cannot control the impact on the economy of advances in technology. Some examples of this approach are the computable general equilibrium (CGE) model[1] based on General Equilibrium Theory and the Input-Output model.

The bottom-up analysis is a technique to build a model in more detailed way. Mainly it aims the construction of models of energy consumption and production for supply-demand forecast and environment impact analysis (Toshihiko, 2004) [67]. The bottom-up model has two branches in terms of research, which were

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[1] CGE models are a class of economic models that use actual economic data to estimate how an economy might react to changes in policy, technology or other external factors. CGE models are also referred to as AGE (applied general equilibrium) models [66].

described by Wei (2005) [68]. The first is based on energy supply and conversion, it is frequently used for the analysis of the introduction of efficient techniques into energy systems and for the analysis on its effects. Typical examples of this approach are MARKAL model, developed by the IEA and EFOM (Energy Flow Optimization Model [1]) model developed by EU [70]. The second branch analyzes and calculates in detail the change in energy demand and consumption caused by the human activities. Representative models are MEDEE (Model for Long-Term Energy Demand Evaluation) model, developed by France and LEAP (Long range Energy Alternatives Planning) model, developed by Stockholm Environment Institute.

Now, we will mention briefly the most relevant models related to energy and emissions, then we will focus on the approach used in this research, System Dynamics (see Section 1.9 in this Chapter).

1.8.1 Input-Output model

Wassily Leontief is credited with developing the Input-Output (I/O model) analysis [71] and he was awarded the Nobel Prize in Economics in 1973 for his development of this model [72], which is still considered as one of the most effective theories to solve the problem of balanced economic growth, as was shown by William (1980) [73]. This approach could help working out the chessboard type of input-output statement and setting up the corresponding linear algebraic equation set to form an economic mathematical model, which could imitate the structure of the actual national economic system and the social production process, to analyze and confirm, comprehensively, the complex relationship among all the sectors in the national economic system and the key production proportional relationship.

1.8.2 LEAP model

LEAP is an integrated modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. This model has

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[1] The Energy Flow Optimization Model (EFOM) is the supply part of the energy model complex of the Commission of the European Communities which has been used for a number of studies during the last decade [69].

been developed by the Stockholm Environment Institute and the Tellus Institute [74]. The model follows the sequence of *resource*, *transition* and *demand*, to assess the energy demand and supply balance at certain region. This model is used to design the energy consumption mode in various development scenarios on the base of the current energy demand of each productive sector. This model also is useful to perform the forecast of social and economic development in the medium and long term with different policy packages and techniques selection modes. The combination of various development modes and their comparison could provide a reference for decision-making about economic and energy development planning in a given country or region.

LEAP model is considerate as a *terminal energy consumption model*. It is mainly focuses on the achievement of the balance in demand and resource transition (Joost, 2004) [75]. Moreover, LEAP uses the existing energy technology and environmental databases to analyze the balance program in terms of cost and pollutant yield. Therefore, LEAP model is suitable to be applied to scenario analysis. It is possible to set up various policies to draft cases of study and then analyze the advantages and shortcomings of them.

1.8.3 MARKAL model

In 1976, the IEA developed MARKAL (Market Allocation) model and promoted many nation initiatives for its use. MARKAL model is an energy system analysis tool based on multi-objective linear planning method. The model is a partial equilibrium model mainly composed of an energy database and a linear planning software. It pays great attention to the energy technologies, it uses 21 kinds of constraint equations to assure supply-demand balance and economic growth, and it sets up an objective function to get an energy program which aim is to get the lowest cost or the minimum pollutant emission. The model is able to be used for optimization and solving, as was shown by Naughten (2003) [76] and Evasio (2004) [77].

1.8.4 SD model

The System Dynamics (SD) is a computer-aided approach to policy analysis and design developed by J. Forrester at Massachusetts Institute of Technology (MIT) in

1956, applicable to modelling and simulating complex systems. SD allows to study the *cause-and-effect* relationship among the factors inside the system and depends on a computer simulation to conduct a quantitative analysis. SD is characterized for dependence on the inherent mechanism of a large complex system to complete the simulation. Thus, once the model is calibrated, it could be used to rightly forecast the system state. SD is also an approach to understanding the behaviour of complex systems over time. It deals with internal feedback cycles and time delays that affect the behaviour of the overall system. What makes different SD from other approaches, to study complex systems, is the use of *feedback-loops, stocks and flows.* These elements, which are described as deceptively simple systems display a bewildering nonlinearity.

This work tries to model, in macro and sectoral basis, the production system of a given country and the use of primary energy and fossil fuel. In addition, this research attempts to use a formation approach of the GDP that includes the effect of renewable energies, which introduces a feedback mechanism. SD is an ideal tool to carry out such a task. Therefore, this approach will allow us to draw robust conclusions about the behavior of the individual components as well as of the whole system.

1.9 The system dynamics approach

SD is an approach to system theory as a method for understanding the dynamic behaviour of complex systems. The basis of the method is the recognition that the structure of any system: the many circular, interlocking, sometimes *time-delayed* relationships among its components, is often just as important, in determining its behaviour, as the individual components themselves. Examples are chaos theory and social dynamics. It is also claimed that because there are often *properties-of-the-whole* which cannot be found among the properties of its *elements*, in some cases the behaviour of the whole cannot be explained in terms of the behaviour of the parts.

SD is currently being used throughout the public and private sector for policy analysis and design (Radzicki and Taylor, 2008) [78]. The best known SD model is probably *The Limits to Growth* (Meadows, Donella H., 1972) [79]. This model predicts that exponential growth that would lead to economic collapse during the 21st century under a wide variety of growth scenarios. The use of SD methodology for the understanding of complex environmental systems has increased significantly in the last decades. SD has been used to study climate change policies and the evolution of the economy (Naill, 1992 [80]; Nordhaus, 1996 [81]; Fiddman, 2002 [82]; Feng, 2012 [83]). Bassi and Baer (2009) [84] carried out an SD study trying to answer whether an annual investment of 1% of GDP to mitigate the negative economic impacts of climate change, would allow for the reduction of GHG emissions in Ecuador.

SD approach involves, in general, the following aspects:

- Defining problems dynamically, in terms of graphs over time.
- Striving for an endogenous, behavioural view of the significant dynamic of a system, a focus inward the characteristics of a system that themselves generates or exacerbates the perceived problem.
- Thinking in all concepts of the real system as continuous quantities interconnected in loops of information feedback and circular causality.
- Identifying independent stocks or accumulations (levels) in the system and their inflows and outflows (rates).
- Formulating a behavioural model capable of reproducing, by itself, the dynamic problem of concern. The model is usually a computer simulation model expressed in nonlinear equations, but it is occasionally left unquantified as a diagram capturing the stock-and-flow/causal feedback structure of the system.
- Deriving understandings and applicable policy insights from the resulting model.
- Implementing changes resulting from model-based understandings and insights.

The theory about SD is extensive, but below we will follow the introduction given by System Dynamics Society [85]. Further information can be found in Garcia (2011) [86].

1.9.1 Modelling and simulation

Mathematically, the basic structure of a formal SD computer simulation model is a system of coupled, nonlinear, first-order differential (or integral) equations,

$$\frac{d}{d_t}x = f(x,p) \tag{1.2}$$

where x is a vector of levels (stocks or state variables), p is a set of parameters, and f is a nonlinear vector-valued function.

Simulation of such systems is easily accomplished by partitioning simulated time into discrete intervals of length d_t. Each state variable is computed from its previous value and its net rate of change $x'(t) : x(t) = x(t-d_t)+d_t*x'(t-d_t)$. The computation interval d_t is selected small enough to have no discernible effect on the patterns of dynamic behaviour exhibited by the model. In more recent simulation environments, more sophisticated integration schemes are available.

In present dissertation, the main use of SD, apart that for calculation the evolution of the system, is for *understanding* the dynamics of complex systems for the purpose of policy analysis and design. The conceptual tools and concepts given by SD, including feedback thinking, stocks and flows, the concept of feedback loop dominance, and an endogenous point of view, are as important as its simulation methods.

1.9.2 Feedback thinking

The feedback concept is at the heart of the SD approach. Diagrams with feedback and causality loops are tools for conceptualizing the structure of a complex system and for communicating model-based insights. Intuitively, a feedback loop exists when information resulting from some action *travels* through the system and eventually returns in some form to its point of origin, potentially influencing future action. If the tendency in the loop is to reinforce the initial action, the loop is called a *positive* or reinforcing feedback loop[1]; if the tendency is to oppose the

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[1] Reinforcing loops are sources of growth or accelerating collapse; they are disequilibrating and destabilizing.

initial action, the loop is called a *negative* or balancing feedback loop[1]. The sign of the loop is called the polarity. Combined, reinforcing and balancing circular causal feedback processes can generate all manner of dynamic patterns.

1.9.3 Loop dominance and nonlinearity

The loop concept underlying feedback and circular causality by itself is not enough, however. The explanatory power and insightfulness of feedback understandings also rest on the notions of active structure and loop dominance. Complex systems change over time. A crucial requirement for a powerful view of a dynamic system is the ability of a mental or formal model to change the strength of influences as conditions change, that is, the ability to shift active or dominant structure. This ability to shift loop dominance comes about endogenously from nonlinearities in the system. Only nonlinear models can endogenously alter their active or dominant structure and shift loop dominance. From a feedback perspective, the ability of nonlinearities to generate shifts in loop dominance and capture the shifting nature of reality is the fundamental reason for advocating nonlinear models of social system behaviour.

1.9.3.1 The endogenous point of view

The concept of endogenous change is fundamental to the system dynamics approach. It dictates aspects of model formulation: exogenous disturbances are seen at most as triggers of system behaviour (like displacing a pendulum); the causes are contained within the structure of the system itself (like the interaction of a pendulum's position and momentum that produces oscillations). Corrective responses are also not modeled as functions of time, but are dependent on conditions within the system. Time by itself is not seen as a cause.

But more importantly, theory building and policy analysis are significantly affected by this endogenous perspective. Taking an endogenous view exposes the natural compensating tendencies in social systems that conspire to defeat many

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[1] Balancing loops can be variously characterized as goal-seeking, equilibrating, or stabilizing processes. They can sometimes generate oscillations, as when a pendulum seeking its equilibrium goal gathers momentum and overshoots it.

policy initiatives. Feedback and circular causality are delayed, devious, and deceptive. For understanding, system dynamics practitioners strive for an endogenous point of view. The effort is to uncover the sources of system behaviour that exist within the structure of the system itself.

1.9.3.2 **System structure**

These ideas are captured in Forrester's (1969) [87] organizing framework for system structure:

- Closed boundary
  - Feedback loops
    - Levels
    - Rates
      - Goal
      - Observed condition
      - Discrepancy
      - Desired action

The closed boundary signals the endogenous point of view. The word *closed* here does not refer to open and closed system in the general system sense, but rather refers to the effort to view a system as causally *closed*. The modeller's goal is to assemble a formal structure that can, by itself, without exogenous explanations, reproduce the essential characteristics of a dynamic problem.

The causally *closed* system boundary at the head of this organizing framework identifies the endogenous point of view as the feedback view pressed to an extreme. Feedback thinking can be seen as a consequence of the effort to capture dynamics within a closed causal boundary. Without causal loops, all variables must trace the sources of their variation ultimately outside a system. Assuming, instead, that the causes of all significant behaviour in the system are contained within some *closed* causal boundary forces causal influences to feed back upon themselves, forming causal loops. Feedback loops enable the endogenous point of view and give it structure.

1.9.3.3 Levels and rates

Stocks (levels) and the flows (rates) that affect them are essential components of system structure. A map of causal influences and feedback loops is not enough to determine the dynamic behaviour of a system. A constant inflow yields a linearly rising stock; a linearly rising inflow yields a stock rising along a parabolic path, and so on. Stocks (accumulations, state variables) are the memory of a dynamic system and are the sources of its disequilibrium and dynamic behaviour.

Forrester (1961) [87] placed the operating policies of a system among its rates (flows), many of which assume the classic structure of a balancing feedback loop striving to take action to reduce the discrepancy between the observed condition of the system and a goal. The simplest rate structure results in an equation of the form $NETFLOW = (GOAL–STOCK)/(ADJTIM)$, where $ADJTIM$ is the time over which the level adjusts to reach the goal.

1.9.3.4 Behaviour is a consequence of system structure

The importance of levels and rates appear most clearly when one takes a continuous view of structure and dynamics. Although a discrete view, focusing on separate events and decisions, is entirely compatible with an endogenous feedback perspective, the system dynamics approach emphasizes a continuous view. The continuous view strives to look beyond events to see the dynamic patterns underlying them.

Moreover, the continuous view focuses not on discrete decisions but on the policy structure underlying decisions. Events and decisions are seen as surface phenomena that ride on an underlying tide of system structure and behaviour. It is that underlying tide of policy structure and continuous behaviour that is the focus of system dynamicity.

There is thus a distancing inherent in the system dynamics approach, not so close as to be confused by discrete decisions and myriad of operational details, but not so far away as to miss the critical elements of policy structure and behaviour. Events are deliberately blurred into dynamic behaviour. Decisions are deliberately blurred into perceived policy structures. Insights into the connections between system structure and dynamic behaviour, which are the goal of the system dynamics approach, come from this particular distance of perspective.

1.10 Hypothesis of environmental Kuznets curve

The Environmental Kuznets Curve (EKC) hypothesis postulates an *inverted-U-shaped* relationship between different pollutants and per capita income, *i.e.*, CO_2 emission of an economy could increased up to a certain level as the income of the economy goes up, after that, this relationship could show a significant change. The EKC actually reveals how a technically specified measurement of environmental quality changes as the income of a country changes. A rich literature on EKC has grown in recent years. The common point of all the studies is the assertion that the environmental quality deteriorates at the early stages of economic development/growth and subsequently improves at the later stages. In other words, environmental pressure increases faster than income at early stages of development and slows down relative to income growth at higher income levels (see Figure 1.2).

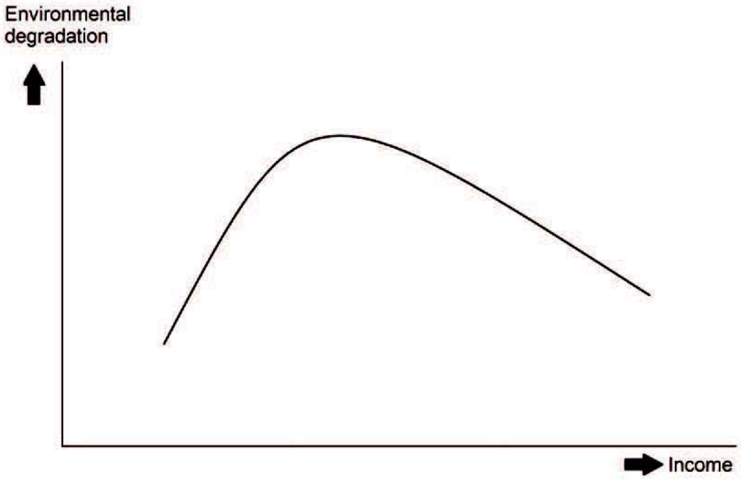

Figure 1.2: Environmental Kuznets Curve.

The name EKC of the *inverted-U* relationship comes from of the work of Kuznets (1955) [88] who postulated a *inverted-U* relationship between income inequality and economic development. The logic of EKC hypothesis follows the general intuition. In the first stage of industrialization process, pollution grows rapidly because high priority is given to increase material output, and the economy is more interested in create jobs and income than to maintain clean air and water (Dasgupta et al., 2002) [89]. The rapid growth due to a industrialization process inevitably results in greater use of natural resources and emission of pollutants, which in turn put more pressure on environment. The country are too poor to pay for abatement, and/or disregard environmental consequences of growth. In a later stage of industrialization, as income rises, the government and people value the environment more, regulatory institutions become more effective, green energy and energy efficiency are more frequent and pollution level declines. Thus, EKC hypothesis posits a well-defined relationship between level of economic activity and environmental pressure (defined as the level of concentration of pollution or flow of emissions, depletion of resources, etc.). The EKC reveals how a technically specified measurement of environmental quality changes as the income of a country.

In brief, Environmental Kuznets Curves are statistical tool that summarize important aspects of collective human behavior in two dimensional space where pollution indicators are plotted against income per capita.

1.10.1 Policy implication for EKC

Nowadays EKC has become standard fare in technical conversations about environmental policy. Understanding the impact of economic growth on environmental quality is becoming increasing important as environmental concerns are making their way into main public policy agenda (Anderson and Cavandish, 2001) [90].The policy implication of EKCs is that promoting economic growth is a sufficient criteria to safeguard the environment. In the long run, the surest way to improve the environment is to *become rich* (Beckerman, 1992) [91]. But environmental policies may or may not be implemented when economy develops (Shafik and Bandyopadhyay, 1992) [92]. There are several points that obstruct a clear policy conclusion derived from the EKCs. The work of Dinda (2004) [93] collects some questions about related policies with EKC, such as:

- *Is EKC valid for all types of environmental pressure?* Empirical evidences suggest that environmental problems may be solved at higher levels of income only for some environmental quality indicators. This is true when there is a direct link between environmental quality and human health impacts (Gangadharan and Valenzuela, 2001) [94]. The EKC applies only to environmental problems that are easy to solve and which are well documented and well known.

- *Is EKC permanent?* The EKC hypothesis assumes that the initial increases in environmental pressure are temporary, but that the subsequent decreases in environmental pressure are permanent. Only a few number of authors have questioned whether these observed decreases could also be a temporary phenomenon due to technological limitation (Dinda et al., 2000) [95]. Grossman and Krueger (1995) [96], de Bruyn and Opschoor (1997) [97] and Sengupta 1997 [98] among other found *N*-shaped curve evidence. An upswing of EKC can be explained by the difficulty of keeping up efficiency improvements (innovation) with continuing growth of production.

- *Is EKC valid both for individual countries and for the World?* In general, EKC estimates use cross-section panel of countries. Such estimates do not guarantee that over time, individual countries will move along the estimated relationship (de Bruyn et al., 1998) [99]. The results of panel countries and that of individual or sub-sample countries vary widely (Dijkgraaf and Vollebergh, 1998 [100]; Stern and Common, 2001 [101]). Developed countries are often associated with lower emission reductions but in developing countries, the environmental pressure increases over time. Developing countries have not yet reached income levels high enough to be able to derive their turning points (TP). The worldwide emission prospects are not optimistic as it might be expected on the basis of EKC results. According to EKC hypothesis, the improvements in environmental quality are not attainable for the majority of the world population that has the standards of living substantially below the estimated turning points (Stern et al., 1996) [102]. Therefore, worldwide emissions are expected to continue to increase due to economic growth (Selden and Song, 1995) [103].

- *Does EKC follow a sustainable development path?* EKCs represent the patterns of flows of pollutants, whereas environmental impacts are often characterized as a stock problem (Arrow et al., 1995) [104]. The EKC, therefore, does not necessarily reflect a sustainable time path of pollution (Dinda, 2003a [105]; Ekins, 1998 [106]; Gruver, 1976 [107]; Zang, 1998 [108]). Maximum level of pollution depends on costs and benefits of pollution abatement, which differ among countries. Differences in absorptive capacities, social preferences and discount rates give rise to different cost–benefit structures, which implies different optimal levels of pollution among countries. This limits the policy relevance of an estimated collective turning point for a whole sample of countries. There is no guaranty that the rising part and top of EKC bypass ecological thresholds and sustainability constraints beyond which environmental deterioration will become irreversible (Arrow et al., 1995 [104]; Panayotou, 1997 [109]). Note that a positive answers to these questions would grant the EKC policy relevance. Negative answers would indicate that the validity and policy relevance of EKCs is partial with respect to countries, indicators, time and cost-effectiveness.

Restructuring the environment may become unnecessarily expensive, and it may be less costly to prevent or abort today than in future (Dinda, 2004) [93]. Most of authors agree that environmental policies are key determinants of the future path of income–environment relationship. The environmental policy is a function of the preferences of society. Actual levels of environmental quality depend on weights placed on various heterogeneous societal preferences by policy makers, which can be generally characterized as the policy regime. One major determinant of environmental policy is the socio-political regime of a particular country.

1.10.2 A critique of EKC

It is clear that EKC can take shape from a multiplicity of possible outcomes of economic development. The EKC model has elicited conflicting reactions from researchers and policymakers. The stakes in the EKC debate are high for both developing and developed countries. Therefore, a special attention is required for multiple factors that form the economic–environmental system, rather than a single dominant one (Ezzati et al., 2001) [110]. It is a very hard task to determine the factors that may dominate and govern the EKC shape due to that these factors are interdependent. The uses of reduced form models deny any insight into the underlying causes of EKCs. Since both income and environmental quality are endogenous variables, *i.e.*, they impact each other, therefore, the estimation of a single equation relationship where simultaneity exists will produce biased and inconsistent estimates (Hung and Shaw, 2002) [111]. The lack of information on the process causing the down-turn in the curve of pollution beyond a particular income level, makes a very difficult task the design of a specific policy from EKC study. The EKC analysis thus has significant deficiencies. There are increasing grounds to be cautious about EKC hypothesis [93].

1.10.2.1 **A conceptual critique**

It is clear from the existing literature that most of the world's population lies on the upward sloping portion of EKCs. Therefore the environmental quality may also deteriorate as population pressure increases more and more. This implies that, even if the EKC exists, income growth across the global population will increase environmental damage (Ekins, 1998) [106]. Such damage is considered to be the main obstacle or hindrance to attaining sustainable development (O'Neill et al., 1996) [112]. Thus, economic growth may not automatically lead to a higher environmental quality and only strong pressure for environmental policy may help in this regard (Grossman and Krueger, 1995) [96]. Better policies and institutional setup can help to flatten the EKC (Panayotou, 1997) [109].

Environmental policy is designed on the basis of empirical findings, which actually depends on the choice of appropriate variables (measured in terms of relative or absolute level). Empirical studies have mostly used absolute measure of pollution like amount of emission or pollution rather than a relative measure (like pollution or emission per unit of output or per square kilometer, etc.). Use of a relative measure of pollution or emission, *i.e.*, pollution intensity, may reveal a *U*-shape or a monotonic relation with income rather than an inverted-*U*-shape (which may be true for absolute level). For example, incorporating spatial intensity of economic activity may turn the relationship between per capita income and atmospheric concentration of SO_2 upside down (Kaufmann et al., 1998) [113]. It should be noted in this context that the effect of income on pollution intensity tends to be negative in open economies, but positive in the closed ones (Dinda, 2002 [114]).

The objective of an empirical study is not only to find the existing relationship but also to help predict the future. Forecasting (or predictions) of environmental quality actually depends on the estimated income-environment relationship (which is based on observed data). Prediction will be meaningful and correct if the existing relations hold in future. Predictive success is really a very limited conception over a longer period of time. For example, the immediate past has allowed much growth and technological progress that does not mean the same holds for an indefinite period of time into the future. The existence of EKC does not ensure to exist in future because of pressures of global competitions for environmental standards and regulations. The EKC analysis does not yet establish the channels through which economic globalization affects the pollution levels or existing environmental quality (Tisdell, 2001) [115].

1.10.2.2 **A methodological critique**

As previously mentioned, several authors have applied various methodologies in their empirical studies. Most of the studies have used cross-section data to examine the EKC hypothesis for group of countries and enough attention has not been given to country-specific EKC. The basic assumption behind pooling the data of different countries in one panel is that economic development trajectory would be the same for all. This assumption should be criticized because wide cross-country variations are observed in social, economical, political and biophysical factors that may affect environmental quality (for example, the quantity and quality of natural resources varies from country to country). Under such heterogeneity of conditions, the use of random effect model may be appropriate for examining shape of economic growth–environment relationship based on cross-country, cross-sectional data (Koop and Tole, 1999) [116].

It should be noted that empirical support for the existence of a global EKC for CO_2 emissions has not been found, although some meaningful relationships between income and CO_2 emissions in individual countries have been observed

(Dijkgraaf and Vollebergh, 1998) [100]. The coefficient estimates for carbon emissions[1] for a panel of OECD countries differ from those obtained for individual country-specific time series that constitute the panel. Little attention has been paid to time series properties of the data, whether variables used in EKC are stationary or/and integrated (Perman and Stern, 1999 [120]; Coondoo and Dinda, 2002 [121]).

A number of relevant factors have so far been omitted in the EKC studies, such as transboundary and intergenerational externalities (Ansuategi et al., 1998 [122] ; Copeland, 1995 [123]). Trade is supposed to be an important explanatory factor for EKC relationship. As argued above, high-income countries have greater emission reduction possibilities because they may shift polluting industries to other countries through trade. The export and import of manufactured goods are likely to be much stronger determinants of the level of energy consumption than income (Suri and Chapman, 1998) [124]. The amount of energy consumption depends on its prices. Thus, the energy price may be a relevant variable for explaining EKC (Agras and Chapman, 1999) [125].

The non-availability of actual data on environmental quality is the major limitation of all EKC studies. Truly speaking, environmental quality is something that is not easy to be measured accurately. Therefore, an index of environmental quality, which could be better measurement, should be developed and used to examine the EKC hypothesis (Fare et al., 2001) [126].

The empirical robustness of EKC relation still remains an open issue (Grossman and Krueger, 1996) [127]. The reduced form rather than structural form equations have been used in most of the EKC studies. Actually, environmental outcomes are related to endowments of individual countries but (economic measures in) reduced forms are silent about causal mechanisms. More structural forms may warrant exploration, for some interdependence, in our environmental indicators (Dinda and Coondoo, 2001) [128].

In sum, the criticisms collected show some of the weaknesses of both the EKC hypothesis itself and the empirical studies that have been conducted to contrast it.

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[1] In this case, non-parametric, Bayesian or/and agent based approach can fit the data better than regression models (Taskin and Zaim, 2000 [117]; Halkos and Tsionas, 2001 [118]; Bartoszezuk et al., 2001 [119]).

Therefore, it is important to advance in the research of the relationship between income and environment. Precisely for the need to provide more detailed information than that provided by global EKC studies, EKC studies are recommended by specific country such as we will carry out in Chapter 5.

1.10.3 Lessons from the EKC studies

Dinda (2004) [93] states that the outcome of EKC inspired a large amount of research. A number of important lessons for the EKC debate are already emerging from the literature.

Local versus global pollution: The EKC relationships are more likely to hold for certain types of environmental damage, *e.g.*, pollutants with more short-term and local impacts, rather than those with more global, indirect and long-term impacts (Arrow et al., 1995 [104]; Cole et al., 1997 [129]; John et al., 1995 [130]).

The role of national and local policy: Most of the EKC studies have concluded that income–environmental degradation relationship is likely to be affected significantly by national and local policies. Several studies in this issue have attempted to estimate the influence of policy explicitly. The strong policies and institutions in the form of more secure property rights, better enforcement and effective environmental regulations can help to *flatten* the EKC (Panayotou, 1997) [109].

Country specific effects: A more productive approach to the analysis of the relationship between economic growth and environmental impact would be the examination of historical experience of individual countries, using econometric and also qualitative historical analysis (Stern et al., 1996) [102].

Structural change: Some authors have attempted to explore empirically which structural factors are responsible for EKC. The scale and the composition of economic activity, and techniques of production (Grossman and Krueger, 1991 [131]; Vukina et al., 1999 [132]; Xiaoli and Chatterjee, 1997 [133]) may lend explanatory power to the observed relationships between income levels and measures of environmental impacts. Although structural change is a very intuitive notion, empirical evidence is found for the impact of difference in the structure of production on polluter manufacturing emissions (Lucas et al., 1992) [134].

Technological progress: In general, technological progress leads to greater efficiency in the use of energy and materials. Therefore, a given amount of goods can be produced with successively reduced burdens on natural resources and environment. One aspect of this progress may be better and more efficient reuse and recycling of materials, which (coupled with greater efficiency in use) can yield large resource savings [93].

Research and development: As income grows, people can adopt better and more efficient technology that provide cleaner environment. This preferential behaviour of people should be reflected through their income elasticity. The income elasticity of public research and development funding for environmental protection is positive (Komen et al., 1997) [135]. The effect of economic growth on pollution/emissions differs substantially among high-income countries. Relative income and political framework in which policy decisions are taken, determine the emergence of downward sloping segment of EKC. This also depends on the adoption of new technologies.

Innovation and adoption: New technologies, unambiguously, improve productivity but create potential dangers to the society such as new hazardous wastes, risk and other human problems. These effects are unknown in the early phase of diffusion of technology, but in later stages, regulation becomes warranted to address it. Once the technology is regulated, this may stimulate the gradual phase out of existing technology. Then, a cyclical pattern arises in technologies, which first diffuse, after become regulated and finally are phased out by next generation of technologies (Smulder and Bretschger, 2000) [136].

Technological and organizational change: Improved technology not only significantly increases productivity in the manufacture of old products but also the development of new ones. There is a growing trend among industries to reconsider their production processes and thereby take environmental consequences of production into account. This concerns not only traditional technological aspects but also the organization of production as well as the design of products. Technological changes associated with the production process may also result in changes in the input mix of materials and fuels (Lindmark, 2002) [137]. Material substitution may be an important element of advance economics (Labys andWadell, 1989) [138] that may result in lower environmental impacts. The economy-wide reforms often contribute simultaneously to the economic, social and environmental gains (Anderson and Cavandish, 2001 [90]; Pasche, 2002 [139]).

The EKC approach seeks to relate the stages of economic development of a country to that of environmental degradation. Developing countries could learn from the experiences of already industrialized countries, and restructure growth and development to tunnel through (Munasinghe, 1999) [140] any potential EKC-thereby avoiding going through the same stages of growth that involve relatively high (and even irreversible) levels of environmental harm.

However, it is not clear which effective environmental policies should be covered to reduce pollution. But, almost all studies investigating EKCs have alluded to the important policy implications (Dinda, 2004)[93].

1.11 The goals of the dissertation

The general objective of this research is to create a useful methodology to estimate CO_2 emissions for a given country, in particular for Ecuador, and to understand the driving forces that guide this process, such as economic growth, energy use, energy mix structure, and fuel use in the productive sectors. The proposed methodology tries to be easily transferable to other countries, regions, and time periods and to be used as a *pedagogical tool* for explaining to policymakers the possible ways to design a policy for reducing CO_2 emissions in a medium term horizon.

A multi-scenarios approach is used to analyze the evolution of energy consumption and energy-related emissions and its implications in the socio-economic and environmental development of the study area. This study could help the development and implementation of proactive policies to the challenge of sustainable development.

The application of *scenario analysis-modelling* in the short-to-medium term is intended to develop insights into plausible future changes with green goals in the driving forces of the national policies. While the decomposition analysis gives insights into historical change. The combination of scenario analysis-modelling, decomposition analysis and EKC hypothesis in this study gives rise to the following specific research objectives:

1. To identify and analyse the historical pattern of income, energy use and the related CO_2 emissions in Ecuador (1980-2010) by applying decomposition analysis in sectoral level.

2. To study in detail the way the changes in the energy matrix and in the Gross Domestic Product (GDP) will affect CO_2 emissions of the country. In particular, we will pay special attention to the effect of a reduction of the share of fossil energy, as well as of an improvement in the efficiency of the fossil energy use.

3. To develop a set of integrated qualitative and quantitative baseline scenarios at both macro and sectoral level to explore plausible alternative development of income, energy use and CO_2 emissions in a medium term (2025) in Ecuador.

4. To test the existence of the EKC hypothesis in Ecuador in the different proposed scenarios. Our proposal goes a step further than previous contributions, and intends to see under which conditions the country could approach the fulfilment of this hypothesis in the medium term.

5. To fill the gap in the literature of studies on the relationship between emissions, energy consumption and income growth in Latin American countries in general, and in Ecuador in particular.

This study combines decomposition analysis with scenario modelling to create a baseline prevision as guidance for possible new policies. This allowed the development of a model with a set of integrated exploratory scenarios about income growth, energy use and CO_2 emissions for Ecuador in a medium term (2025). The scenarios show plausible more *environmental-friendly* trends that the country could take like pathways to get closer to a sustainable development. The study offers potential *longer-term insights* through the exploration of changes in the driving forces to evaluate the fulfillment of the EKC hypothesis.

1.12 Overview of thesis chapters

The thesis is organized into six chapters and seven appendices. Chapter 1 shows the introduction of the most important aspects of the methodology and aims of the research, the following, Chapter 2 shows the main figures of economy, productive sectors, energy use, etc., in Ecuador since 1980 until 2010; also it discusses about critical factors for the adoption of renewable technologies in the country.

Chapter 3 presents a System Dynamic (SD) model approach of CO_2 emissions in Ecuador in the upcoming years, up to 2025 [141, 142]. In this chapter, the way the changes in the energy matrix and in the Gross Domestic Product (GDP) will affect the CO_2 emissions in the country is studied. In particular, it will pay special attention to the effect in emissions of a reduction of the share of fossil energy, as well as of an improvement in the efficiency of the fossil energy use. The results obtained with the model are the starting point for the decomposition analysis in Chapter 4 and for the study of Environmental Kuznets Curve (EKC) in Chapter 5.

Chapter 4 presents a decomposition analysis of income and energy-consumption related CO_2 emissions. Also a review of the main decomposition techniques is shown. Since one of the goals of this research is to analyze the effects of scale, structure and intensity on CO_2 emissions in Ecuador, LMDI approach for this case study has been selected. Note that, the kind and level of disaggregation of the data available for the country are supporting the LMDI approach used. We use three periods of 16 years to perform the analysis, two within the set of historical data (1980-1995 and 1995-2010) and the last one corresponds to the estimate period (2010-2025). This analysis will allow us to determine the relative importance of each term related with CO_2 emission.

In Chapter 5 we try to respond *if is it possible for a country in the process of development to comply with the EKC hypothesis in the medium term?* This chapter uses the model that has been developed previuosly to analyze whether the EKC hypothesis holds within the period 1980-2025 under four different scenarios [142, 143]. We used co-integration techniques [144] to test the existence of the EKC hypothesis in Ecuador in the medium term using the Jaunky's specification [145]. Our proposal goes a step further than previous contributions, and intends to see under which conditions a country could approach the fulfilment of this hypothesis in the medium term. Results do not support the fulfilment of the EKC, nevertheless, our estimations show that Ecuador could be on the way to achieving environmental stabilization in the near future if economic growth is combined with an increase in the use of renewable energies, an improvement of the productive sectoral structure, and the use of a more efficient fossil fuel technology.

Finally, in Chapter 6 summary and conclusions are drawn from research findings. Scopes for further research and limitations are also discussed.

The indifferent men to the misfortunes of the nation, whether privately laborious, are auxiliary unaware of corruption and misery of the people.

Eloy Alfaro

CHAPTER 2

Ecuador in figures (1980-2010)

2.1 Overview

Ecuador (officially the Republic of Ecuador) has an area of 272046 km^2 and a population of more than 15.49 million (2012) (WB, 2012) [146]. The population growth rate has shown a downward trend since 1980. During the period 1981-1995, the growth rate was 2.42% and the population multiplied by 1.39, while in the period 1996-2010, the growth rate was 1.25% and the population grew by 1.25 (see Figure 2.1). Ecuadorian territory, which includes the Galapagos Islands, 1000 km off the west coast, has the planet's densest biodiversity. This species diversity makes Ecuador one of the 17 mega-diverse countries in the world (CI, 2012) [147]. The new Ecuadorian constitution of 2008 is the first one in the world to recognize legally enforceable rights of Nature, or ecosystem rights (TCELDF, 2011)[148].

Ecuador is a medium-income country with a Human Development Index score of 0.724 in 2012 (UN Development Program, 2012) [149] and about 35.1% of its population lives below the poverty threshold (IM, 2014) [150]. Its economy is the eighth largest in Latin America and experienced an average annual growth of 6.48% in the period 2011-2012 (WB, 2014) [151].

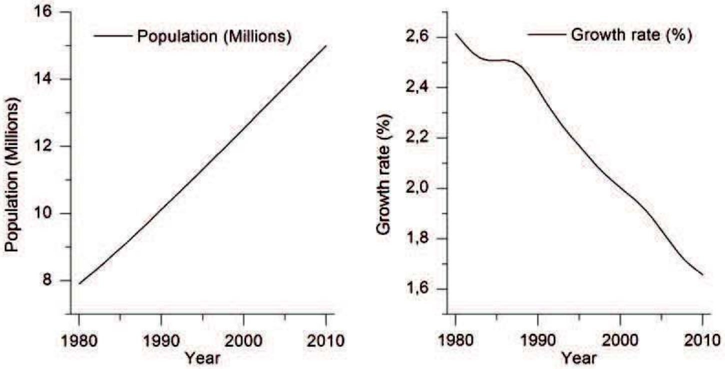

Figure 2.1: Left: Evolution of population in Ecuador 1980-2010. Right: Growth rate.

The Ecuadorian income was multiplied by 2.35 times between 1980 and 2010, and the GDP reached a value of around 131 billion US- 2005-PPP[1] dollars (USD) in 2012 (WB, 2014) [151]. Note that the country's public finances are healthy, but they have recognized that the Achilles heel of the Ecuadorian economy is the external sector, due to the deficit, without including oil exports, in the trade balance [152]. Since the late 1960s oil extraction increased. Proven reserves of the country in 2013 are estimated at around 8 billion barrels (IEA, 2013 [153]; Ecuadorian Central Bank, 2012 [152].

The extreme poverty[2] rate has declined significantly between 2000 and 2010. In 2000, the estimate was approximately 20.7% of the population, while by 2010 this number has dropped down to 4.6% of the total population. This is largely explained by emigration and the economic stability achieved after the dollarization of the economy. Poverty rates were higher for indigenous peoples, afro-descendants and rural areas, reaching 44% of the native population (WB, 2012) [146].

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[1] Purchasing power parity. An international dollar has the same purchasing power over GDP as a U.S. dollar has in the United States.

[2] Population below 1.25 USD a day is the percentage of the population living on less than 1.25 USD a day at 2005 international prices.

2.2 Economic figures

Ecuador is substantially dependent on its petroleum resources, which have accounted for more than half of the country's export earnings and approximately two-fifths of public sector revenues in recent years. The average growth rate of GDP in the period 1980-1997 was 2.4% (see Figure 2.2), with an income per capita around of 5500 USD (WB, 2012) [146]. In 1998-1999, the economy of Ecuador suffered a banking crisis, with GDP contracting by 6.3% and poverty increasing significantly. Per capita income went back to values of a decade earlier (around 5300 USD) (WB, 2012) [146]. In March 2000, the Congress approved a series of structural reforms that including for the adoption of the U.S. dollar as legal tender. Dollarization stabilized the economy, and positive growth returned in the country, helped by high oil prices, remittances, and by increased non-traditional exports (TCELDF, 2011) [148].

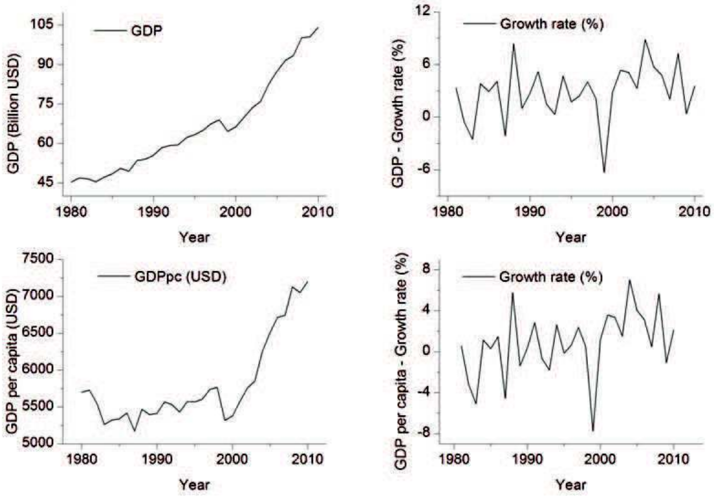

Figure 2.2: Left: Evolution of GDP and GDP per capita in Ecuador 1980-2010. Right: Growth rate.

Between 2002 and 2006 the economy grew an average of 5.54% per year, the highest five-year average in last 25 years and is the first time that the per capita income exceeds 6000 USD (see Figure 2.2). After moderate growth in 2007 (2.04%), the economy reached a growth rate of 7.24% in 2008 and per capita income breaks the barrier of 7000 USD (WB, 2012) [146], buoyed by high global petroleum prices and increased public sector investment. Present President Rafael Correa (who took office in January 2007) defaulted sovereign debt of Ecuador in December 2008, which with a total face value of approximately 3.2 billion USD, represented about 30% of public external debt of the country. In May 2009, Ecuador bought back 91% of its ”defaulted” bonds via an international reverse auction (IM, 2014) [150].

Some economic policies under Correa administration to cancel a number of international treaties, which in the opinion of the government are not beneficial to the country[1], have generated economic uncertainty and discouraged private investment. The Ecuadorian economy slowed to under 1% growth in 2009 due to the global financial crisis and to the sharp decline in world oil prices and remittance flows. Growth picked up to 3.58% in 2010 with an income per capita of 7200 USD (WB, 2012) [146] and nearly 8% in 2011, before falling to 5% in 2012 [151]. China has become Ecuador's largest foreign lender since Ecuadorian government defaulted in 2008, allowing the government to maintain a high rate of social spending; Ecuador contracted with the Chinese government for more than 9 USD billion in oil for cash and project loans in December 2012 (IM, 2014) [150].

Given the availability of data and following the division of the productive sectors of Ecuadorian government (Mosquera, 2008) [154], the productive sectors matrix (PSM) used in this study consists of 5 sections: $i)$ Agriculture, fishing and mining, $ii)$ industry, $iii)$ construction, $iv)$ trade and public services and $v)$ transport. Note that this is not the standard division of the productive sectors, but it is the most appropriate according to the structure of the available data-set and to the goal of this work[2]. In Figure 2.3 can be observed that the largest sector is Trade

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[1] For example, an announcement in late 2009 of its intention to terminate 13 bilateral investment treaties, including one with U.S.

[2] The usual standard division of productive sectors follows the ISIC specification (International Standard Industrial Classification of All Economic Activities, Rev.4). In particular, the aggregate classification of different economic activities of the same level is: Primary Sector (agriculture, hunting, fishing, ...), Secondary Sector (manufacturing, mining and quarrying, electricity, gas and

and Public services that represented around 38% of GDP in the period 1980-2010, followed by the Agriculture, Fishing and Mining sector (includes income from petroleum) (30%), Industry sector (14%), Transport sector (10%) and Construction Sector (8%).

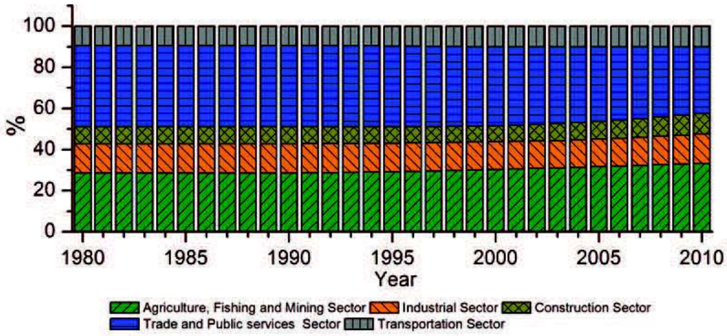

Figure 2.3: Productive Sector Matrix in Ecuador 1980-2010.

Regarding the agriculture, fishing and mining sector, it is seen that has grown by 2.66, from 12.99 billion USD in 1980 to 34.60 billion USD in 2010 with an average growth rate of 3.37%. Industrial sector was multiplied by 2.33, growing from 6.41 to 14.95 billion USD with an average growth rate of 2.92% during the same period. While the construction sector was multiplied by 2.72, growing from 3.79 to 10.29 billion USD with an average growth rate of 3.46% during the period 1980-2010. In the trade and public services sector, the growth rate was the smallest of all sectors, multiplying by 1.90 with an average growth rate of 2.20% and growing from 17.90 to 33.92 billion USD between 1980 and 2010. Finally, in the transport sector the average growth has been 3.07%, growing from 4.26 to 10.41 billion USD, multiplying by 2.04 the value between 1980 and 2010 (see Figure 2.4).

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water supply and construction) and Tertiary Sector (services, trade, residential and transportation) (UN, 2008) [155].

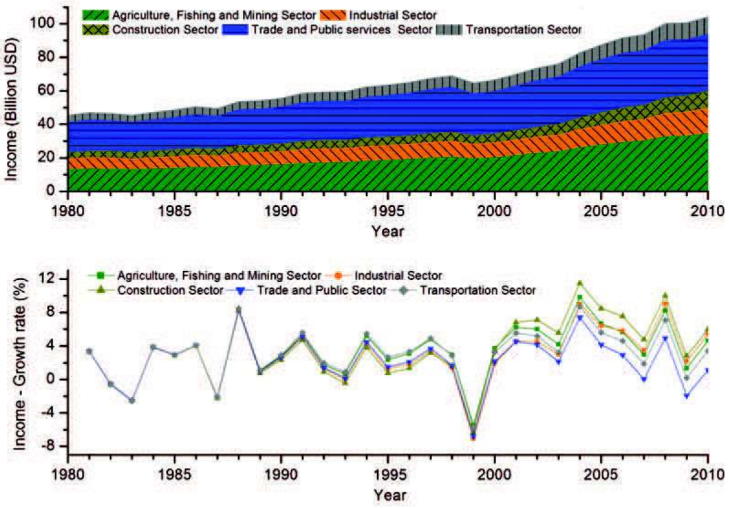

Figure 2.4: Top: Evolution of income by productive sector in Ecuador 1980-2010. Bottom: Growth rate.

2.3 Energy figures

The analyzed historical data (1980-2010) indicates that Ecuador has become a net exporter of energy but not self-sufficient. The structure of the processing plants, refineries specifically, is inadequate in relation to the composition of the local market, preventing meet energy needs. The request is subject to population growth, economic development and technological advancement. Ecuador, like other countries in the region, does not have complete information and data of its energy potential.

The country energy transition has followed, in general terms, the global trends. The substitution of primary energy supply registered a loss of penetration of the wood on fossil fuels and moderate growth of hydropower. The choice of oil as the main source of energy supply makes the country very vulnerable energetically. The relative abundance of this resource has reduced the prospects for increasing the use of other technologies and diversification of the energy matrix. Despite the high

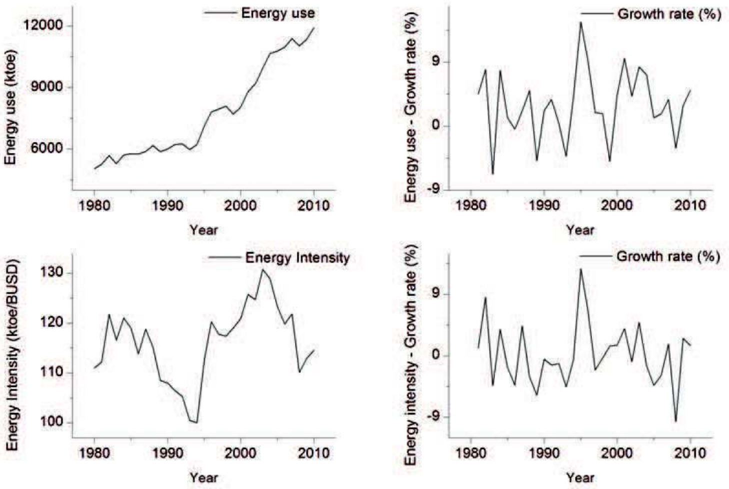

Figure 2.5: Left: Evolution of primary energy consumption and energy intensity in Ecuador 1980-2010. Right: Growth rate. BUSD corresponds to billion USD.

hydropower potential, a little progress in the effort to transform this potential into an installed capacity for energy generation has been developed. Also, geothermal, wind and solar potential has not been exploited, except in small projects that are developed with international cooperation in specific locations.

Changes in lifestyles and advances in technology have led to changing consumer preferences for energy sources with a increased yield, quality and lower cost. Note that energy consumers are not interested in the sources of the energy they spend, but in a reliable, quality and appropriate service for their machines and devices.

The efficiency of the machines and devices is a decisive factor to reduce fuel consumption, as well as the rational use of the energy. In recent years the concern is evidenced by the use of more efficient equipment which use cheaper energy such as liquefied petroleum gas (LPG) and efficient light bulbs, among others.

The consumption of primary energy by the country have increased by 2.37 between 1980 and 2010, going from 5032 to 11931 kt of oil equivalent (ktoe) (see Figure 2.5). Global energy intensity has a fluctuating evolution and the average value is 116 ktoe/BUSD in the period 1980-2010 (see Figure 2.5).

2.3.1 Energy matrix and energy intensity by sectors

Agriculture, fishing and mining sector uses mainly gasoline and diesel [154] and historically is the least energy-intensive sector. It represents less than 5% within the energy matrix by sector (see Figure 2.6), showed decreasing trend in the 1980s, with a subsequent stabilization in the following years. The average growth rate is 1.14% but the historical data shows a decline in the use of energy going from 151 ktoe in 1980 to 123 ktoe in 2010 (see Figure 2.7). The energy intensity in the sector is the lowest of all sectors, with a clear downward trend that leds its value from 11.6 to 3.57 ktoe/BUSD between 1980 and 2010 (see Figure 2.8).

In the industrial sector, energy consumption appears less concentrated (regarding the source), due to the characteristics of each production process in various industries. In the first decade of the 21st century, the use of fuel oil predominates (35%), followed by the use of diesel oil (21%), cane products (20%) and finally electricity (15%), while the wood lost penetration (Mosquera, 2008) [154]. Fossil fuels and electricity are used to provide power to industrial cycles for generating prime mover and heat. However, these activities have low productivity per unit of energy, derived from the technologies used, which affects the competitiveness of Ecuadorian products in the international market.

Energy consumption in the industrial sector accounts for about 21% of the energy matrix by sector (see Figure 2.6). The amount of energy used by the sector increased from 856 to 2565 ktoe between 1980 and 2010 (see Figure 2.7). Energy intensity of the sector indicates a fluctuating evolution around an upward trend with a peak of 250 ktoe/BUSD in 2004 that was originated because the fuel mix and the lower efficiency of the technologies used. Since 2005 the sector has shown a shift in energy intensity, leading this intensity to a much lower value in 2010, 172 ktoe/BUSD (see Figure 2.8).

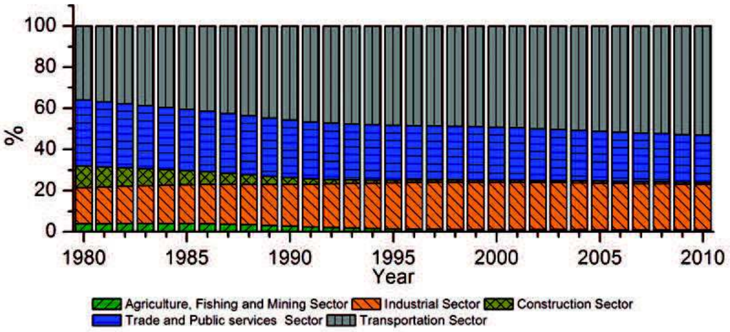

Figure 2.6: Evolution of Energy Matrix by productive sectors in Ecuador 1980-2010.

Note that the industrial sector, whose indicators are based on large aggregates, includes a set of very different situations in terms of generating value added. It is necessary to consider features and updated technology as well as energy consumption.

Construction sector mainly uses electricity [154]. It is the second least energy-intensive sector and represents less than 5% of the energy matrix by sector (see Figure 2.6). The average growth rate of energy use is negative with a value of 2.80% in the period 1980-2010. Therefore, the energy use in the sector passed from 554 to 123 ktoe in the same period (see Figure 2.7). The energy intensity shows a clear downward trend, passing from 146 to 12.0 ktoe/BUSD between 1980 and 2010 (see Figure 2.8).

The use of electricity for lighting in trade and public services sector is predominant, which in turn, replaced the diesel oil and gasoline in prime mover. LPG also increased but at a slower pace [154]. It is the second most energy intensive sector after transport sector and represents 27% of the energy matrix by sector (see Figure 2.6). The average growth rate of energy use is 1.93% between 1980 and 2010 passing the energy use from 1661 ktoe in 1980 to 2788 ktoe in 2010 (see Figure 2.7). Energy intensity shows a relatively stable value, which in average has been 81.5 ktoe/BUSD with a small downward trend, passing from 92.8 to 82.2

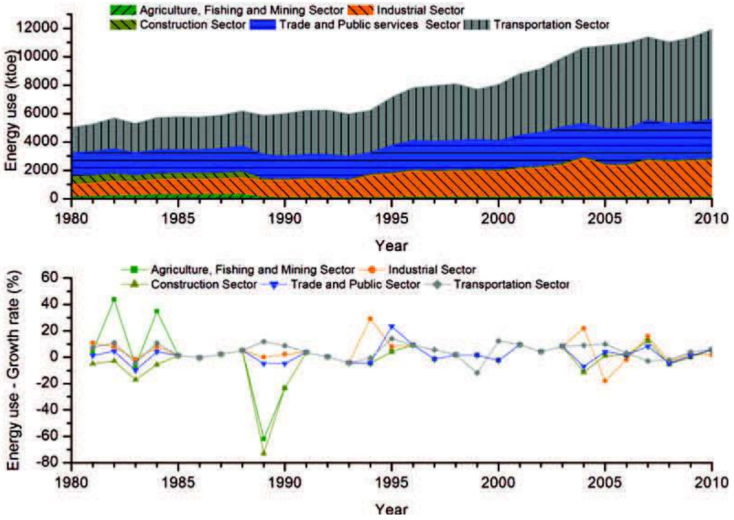

Figure 2.7: Top: Evolution of energy use by productive sectors in Ecuador 1980-2010. Bottom: Growth rate.

ktoe/BUSD between 1980 and 2010 (see Figure 2.8).

The residential energy consumption that is included in this sector, shows a significant drop in firewood consumption and an increase in penetration of the LPG and electricity. LPG is dominant in houses for various uses such as water heating and cooking, especially in isolated areas without electricity. The downward trend in the average energy intensity of the residential sector is a reflection of a historical process of improvement in household equipment that has allowed the replacement of inefficient energy sources by others more efficient [154].

The transport is the most energy-intensive sector, accounting for nearly 50% of the country's energy use (see Figure 2.6). With a clear upward trend and it has increased its consumption by 3.50 going from 1812 ktoe in 1980 to 6332 ktoe in 2010 (see Figure 2.7). It is also the largest consumer of liquid fuels. There is a significant fall in the use of gasoline in favor of oil diesel, as a result of the increase use of

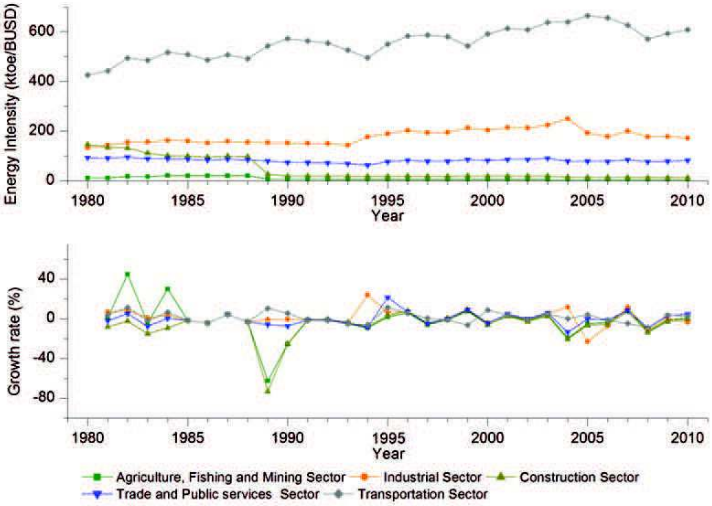

Figure 2.8: Top: Evolution of energy intensity by productive sectors in Ecuador 1980-2010. Bottom: Growth rate.

internal combustion engines in freight transport (trucks) and passenger (buses) for middle and long distance (Mosquera, 2008) [154]. The growth of the national fleet has given increasing consumption of gasoline and diesel oil, helped by subsidized prices of these fuels, which are still below the average values of the region. On the other hand, it is observed that energy intensity fluctuates around 550 ktoe/BUSD, with a slightly increasing trend and much higher levels than in the case of industry (see Figure 2.8).

As mentioned above, this sector is the largest energy consumer in the country (about 50% of energy consumption), but it represents only 10% in the generation of income. Transport sector is intensive in the use of energy and shows signs of inefficiency arising from inadequate modal distribution to meet the demand of passengers and freight transport.

2.3.2 **Energy matrix by sources**

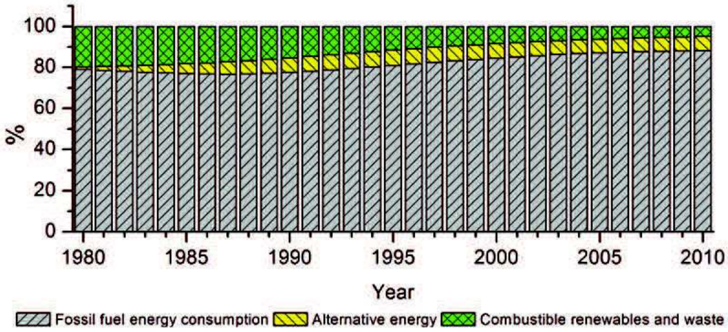

Figure 2.9: Evolution of Energy Matrix by energy source in Ecuador 1980-2010.

The energy matrix by sources is composed by the following primary energy sources: $i)$ Fossil fuel comprising coal, oil, petroleum, and natural gas products. $ii)$ Alternative and nuclear energy, refers to clean energy that is non-carbohydrate energy and does not produce carbon dioxide when generated. It includes hydropower, geothermal, and solar power, among others. $iii)$ Combustible renewables and waste that comprise solid biomass, liquid biomass, biogas, industrial waste, and municipal waste (WB, 2012) [146].

Following the trend of the region and most of the world, in Ecuador there is a strong dependence on fossil fuels, which represents more than 80% of the energy matrix in the period from 1980 to 2010 and has reached a peak of 88% in 2010 (see Figure 2.9).

The use of alternative energy sources has had a very poor increase going from 1.22% to 7.06% (see Figure 2.9) in the national energy matrix between 1980 and 2010.

Furthermore, renewable and waste fuel have presented a considerable reduction passing from 19.7% in 1980 to only 4.9% of the energy matrix in 2010 (see Figure

2.9). This decrease is mainly due to the replacement of firewood by more modern fuels such as LPG within different sectors.

2.3.3 Fuel matrix by sources

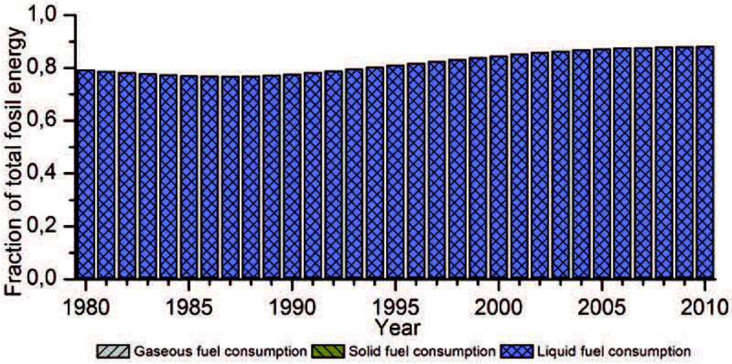

Figure 2.10: Evolution of Fuel Matrix by source in Ecuador 1980-2010.

The Fuel Matrix (FM-Sou) refers to the different types of fossil fuels: i) Gaseous fuel mainly from natural gas, ii) Solid fuel mainly by use of coal, iii) Liquid fuel mainly from petroleum-derived fuels. In Ecuador, the use of liquid fuel is predominant in the fuel matrix, over 95% between 1980 and 2010. The rest comes from the use of gaseous fuels and do not have the contribution of solid fuels (see Figure 2.10).

In regard to the use of liquid fuels, the most intensive sector is the transport sector with an average consumption of 3031 ktoe in the period 1980-2010, followed by commerce, public services and residential sector with 1570 ktoe, industry sector with 1306 ktoe, construction sector with 157 ktoe and agriculture, fishing and mining industry with 111 ktoe (see Figure 2.11).

The most intensive sector in gaseous fuel consumption is trade, public services and residential sector with an average consumption of 101 ktoe during the period 1980-2010, followed by the industrial sector with 196 ktoe, transport sector with 37 ktoe, construction sector with 10 ktoe and agriculture, fishing and mining industry with 7 ktoe (see Figure 2.11).

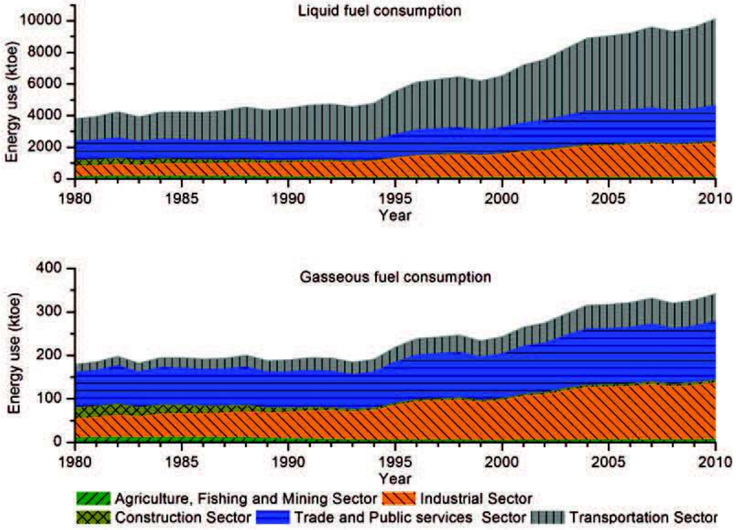

Figure 2.11: Evolution of Fuel consumption by productive sectors in Ecuador 1980-2010. Top: Liquid fuel consumption. Down: Gaseous fuel consumption. Note that there is not consumption of solid fuel in the country.

2.4 Emissions figures

Ecuador has had a modest but steady increase in CO_2 emissions[1], mainly due to the increase of population and the growht of the economy, changing habits and more frequent use of devices that require more energy in the different productive sectors of the country. Emissions have increased by 2.37 between 1980 and 2010, passing

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[1] CO_2 represents 76.7% of the GHG emissions (approximately 56.6% is from fossil fuels, 17.3% from deforestation, and 2.8% from other sources) (IPCC, 2007) [156], in this dissertation all CO_2 data correspond to burning of fossil fuels

from 12 to 28 Mtonnes (Mt). Global CO_2 intensity, defined as CO_2 emissions over energy, has a fluctuating evolution and the average value is 2.51 kt/ktoe in the period 1980-2010 (see Figure 2.12).

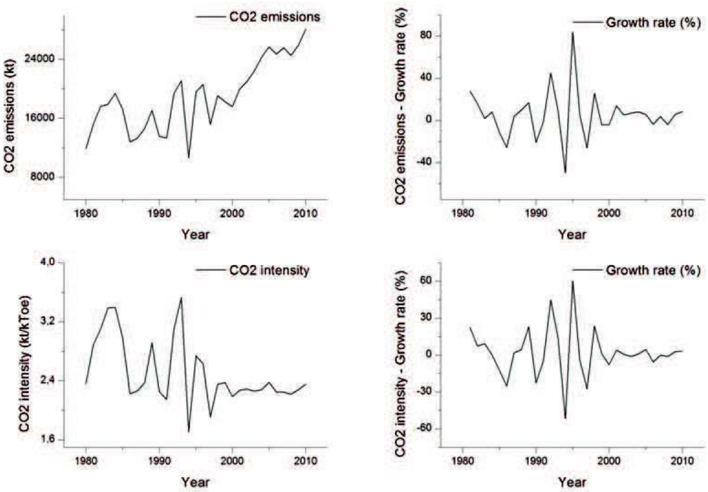

Figure 2.12: Left: Evolution of CO_2 emissions and CO_2 intensity in Ecuador 1980-2010. Right: Growth rate.

The sector that reported more emissions is transport which represents more than 50% of emissions in the period 1980-2010, increasing by 3.79, passing from 4.50 Mt in 1980 to 17.1 Mt in 2010 (see Figure 2.13). CO_2 intensity has a clear growing trend and it was multiplied by 3 passing from 19.81 to 59.5 kt/ktoe in this period (see Figure 2.14).

Trade and public services represents more than 20% of emissions between 1980 and 2010. The emissions of this sector has been multiplied by 1.81, going from 3.99 Mt in 1980 to 7.22 Mt in 2010 (see Figure 2.13). CO_2 intensity has a growing trend and it was multiplied by 6.31 passing from 22.3 to 141 kt/ktoe in the same period 1980-2010 (see Figure 2.14).

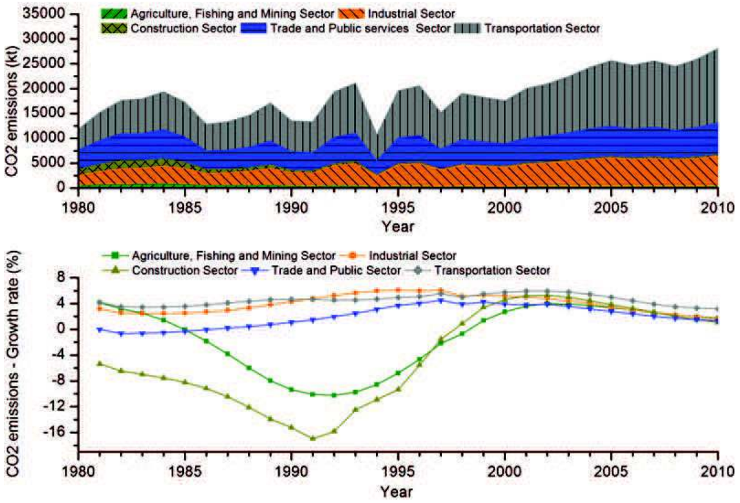

Figure 2.13: Top: Evolution of CO_2 emissions by productive sectors in Ecuador 1980-2010. Bottom: Growth rate.

Industry sector represents accounts for about 20% of emissions between 1980 and 2020. This sector has increased by 3.20, going from 2.19 Mt in 1980 to 6.99 Mt in 2010 (see Figure 2.13). This sector has the second largest growth after transportation. CO_2 intensity also has a growing trend and was multiplied by 5.32 passing from 10.8 to 57.6 kt/ktoe between 1980 and 2010 (see Figure 2.14).

The aggregation of agriculture, fishing and mining sector and construction sector both represents less 10% of emissions between 1980 and 2020. In addition, both sectors have decreased their emissions. Agriculture, fishing and mining sector emissions were multiplied by 0.67 and construction sector by 0.26, going from 0.49 to 0.32 Mt and from 1.32 to 0.34 Mt respectively in the same period (see Figure 2.13). In CO_2 intensity, there is a significant difference between both sectors, while the agriculture, fishing and mining sector has keep an almost constant intensity of 2.48 kt/ktoe for the period 1980-2010, the construction sector has shown a clear downward trend, from 6.53 to 2.78 in the same period. (see Figure 2.14).

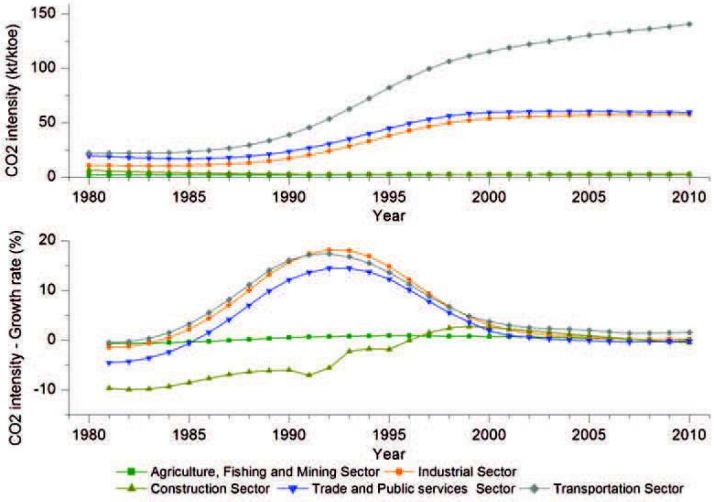

Figure 2.14: Top: Evolution of CO_2 intensity in Ecuador 1980-2010. Bottom: Growth rate.

Now we disaggregated emissions by type of fossil fuel and by sector. Regarding emissions from gaseous fuel, the most intensive sector is trade, public services and residential sector with an average emission of 237 kt during the period 1980-2010, followed by the industrial sector with 196 kt, transport sector with 87.1 kt, construction sector with 20.2 kt and agriculture, fishing and mining industry with 15.5 kt (see Figure 2.15).

In regard to emissions by liquid fuels, the most intensive sector is the transport sector with an average emission of 5306 kt in the period 1980-2010, followed by trade, public services and residential sector with 4819 kt, industry sector with 4009 kt, construction sector with 483 kt and agriculture, fishing and mining industry with 17.1 kt (see Figure 2.15).

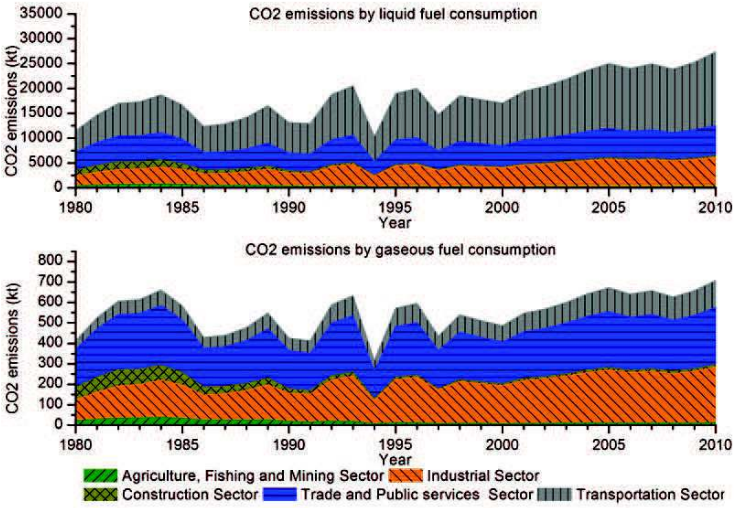

Figure 2.15: Top: Evolution of CO_2 emissions by fuel in Ecuador 1980-2010. Bottom: Growth rate. Note that there is not consumption of solid fuel in the country.

2.5 Renewable energy figures

The Ecuadorian government has, among its goals, the development of strategies to guarantee the energy supply, increase energy cost efficiency, and last, but not least, to minimize the negative impact of economic development on the environment (Mosquera, 2008) [154].

Renewable energy sources could play an important role in the diversification of the energy matrix in Ecuador. In particular, CONELEC-004 /11 regulation (Conelec, 2011) [157] establishes the conditions for selling electricity from renewable sources to the national grid, which is encouraging new projects. Below we summarize projects and potential sources that could increase the use of renewable energy in Ecuador in the upcoming years.

2.5.1 Bioenergy

Ecuador has a good potential to use modern, clean and efficient bioenergy technologies using diverse crop and livestock production to generate waste energy. The type of animal waste can be harnessed through anaerobic digestion to produce biogas (methane) (Conelec, 2009) [3].

The country has about 71 thousand ha (2009) of sugarcane mostly concentrated in the cost region, near Guayaquil (MAG, 2011) [158]. A fuel ethanol pilot program has been planned in Guayaquil and Quito, initially consisting of 5% ethanol blend with gasoline [159]. If it is successful, this could set the ground for a nation-wide ethanol fuel program. The use of this kind of fuel will generate savings of about 32 million USD a year, as the country would stop importing about 320 thousand of barrels of high octane naphtha[1] (15%) (MEER, 2011) [159].

On the other hand, the total area planted with African palm in Ecuador is 240 thousand ha, with about 200 thousand ha currently being harvested [158]. Ecuador could potentially plant up to 760 thousand ha of African palm according to Ecuador's Association of African Palm Growers (ANCUPA, 2013) [160]. Based on projections from the sector in terms of production, domestic consumption and export surplus of red oil, the surplus could grow significantly and reach more than 850 kt of red oil in 2025 (USDA, 2011) [161].

In Ecuador, more than 300 thousand tonnes of husk is produced annually. A tonne of this residue has the ability to displace the consumption of 90 gallons of diesel used in steam generation for both processing and food production. So the 300 thousand tonnes would reduce the use of about 27 million gallons of diesel a year, besides avoiding the emission of CO_2 and other primary pollutants (Neira et al., 2006) [162].

Note that, according to the cycle of sugar cane harvest, these plants operate with variability in their production. The annual average load factor in 2010 was 29%. During the months of August to November has come to be greater than 60% while between January and April has not been operated for lack of waste (Conelec, 2011) [157]. The implementation of these initiatives require institutional efforts and that

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[1] Naphtha is used primarily as feedstock for producing high octane gasoline.

the market offers the conditions for collection and storage of husk, combined with incentives to the diffusion of technology in rural areas.

2.5.2 Geothermal energy

Ecuador is a country with active volcanism that is part of the Pacific Ring of Fire and has a great geothermal potential. This is illustrated by the presence of around 180 hot springs in the country and a geothermal potential of 534 MW (CEPAL, 2010) [163]. Studies have identified 17 potential geothermal exploitation for production of electrical, industrial and agricultural energy (Conelec, 2009) [3].

Three sites, Tufiño-Chiles (139 MW), Chachimbiro (113 MW) and Barges (282 MW) in which has been quantified an installable power of 534 MW. The Chalupas geothermal project has been determined like priority. This project is in the feasibility stage (2011) and it requires further geophysical exploratory work to bring it to the next stage. The cost of exploration and feasibility stage represents 10% of the total budget. When this feasibility is confirmed, additional drilling are required. Then, stages of design, construction and installation should continue. These stages would be the most expensive, arround 90% of the budget (Conelec, 2009) [3].

The loading factors at the global level are between 60% and 90%; which are considered efficient levels of use of the resource (levels of basic energy source). Geothermal has an advantage over other renewable: short term variable technologies (solar, wind, wave and tidal), and hydroelectricity where load factors are between 40% and 80% (Bruckner et al., 2011) [4].

2.5.3 Hydropower

As was mentioned above, Ecuador has a huge hydroelectric potential unexploited, despite that hydropower is the renewable resource more exploited in the country. In 2011 Ecuador had $2,215$ MW of installed hydropower capacity and another $2,756$ MW under construction (Conelec, 2013) [164]. The biggest hydroelectric project is called Coca Codo Sinclair and has a capacity of 1500 MW and an estimated cost of 2.25 billion USD (the overall project progress is 27.4% up to November 2012). Other hydroelectric projects are: Deisitanisagua with 115 MW, Maduriacu with 60

MW, Mazar Dudas with 21 MW, Minas de San Francisco with 270 MW, Quijos with 50 MW, Sopladora with 487 MW, and Toachi Pilatón with 253 MW [159].

2.5.4 **Solar energy**

The potential of this energy in Ecuador is not among the highest in the world, compared to countries with high desert irradiations (*e.g.* North Africa), however, it is at an appropriate level to become a significant source of national power. Note that solar radiation is uniform throughout the year in Ecuador, which reduces the problem of variations, and makes the use of technology more reliable (Conelec, 2009) [3].

Most of the Ecuadorian territory has an average annual potential of 4.4 to 4.7 kWh/m^2/day solar radiation. Among the places with the most potential are Quito (5.1 kWh/m^2/day), Sigchos and Pedernales (5.25 kWh/m^2/day), southern (5.25 kWh/m^2/day) and west (5.4 kWh/m^2/day) of Zapotillo and Macara (5.5 kWh/m^2/day) (CIE, 2008) [165]. Considering that it requires direct radiation of at least 5 kWh/m^2/day in order to be able to generate electricity from concentrated solar power (CSP) (WB, 2010a), there are few places in the country to exploit this technology as is the case of Macara in the south of Loja (5.1 kWh/m^2/day direct sunlight) (CIE, 2008) [165].

In addition, through Rural Electrification and Urban Marginal Funds (Fondos de Electrificación Rural y Urbano Marginal-FERUM), Ecuador initiated in 2004 a program of electrification in the countryside using PV generation units. This program started in zones near the border with Peru and in the Amazonian region. Another program using PV (Photovoltaic) panels is executed in the Galapagos Islands to generate a power of 2.1 MW (MEER, 2011) [159].

2.5.5 **Wave and tidal energy**

There are no reviews or studies in Ecuador about the potential of this energy. The Expansion Master Plan 2009-2020 states that a wave and tidal potential in the country could be and it can be used as an energy option in places close to the coast. Global information estimated a moderate potential of this type of energy for the

Ecuadorian coast (between 15 and 16 kW per meter of wave), which is low compared to sites with high potential as southern Chile with 74 kW/m.

Load factors of this energy are between 22.5% and 28.5%, which shows its variable nature. Note that, the useful life of tide dams is about 40 years. In order to integrate these energies to the system, it is required to expand the transmission infrastructure near the coast, or even a few kilometers off to the coast if the generators are located offshore. The electrical characteristics of the power plants of both waves and tides is similar to those of wind energy technologies, therefore, the technical connection requirements are often similar (Sims et al., 2011) [24].

2.5.6 Wind energy

A challenge for the integration of wind energy to electrical systems is their intermittent nature for the energy generation (Arent, 2011) [2]. That is, the wind is a variable resource so that the generation fluctuates according to weather conditions and wind in a given plant or wind turbine. When wind electricity generation represents more than 20% of country's electricity matrix, it requires technical and institutional adjustments by the authority (Wiser et al, 2011 [14]; Taylor, 2004 [166]).

Although latitudes located on the equator are not rich in winds, the presence of the Andes Mountains and the Pacific Ocean provide thermal gradients that allow the existence of areas of high wind interest in Ecuador. To determine the potential of wind generation site, it is required to evaluate different parameters such as wind speed, daily, monthly and seasonal variations. Wind energy is one of the most variable renewable sources in the short term (Sims et al., 2011) [24], and even more than solar, because the wind varies dramatic and randomly.

The areas with the highest wind potential in Ecuador are at the tops of the mountains and coastal sites. Among these sites Villonaco hill located in the province of Loja in the south of the country is recognized, with a cost of 41.8 million USD, a power capacity of 16.5 MW and considered in the Plan of Expansion of Generation 2009-2020 of Ecuador. There are some other identified sites with wind generation potential, such as The Angel in Carchi, Salinas in Imbabura, Tixán in Chimborazo and Huascachaca in Azuay. A specific technical evaluation, both national and local levels to get a full wind atlas of the country is still required (Conelec, 2009) [3].

Programs for using wind energy started in 2004. Other important program, promoted by the Ministry of Electricity and Renewable Energy (MEER), aim at replacing the existing thermal generation plant by wind and PV plants in the Galapagos Islands. With the new facilities, 5.7 MW of wind power (plus 2.1 MW of PV power) will substitute most of the 8.8 MW of the thermal generation installed (MEER, 2011 [159]; Conelec, 2013 [164]).

2.6 Cost of the adoption of renewable energy

The cost of renewable energy is an important factor in determining the competitiveness of a given technology in the energy sector. Thus, if a technology generates electricity at below market price, estimated for the long term, this technology would be selected by investors for future expansion (Caspary, 2009) [167]. Costs are still a critical factor, then, it is most feasible and likely to adopt technologies that have competitive costs compared to the traditional electricity sector.

This section compares overall average technology costs ranges of renewable energy with the costs paid to electricity generators in Ecuador. The average costs of renewable energy generation technologies are taken from IPCC[1]. The data correspond to the global aggregate costs of renewable energy technologies commercially available.

Further, costs are not the only factor used but also the commercial availability of technologies. These cost ranges are constructed based on information from countries where there are projects, studies and information on these technologies. Also, are listed the natural and technological factors affecting the feasibility of using each type of renewable source such as load factor (which expresses the variability and natural availability of a source), life-cycle and size of the plant, and costs incurred in investment, operation, maintenance and fuel (for bioenergy).

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[1] The average costs of technologies for renewable energy sources given by the IPCC are calculated for the life-cycle of each of the technologies and are calculated at present value with a discount rate of 7%. None of these average costs include effects of energy subsidies granted in different countries (Bruckner et al 2011) [4].

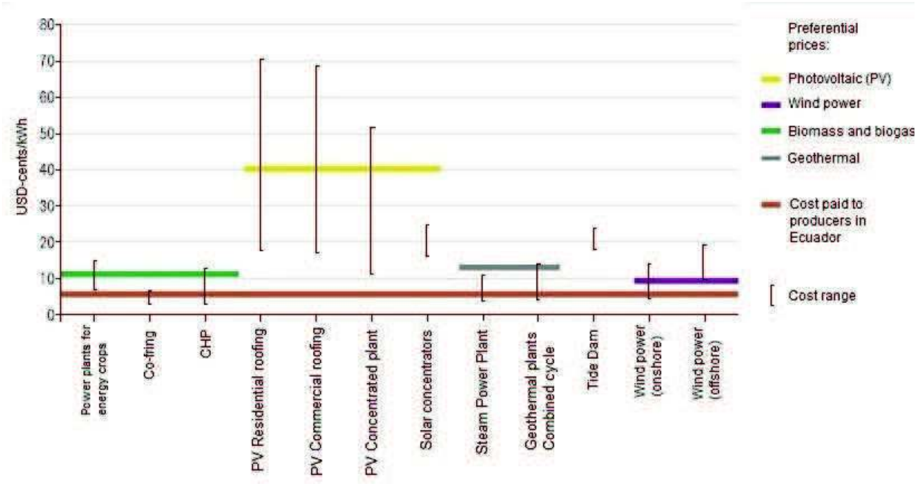

Figure 2.16: International average cost range versus preference prices for renewable energy in Ecuador based on (Conelec 2009) [3] and (Bruckner et al 2011) [4].

The comparison of cost is a first step in the analysis of the feasibility of incorporating renewable technologies in the energy matrix of the country. Moreover, the comparative cost used is the generation of electricity in Ecuador determined by Conelec[1] (Conelec, 2009)[3].

Figure 2.16 shows that four technologies of renewable energy would have incentives to be adopted without the support of preferential prices[2]. These technologies show a global average cost range lower than the recognized power generation

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[1] In 2011 a new regulation of Conelec (Regulation No. CONELEC-004/11) was approved for the treatment of the price of energy produced from non-conventional renewable energy resources, which seeks to encourage the spread of these technologies in Ecuador through the payment of preferential prices to allow greater competitiveness thereof. The costs of electricity generation of Conelec are average values of domestic industries (Conelec 2009) [3]

[2] The Conelec's regulation (feed in tariff) contributes to the adoption of technologies of renewable energy in Ecuador's electricity market. These regulations provide for different preferential prices for different technologies (see the different lines in Figure 2.16). Technologies that have their range of prices below these ceilings become economically viable energy in Ecuador.

in Ecuador (range of cost below the red line in the graph) cost. These technologies are: bioenergy for electricity generation by combined combustion (co- firing), gasification of biomass for heat and power generation (combined heat and power, CHP); geothermal flash steam technologies (flash condensing plants) and binary cycle plants.

The regulation of preferential prices govern the payment of costs for a period of 15 years, after which the authority will conduct a review. With this time horizon and with the downward trend in the cost of renewable technologies is likely that more options will become financially viable in the medium and long term.

The energy generation based on fossil fuels produces global effects such as GHG and local effects such as the emission of primary pollutants (eg SO_x, NO_x, etc.). If these effects are incorporated, the real cost of power generation from these sources will be higher. Then, renewable technologies produces least amount and less intense effects, especially in GHG. This option would become more competitive in front of polluter energy generation.

Since the incorporation of these effects are not included in the price of energy generation in Ecuador, we can only refer to the financial costs. Note that this financial cost of energy generation is not the actual cost, because the energy sector (especially the thermoelectric generation) use subsidized fuel. These factors, subsidies for fossil fuels and non-inclusion of external environmental costs make the price of conventional energy generation technologies in Ecuador cheaper than renewable energy sources. However, the low price is not based on real and sustainable benefits in the long term.

Regarding energy costs for transportation, there is a global downward trend in the prices of first generation biofuels (see Figure 2.16). Particularly in Latin America, Brazil is the leader in biofuels production, and is achieving lower cost and not requiring subsidies to be competitive (Chum et al., 2011) [18]. But in Ecuador, gasoline and diesel have costs below the world average price and even below that of its Andean neighbors, Peru and Colombia, because of subsidies.

Education is the most powerful weapon which you can use to change the world.

Nelson Mandela

CHAPTER 3

System dynamics modelling for renewable energy and CO_2 emissions in Ecuador (1980-2025)

3.1 Overview

It is a very complicated task to predict how much the economy will grow in the near future. This growth will strongly modulate CO_2 emissions of any country and therefore it will be crucial to make a realistic estimate of this emissions. On the other hand, the different *feedback-mechanisms*, both in the climatic and in the economic system make any prediction highly questionable beyond 5-10 years (Fiddman, 2002) [82]. However, it is critical to provide accurate information to policymakers in order to design appropriate energy policies for the near future (Bahrman, 2007) [168].

This Chapter explores the relationship between economic growth, productive sectors, energy consumption, changes in the use of renewable energy, improvements in the efficiency of fossil energy, and CO_2 emissions of Ecuador. To estimate

CO$_2$ emissions in the near future we will define different scenarios in both income and energy use.

The model is based on a variation of the Kaya identity (Kaya, 1993) [169] and on an approach of formation of GDP which includes a contribution from renewable energy (Chien and Hu) [5]. The model has been implemented using a SD technique (Forrester, 1961) [170] on a Vensim platform (Vensim, 2011) [171]. The considered data corresponds to the period 1980-2010 and it has been extracted from the official data sources such as: Ecuadorian Institute of Statistics and Census (INEC, 2012) [172], Central Bank of Ecuador (BCE) [152], World Bank[1] (WB) [146], and International Energy Agency (IEA) [153]. The raw data has been processed using a Hodrick-Prescott filter (HP) (Hodrick and Prescott, 1997) [173] which allows to generate a smooth representation of a time series.

The Kaya identity is commonly used as an analytical tool to explore the main driving forces that control the amount of carbon dioxide emissions (Alcantara, 2005 [174]; Mena, 2009 [175]). According to this identity, CO$_2$ emissions of a given country could be broken down into the product of four factors: carbon intensity (defined as the CO$_2$ emitted per unit of energy consumed), energy intensity (defined as the consumed energy per unit of GDP), economic rent (defined as GDP per capita), and population.

The technique was originally proposed by J. Forrester to understand how systems change as a function of time (Begueri, 2001) [176]. SD is a method for modeling, simulating and analyzing complex systems. A system is defined as a collection of elements in which interactions are modeled as flows between reservoirs in time steps, and in which the rate of change depends on the value of the variables that define the system (feedback mechanisms). Therefore, the main goal of SD is to *understand* how a given system evolves, and even more importantly, to understand the causes that govern its evolution (Garcia, 2011) [86]. The basis of SD has been analyzed in detail in Radzicki (2009) [177] and Tan (2010) [178], in addition a brief review is in Section 1.9 of Chapter 1.

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[1] Economic official data set used is given in constant 2005 PPP international dollars.

3.2 Formulation of model

The model uses a variation of the Kaya identity, where the amount of CO_2 emissions from industry and from other energy uses may be studied quantifying the contributions of five different factors: $i)$ global industrial activity, $ii)$ industry activity mix, $iii)$ sectoral energy intensity, $iv)$ sectoral energy mix and $v)$ CO_2 emission factors. Moreover, we consider different sub-categories concerning the industrial sectors and the fuel type. The CO_2 emissions can be written as,

$$C = \sum_{ij} C_{ij} = \sum_{ij} Q \frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} = \sum_{ij} Q \cdot S_i \cdot EI_i \cdot M_{ij} \cdot U_{ij}, \tag{3.1}$$

where C is the total CO_2 emissions (in a given year); C_{ij} is the CO_2 emission arising from fuel type j in the productive sector i (note that the index i runs over five productive sectors and the index j over five type of energy sources); Q is the total GDP of the country; Q_i is the GDP generated by the productive sector i; E_i is the energy consumption in the productive sector i; E_{ij} is the consumption of fuel j in the productive sector i, verifying that the total consumed energy, $E = \sum_{ij} E_{ij}$; $S_i \left(\frac{Q_i}{Q}\right)$ is the share of sector i in the total GDP; the energy intensity of sector i is given by $EI_i \left(\frac{E_i}{Q_i}\right)$; the energy matrix is given by $M_{ij} \left(\frac{E_{ij}}{E_i}\right)$ and the CO_2 emission factor by $U_{ij} \left(\frac{C_{ij}}{E_{ij}}\right)$. Throughout this work, as a convention, we will always refer to the productive sector with the *i* index and to the type of energy source with the j index.

This equation is an extension of the Kaya identity because we disaggregate in type of productive sector and kind of fuel used, while in the original formulation only aggregated terms are considered: C, Q, and E.

The raw data to perform the model correspond to the official available data on Ecuador, provided by the INEC[1], the BCE[2], the WB[3], and the International Energy Agency[4]. The subsequent data analysis and the preprocessing of the time series was performed using the Hodrick-Prescott (HP) filter [173], which allows isolation

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[1] http:// www.inec.gob.ec/estadisticas/, http://www.ecuadorencifras.com/

[2] http://www.bce.fin.ec/indicador.php

[3] http://data.worldbank.org/country/ecuador

[4] http://www.iea.org/ countries/non-membercountries/ecuador/

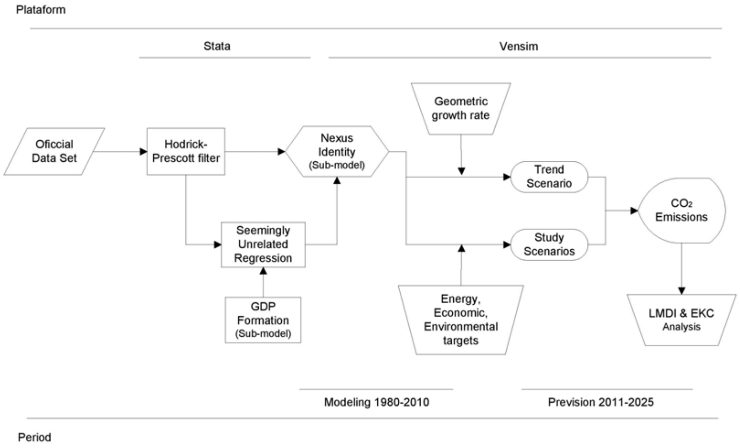

Figure 3.1: Schematic diagram of the methodology used to build the model.

of outliers (economic crises, random behavior of markets, etc) of the time series under study. After that, it is possible to get the trend component of a time series and to perform more adequate estimations[1]. Indeed, all time series used in this work have been computed using the HP filter with a λ value of 100.

The simulation period extends from 1980 to 2025, where 1980-2010 is used to fix the parameters of the model and 2011-2025 corresponds to the forecast period, under the assumption of different scenarios concerning the evolution of the income, the evolution of the energy mix, and the efficiency of the used technology. The geometric growth rate (Rowland, 2003 [179]; Jin et al., 2009 [180]) has been used to extrapolate the trends into the forecast period. The Seemingly Unrelated Regression (SUR) (Zellner, 1962) [181] in STATA software platform (Stata, 2012) [182] has been used to parameterize the GDP formation. The validation of the model has

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[1] The smoothing parameter λ of the filter, which penalizes acceleration in the trend relative to cycle component, needs to be specified. Most of the business cycle literature use past data and a value of the smoothing parameter λ equal to 100 (Hodrick and Prescott) [173] (see Section 1.5.3 in Chapter 1).

been done with the mean absolute percentage error (MAPE).

Figure 3.1 shows in a schematic way how the calculations have been performed using the different techniques described in previous paragraphs.

3.3 Economic model approach

3.3.1 Introduction of economic appoach

The promotion of renewable energy is a well accepted solution to the mitigation of CO_2 emission. Furthermore, Chien and Hu (2007) [183] show that increasing the use of renewable energy improves the macroeconomic efficiency of economies.

Energy, labor, and capital stock are key inputs to produce the economic output-GDP (Hu and Kao, 2007 [184]; Hu and Wang, 2006 [185]). It is desirable for an economy to increase its income and to decrease its inputs in order to maximize production efficiency.

It is worth noting that increasing the input of traditional energy decreases technical efficiency. To improve the technical efficiency of an economy, it is important not to increase the total input of energy. By substituting traditional energy with renewable energy, technical efficiency can be improved (Hu and Kao, 2007) [183].

Renewable energy systems are considered to be environmentally superior to traditional technologies from the viewpoint of CO_2 mitigation and the effective utilization of resources. Several studies show that substitution of conventional fossil fuels by biomass, for energy production results, in both a net reduction of GHG and in the replacement of non-renewable energy sources (Schneider and McCarl, 2003 [186]; Dowaki and Mori, 2005 [187]; Caputo et al., 2005[188]).

Abulfotuh (2007) [189] suggests that one possible solution to the environmental risks brought by the escalating demand for energy is to consider immediate change in the composition of the energy resource portfolio. It is expected that renewables have great potential to solve a major part of global energy sustainability. Increasing the use of renewables in power industries has already been seriously reviewed in some countries.

Various new policies to achieve the national goals of a renewables ratio in the energy portfolio are adopted in different economies. Lund (2007) [190] groups policies on renewable energy and efficient energy use into subsidy type and catalyzes measures based on the use the public financial resources according to REN21 (Renewable Energy Policy for the 21st Century, 2012) [191] in Renewables Global Status Report (RGSR, 2012) [191] at least 118 countries, more than half of which are developing countries, had renewable energy targets in place, and 109 countries have policies to support renewables in the power sector by early 2012. Renewable energy targets and support policies continued to be a driving force behind increasing markets for renewable energy, despite some setbacks resulting from a lack of long-term policy certainty and stability in many countries.

Feed-in-tariffs (FITs) and renewable portfolio standards[1] (RPS) are the most commonly used policies in this sector. FIT policies were in place in at least 65 countries by early 2012 (REN, 2012) [191].

Renewables are currently accepted as one of the key solutions to climate change and escalating energy demand. Many economies have adopting policies to promote the use of renewables. However, the mechanism of how renewables improve GDP is still unknown (Chien and Hu, 2008) [183].

3.3.2 Theory of the impact of renewables on GDP

In this section, we will review the work of Chien and Hu (2008) [5] that broadens the perspective of environmental economics to include an analysis of renewable usage directly contributing to the important elements of economies or regional development. Domac et al. (2005) [192] suggest that renewable energy increases the macroeconomic efficiency by the following process: $i)$ The business expansion and new employment brought by renewable energy industries result in economic growth. $ii)$ The import substitution of energy has direct and indirect effects in increasing income of the economy and trade balance.

Measured by expenditures, GDP is the sum of goods and services produced during a giving period. Total output comprises four groups' purchases of final goods

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[1] RPS is a regulation that requires the increased production of energy from renewable energy sources, such as wind, solar, biomass, and geothermal. The RPS mechanism generally places an obligation on electricity supply companies to produce a specified fraction of their electricity from renewable energy sources. Certified renewable energy generators earn certificates for every unit of electricity they produce and can sell these along with their electricity to supply companies.

and services: $i)$ households purchase consumption goods; $ii)$ businesses purchase investment goods (and retain unsold production as inventory increases); $iii)$ governments purchase goods and services used in public administration and $iv)$ welfare transfers; and foreigners purchase (net) exports. There is substantial uniformity in the shares of consumption and investment (the sum of capital expenditures and inventories) across nations with quite disparate income levels (Mack, 2008) [193] [1]. It is important to note that if one counts some major activities such as child-rearing (generally unpaid) as production, GDP ceases to be an accurate indicator of production. Similarly, if there is a long term shift from non-market provision of services (for example cooking, cleaning, child rearing, do-it yourself repairs) to market provision of services, then this trend toward increased market provision of services may mask a dramatic decrease in actual domestic production, resulting in overly optimistic and inflated reported GDP. This is particularly a problem for economies which have shifted from production economies to service economies.

The expenditure approach estimates GDP by the following equation:

$$GDP = C + I + G + X - M, \tag{3.2}$$

where:

- C (consumption) is normally the largest GDP component in the economy, consisting of private (household final consumption expenditure) in the economy. These personal expenditures fall under one of the following categories: durable goods, non-durable goods, and services. Examples include food, rent, jewelry, gasoline, and medical expenses but does not include the purchase of new housing.

- I (investment) includes, for instance, business investment in equipment, but does not include exchanges of existing assets. Examples include construction of a new mine, purchase of software, or purchase of machinery and equipment for a factory. Spending by households (not government) on new houses is also included in investment. In contrast to its colloquial meaning, *investment* in GDP does not mean purchases of financial products.

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[1] Note that, if you knit yourself a socks, it is production but does not get counted as GDP because it is never sold.

- G (government spending) is the sum of government expenditures on final goods and services. It includes salaries of public servants, purchases of weapons for the military and any investment expenditure by a government. It does not include any transfer payments, such as social security or unemployment benefits.

- X (exports) represents gross exports. GDP captures the amount a country produces, including goods and services produced for other nations' consumption, therefore exports are added.

- M (imports) represents gross imports. Imports are subtracted since imported goods will be included in the terms G, I, or C, and must be deducted to avoid counting foreign supply as domestic.

The deduction of imports from exports (X–M) is the trade balance (TB).

Another way of measuring GDP is to measure total income (Income approach). This way of counting is sometimes called gross domestic income (GDI[1]) and should provide the same amount as the expenditure method described previously[2]

Following to Chien and Hu (2008) [5] the impact of renewables on GDP has evaluated by the expenditure approach, because the import substitution effect of renewables seems to have a direct impact on trade balance.

3.3.3 Path analysis of the impacts of renewables on GDP

The influences of renewables on GDP are illustrated by Figure 3.2. This represents the original constitution of GDP by household consumption, government consumption, capital formation, and trade balance.

Closely following Chien and Hu (2008) [5], in Figure 3.3, the diagram shows that the use of renewables influences GDP through two paths: i) the emergence of renewable energy industries brings business expansion, which results in increased capital formation and ii) the import substitution of traditional energy by locally

---

[1] This method measures GDP by adding incomes of salaries for labour, interest for capital, rent for land and profits for entrepreneurship.

[2] By definition, GDI = GDP. In practice, however, measurement errors will make the two figures slightly off when reported by national statistical agencies.

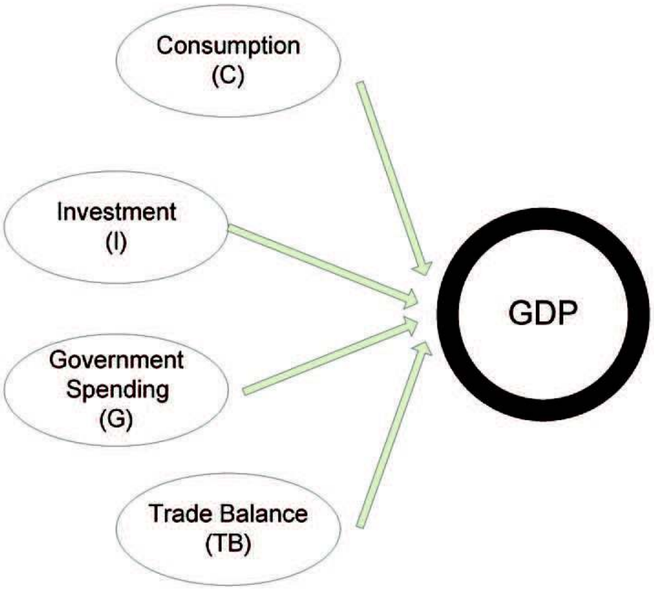

Figure 3.2: Conceptual framework of GDP constitution in Chien and Hu (2008) [5]

produced renewables has direct and indirect effects on increasing trade balance in an economy. The increases of capital formation and trade balance would lead to the increase of the GDP.

Policy makers have to choose from different policy instruments to identify the most effective instrument. This became very important issue and therefore the mechanism for renewables to create economic impacts should be first identified.

Chien and Hu (2008) [5] use the path analysis of Structural Equation Modeling (SEM) to test the conceptual model, specifying causal relationships between renewables and the other relevant variables [1]. The output of path analysis in Chien and Hu (2008) [5] work provides significance tests for specific causal paths. The

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[1] Path analysis can be used to determine whether the theoretical model accounts for the actual relationships in the observed data.

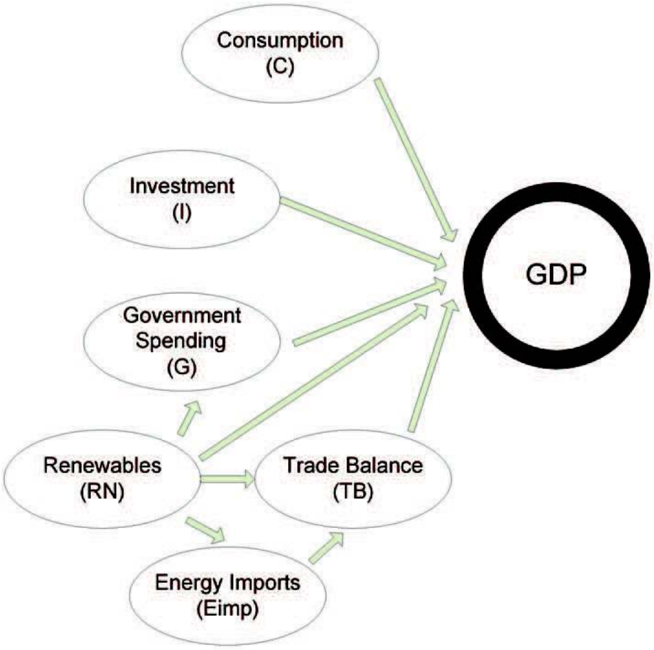

Figure 3.3: Conceptual framework of the influences of renewables on GDP in Chien and Hu (2008) [5]

significant links point out where the policies should be executed.

In the work of Chien and Hu (2008) [5] the sample profile contains 116 economies. The results of this work show that technical efficiency is higher in developed economies than in developing economies. The share of renewable energy in total energy supply is higher in developing economies than in developed economies due to the widespread biomass use in the residential sector of developing economies. The share of geothermal, solar, tide and wind fuels in renewable energy is higher in developed economies than in developing economies.

In this research, we apply the model of Chien and Hu (2008) [5] for the case of Ecuador. We also conduct an analysis performed using the correlation matrix (Table 3.1).

Table 3.1: Summary of descriptive statistics for the economic model.

Measure	Means	Stan.Dev	GDP	I	TB	C	Eimp	RN
GDP[a]	7.54	1.97	1.00	0.93	-0.12	0.97	-0.86	-0.86
I[b]	1.71	0.54	0.93	1.00	-0.24	0.85	-0.67	-0.70
TB[c]	-0.10	0.24	-0.12	-0.24	1.00	0.22	-0-05	0.02
C[d]	5.00	1.37	0.97	0.85	-0.22	1.00	-0.89	0.87
Eimp[e]	-12.72	3.81	-0.86	-0.67	-0.05	-0.89	1.00	0.87
RN[f]	3.81	0.18	-0.86	-0.70	0.02	-0.90	0.87	1.00

[a] GDP in 10^{10} USD.
[b] I in 10^{10} USD.
[c] TB in 10^{10} USD.
[d] C in 10^{10} USD.
[e] Eimp in 10^{6} toe.
[f] RN in 10^{6} toe.

On the other hand, according to these authors the government spending G ($G = GDP - C - I - (X - M)$) is eliminated from the model estimation to avoid multicollinearity. To avoid the problems of inputting raw data, a rescaling of the smoothed time series has been used so that they are all on approximately the same scale. The system of theoretical GDP formation model is made up by the following equations:

$$Q = a_1 \cdot I + a_2 \cdot TB + a_3 \cdot C + a_4 \cdot Eimp + a_5 \cdot RN + \epsilon_1, \tag{3.3}$$

$$I = b_1 \cdot RN + b_2 \cdot C + \epsilon_2, \tag{3.4}$$

$$TB = c_1 \cdot Eimp + c_2 \cdot RN + \epsilon_3, \tag{3.5}$$

$$Eimp = d_1 \cdot RN + \epsilon_4, \tag{3.6}$$

$$C = f_1 \cdot Eimp + f_2 \cdot TB + \epsilon_5, \tag{3.7}$$

where Q refers to GDP of the country, $Eimp$ is the energy import, RN is the renewable energy and ϵ_1... ϵ_5 are residuals. Note that Equations 3.3-3.7 form the model for the formation of GDP. Coefficients appearing in these equations are determined using SUR technique[1] in the datasets of 1980-2010 period and therefore their values are a consequence of the data. The SEM model is present in Figure 3.4.

In Equation 3.3, income (Q) is influenced by invest (I), trade balance (TB), and consumption (C). Chien and Hu (2007) [183] suggested that energy inputs may affect income, therefore, energy imports ($Eimp$) and renewable energy (RN) are included as well Equation (3.3). Note the negative value of coefficient a_5 in Table 3.2.

In Equation 3.4 investment is influenced by renewable energy, since theory predicts that increasing the use of renewable energy will result in business expansion and thus capital could be accumulated in long term, but its implementation (infrastructure and incentives in early stages, see Section 2.6 in Chapter 2) is expected to have a negative short term effect over income (this is confirmed with a negative value of b_1 in Table 3.2).

In Equation 3.5 energy imports and renewable energy influence trade balance (both coefficients, c_1 and c_2, have positive values in Table 3.2). The theory proposed by Domac et al. (2005) [192] suggests that the use of renewable energy results in import substitution by domestic-produced renewable energy, and thus trade balance will increase by the use of renewable energy. Furthermore, if renewable energy could cause import substitution, then the imports of energy should be

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[1] A single model may contain a number of linear equations. In such a model it is often unrealistic to expect that the equation errors would be uncorrelated. A set of equations that has contemporaneous cross-equation error correlation (*i.e.* the error terms in the regression equations are correlated) is called a seemingly unrelated regression (SUR) system (Zellner, 1962) [181]. At first look, the equations seem unrelated, but the equations are related through the correlation in the errors. The model can be estimated equation by equation using standard ordinary least squares (OLS). Such estimates are consistent, however generally not as efficient as the SUR method, which amounts to feasible generalized least squares with a specific form of the variance- covariance matrix. Two important cases when SUR is in fact equivalent to OLS, are: either when the error terms are in fact uncorrelated between the equations (so that they are truly unrelated), or when each equation contains exactly the same set of regressors on the right-hand-side.

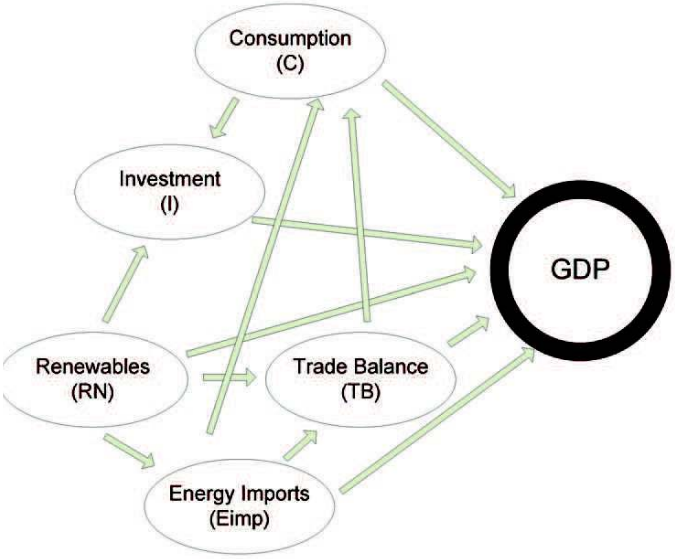

Figure 3.4: SEM model in Chien and Hu (2008) [5]

reduced by the increase of renewable energy (in Equation 3.6 the value of the coefficient d_1 is negative). Although Ecuador is a net exporter of fossil energy, the use of renewable energy can help diversify its energy matrix and reduce emissions.

In Equation 3.7, according to international trade theories, the domestic price of goods increases as the same kind of goods are exported, while it decreases as the same kind of goods are imported. Thus, trade balance influences consumption through changes in domestic prices. The imports of energy influence domestic energy prices and the consumption of energy. As a result, consumption of energy-related products is also affected. Ecuador exports crude oil and imports refined products, such as diesel and liquid petroleum gas (LPG) which affects the value of TB and $Eimp$ in Equation 3.3.

The results obtained after the fitting of the smoothed series of data is depicted

Table 3.2: Estimated coefficients for the GDP formation equations (see Eqs. 3.3-3.7)^a.

Variable	GDP ^{b}	I	TB	C	Eimp
I ^{c}	1.16*** (5.11)			-6.07*** (-41.44)	
TB ^{d}	0.99*** (3.46)				
C ^{e}	1.21*** (7.70)	0.50*** (100.40)			
E$_{imp}$ ^{f}	0.05*** (2.66)		0.01*** (4.14)	-0.27^{***} (-100.17)	
RN ^{g}	-0.50^{***} (-4.44)	-0.84^{***} (-5.40)	0.04 (0.28)		-36.79^{***} (-5.47)

[a] *** represents significance at the 1% level and numbers in parentheses are t-statistics. Estimation Method: SUR. Sample: 1980-2010. Included observations: 155.

[b] GDP in 10^{10} USD.

[c] I in 10^{10} USD.

[d] TB in 10^{10} USD.

[e] C in 10^{10} USD.

[f] Eimp in 10^6 toe.

[g] RN in 10^6 toe.

in Table 3.2. Note that the error terms are correlated through the equations of formation of GDP, because the variables in Equation 3.3 are not fully statistically independent. All the coefficients are individually significant at the 0.01 level except the coefficient between $Eimp$ and TB.

According to the results of Table 3.2 renewable energy generates a reduction on income (Q) and on invest (I) in the short term, however they have a positive impact on the trade balance (TB) and a large negative effect on the energy imports ($Eimp$).

3.4 Energy consumption and productive sectoral structure submodel

Energy consumption refers to the use of primary energy before transformation into any other end-use energy, which is equal to the local production of energy plus imports and stock changes, minus the exports and the amount of fuel supplied to ships and aircraft engaged in international transport. It is given in kt of oil equivalent (ktoe). Energy intensity is defined as the ratio of energy consumption and GDP [146].

The energy demand analysis starts from an analytical method that is based on energy end use, in order to model the requirements of consumption in the different productive sectors. Economic, demographic and energy use information applies to build different scenarios, in order to determine how the total and disaggregated energy sources consumption evolve over time in each industry and in each scenario. The energy demand analysis is a starting point for assessing the energetic area in integrated form, since all processing calculations and use of resources are determined by the calculated levels of final demand.

In general, sectoral structure comprises households, industry, transport, trade, agriculture, etc.. In turn, each sector can be divided into different sub-sectors, final consumption and equipment that use energy. However, given the availability of data in Ecuador, it is only possible to identify the primary energy consumption by source and type in each of the sectors mentioned previously.

As was already mentioned in Section 2.2 in Chapter 2, the usual standard division of productive sectors follows the ISIC specification (International Standard Industrial Classification of All Economic Activities, Rev.4), but taking in account the availability of data, we follow the division of the productive sectors given in Mosquera (2008) [154]: $i)$ agriculture, fishing and mining (sec-1), $ii)$ industry (sec-2), $iii)$ construction (sec-3), $iv)$ trade and public services (sec- 4), and $v)$ transportation (sec-5).

Sectors will be represented inside the model by their contribution to the country's economy (S_i), by their energy intensity[1] (EI_i) and by their energy mix (M_{ij}).

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[1] Energy intensity measures the amount of energy required per unit of consumption or product, expressed in terms of a value which is determined by the used sources which have different caloric

Index i runs over each sector of the productive sectoral structure and index j runs over each kind of fuel: $i)$ natural gas ($j = 1$), $ii)$ coal ($j = 2$), $iii)$ petroleum ($j = 3$), $iv)$ renewable ($j = 4$), and $v)$ alternative energy ($j = 5$).

3.5 CO$_2$ intensity and energy matrix submodel

CO$_2$ intensity ($CO2_{int}$) of a given country corresponds to the ratio of CO$_2$ emissions and the total consumed energy written in terms of mass of oil equivalent.

$$CO2_{int} = \frac{\sum_{ij} C_{ij}}{\sum_{ij} E_{ij}} \tag{3.8}$$

The value of the $CO2_{int}$ in a given year depends on the particular energy mix during that year. M_{ij} gives the energy matrix, but it is more convenient to sum over the different sectors and aggregate the fossil fuel contributions, therefore, we define:

$$M_j = \frac{\sum_{i} E_{ij}}{\sum_{ij} E_{ij}} \tag{3.9}$$

On one hand, M_1, M_2, and M_3 correspond to the energy consumption from natural gas, coal, and petroleum, respectively. Therefore, the share of fossil energy in the total consumption will be $M_1 + M_2 + M_3$. On the other hand, M_4 and M_5 stand for the energy consumption from renewable and alternative sources, respectively. Therefore:

$$M_1 + M_2 + M_3 + M_4 + M_5 = 100\% \tag{3.10}$$

In order to simplify the description, we assume that M_4 and M_5 do not contribute to the CO$_2$ emissions. Following the methodology recommended by the IPCC, that is, the *Reference method* (IPCC, 2006) [42], the approach of the first level for the fossil energy mix was used. The emission factors, U_{ij}, are taken from the $IPCC$ methodology to estimate the CO$_2$ emission of each fuel (IPCC, 2006) [42].

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powers and by the equipment used with different technologies and efficiency levels (WB, 2012) [146]. Note that the different economic sectors have different intensive use of energy (Cancelo, 2002) [194]. Two factors explain the differences in energy intensity between each sector: $i)$ differences in the efficiency of the energy used in each sector and $ii)$ differences in the economic activity of each sector.

3.6 CO_2 emission factors

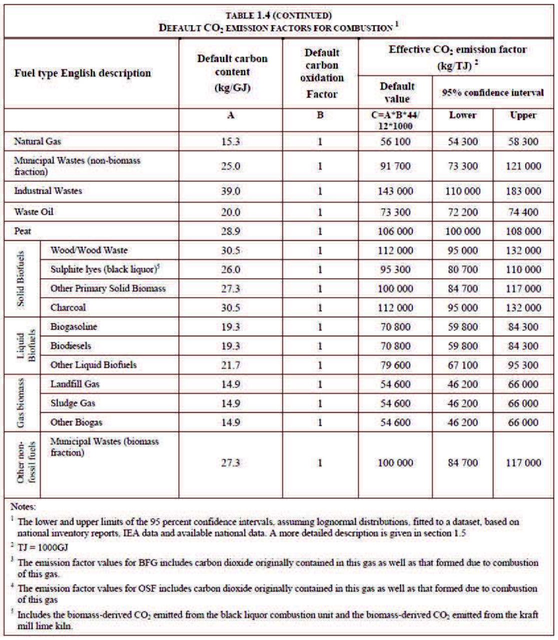

TABLE 1.4 (CONTINUED)
DEFAULT CO_2 EMISSION FACTORS FOR COMBUSTION [1]

Fuel type English description		Default carbon content (kg/GJ)	Default carbon oxidation Factor	Effective CO_2 emission factor (kg/TJ) [2]		
				Default value	95% confidence interval	
		A	B	C=A*B*44/12*1000	Lower	Upper
Natural Gas		15.3	1	56 100	54 300	58 300
Municipal Wastes (non-biomass fraction)		25.0	1	91 700	73 300	121 000
Industrial Wastes		39.0	1	143 000	110 000	183 000
Waste Oil		20.0	1	73 300	72 200	74 400
Peat		28.9	1	106 000	100 000	108 000
Solid Biofuels	Wood/Wood Waste	30.5	1	112 000	95 000	132 000
	Sulphite lyes (black liquor)[5]	26.0	1	95 300	80 700	110 000
	Other Primary Solid Biomass	27.3	1	100 000	84 700	117 000
	Charcoal	30.5	1	112 000	95 000	132 000
Liquid Biofuels	Biogasoline	19.3	1	70 800	59 800	84 300
	Biodiesels	19.3	1	70 800	59 800	84 300
	Other Liquid Biofuels	21.7	1	79 600	67 100	95 300
Gas biomass	Landfill Gas	14.9	1	54 600	46 200	66 000
	Sludge Gas	14.9	1	54 600	46 200	66 000
	Other Biogas	14.9	1	54 600	46 200	66 000
Other non-fossil fuels	Municipal Wastes (biomass fraction)	27.3	1	100 000	84 700	117 000

Notes:

[1] The lower and upper limits of the 95 percent confidence intervals, assuming lognormal distributions, fitted to a dataset, based on national inventory reports, IEA data and available national data. A more detailed description is given in section 1.5

[2] TJ = 1000GJ

[3] The emission factor values for BFG includes carbon dioxide originally contained in this gas as well as that formed due to combustion of this gas.

[4] The emission factor values for OSF includes carbon dioxide originally contained in this gas as well as that formed due to combustion of this gas

[5] Includes the biomass-derived CO_2 emitted from the black liquor combustion unit and the biomass-derived CO_2 emitted from the kraft mill lime kiln.

Figure 3.5: Default CO_2 emission factors for combustion - Table 1.4 in IPCC Guidelines for National Greenhouse Gas Inventories (2006), Volume 2: Energy [6].

Following the IPCC Guidelines for National Greenhouse Gas Inventories (2006), Volume 2: Energy [6], combustion processes are optimized to derive the maximum amount of energy per unit of fuel consumed, hence delivering the maximum amount of CO_2. Efficient fuel combustion ensures oxidation of the maximum amount of carbon available in the fuel. CO_2 emission factors for fuel combustion are therefore relatively insensitive to the combustion process itself and hence are primarily dependent only on the carbon content of the fuel.

The carbon content may vary considerably both among and within primary fuel types on a per mass or per volume basis:

- For natural gas, the carbon content depends on the composition of the gas which, in its delivered state is primarily methane, but can include small quantities of ethane, propane, butane, and heavier hydrocarbons. Natural gas flared at the production site will usually contain far larger amounts of non-methane hydrocarbons. The carbon content will be correspondingly different.
- Carbon content per unit of energy is usually less for light refined products such as gasoline than for heavier products such as residual fuel oil.
- For coal, carbon emissions per tonne vary considerably depending on the coal's composition of carbon, hydrogen, sulphur, ash, oxygen, and nitrogen.

By converting to energy units this variability is reduced. A small part of the fuel carbon entering the combustion process escapes oxidation. This fraction is usually small (99 to 100 percent of the carbon is oxidized) and so the default emission factors in Figure 3.5 (Table 1.4 in IPCC Guidelines for National Greenhouse Gas Inventories (2006), Volume 2: Energy [6]) are derived on the assumption of 100 percent oxidation. For some fuels, this fraction may in practice not be negligible and where representative country-specific values, based on measurements are available, they should be used. In other words: the fraction of carbon oxidised is assumed to be 1 in deriving default CO_2 emission factors.

Figures 3.6 and 3.7 (Table 1.3 in IPCC Guidelines for National Greenhouse Gas Inventories (2006), Volume 2: Energy [6]) give carbon contents of fuels from which emission factors on a full molecular weight basis can be calculated (Figure 3.5). These emission factors are default values that are suggested only if country-specific factors are not available. More detailed and up-to-date emission factors may be available at the IPCC [6].

Note that CO_2 emissions from biomass fuels are not included in the national total but are reported as an information item, also peat is treated as a fossil fuel and not as a biofuel and emissions from its combustion are therefore included in the national total.

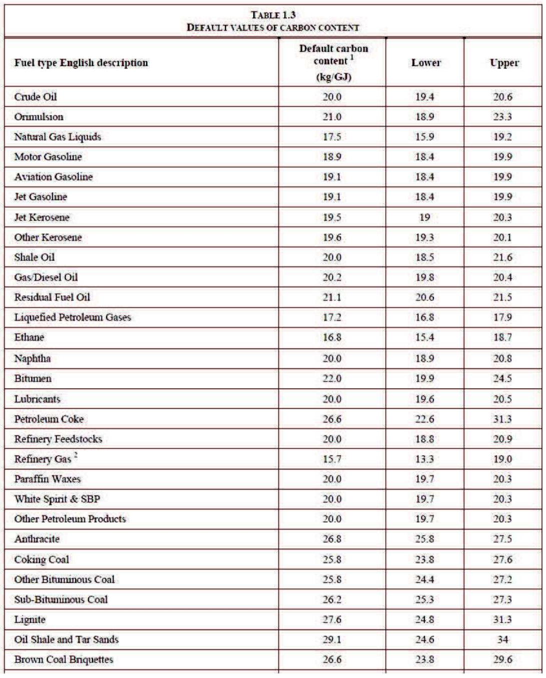

TABLE 1.3
DEFAULT VALUES OF CARBON CONTENT

Fuel type English description	Default carbon content [1] (kg/GJ)	Lower	Upper
Crude Oil	20.0	19.4	20.6
Orimulsion	21.0	18.9	23.3
Natural Gas Liquids	17.5	15.9	19.2
Motor Gasoline	18.9	18.4	19.9
Aviation Gasoline	19.1	18.4	19.9
Jet Gasoline	19.1	18.4	19.9
Jet Kerosene	19.5	19	20.3
Other Kerosene	19.6	19.3	20.1
Shale Oil	20.0	18.5	21.6
Gas/Diesel Oil	20.2	19.8	20.4
Residual Fuel Oil	21.1	20.6	21.5
Liquefied Petroleum Gases	17.2	16.8	17.9
Ethane	16.8	15.4	18.7
Naphtha	20.0	18.9	20.8
Bitumen	22.0	19.9	24.5
Lubricants	20.0	19.6	20.5
Petroleum Coke	26.6	22.6	31.3
Refinery Feedstocks	20.0	18.8	20.9
Refinery Gas [2]	15.7	13.3	19.0
Paraffin Waxes	20.0	19.7	20.3
White Spirit & SBP	20.0	19.7	20.3
Other Petroleum Products	20.0	19.7	20.3
Anthracite	26.8	25.8	27.5
Coking Coal	25.8	23.8	27.6
Other Bituminous Coal	25.8	24.4	27.2
Sub-Bituminous Coal	26.2	25.3	27.3
Lignite	27.6	24.8	31.3
Oil Shale and Tar Sands	29.1	24.6	34
Brown Coal Briquettes	26.6	23.8	29.6

Figure 3.6: Default values of carbon content - Table 1.3 in IPCC Guidelines for National Greenhouse Gas Inventories (2006), Volume 2: Energy [6].

The data presented in Figures 3.6 and 3.7 is used to calculate default emission factors for each fuel on a per energy basis. If activity data is available on a per mass basis, a similar approach can be applied to these activity data directly. Obviously the carbon content then should be known on a per mass basis.

3.7 Model equations

Below we summarize the difference equations that are used in each submodel:

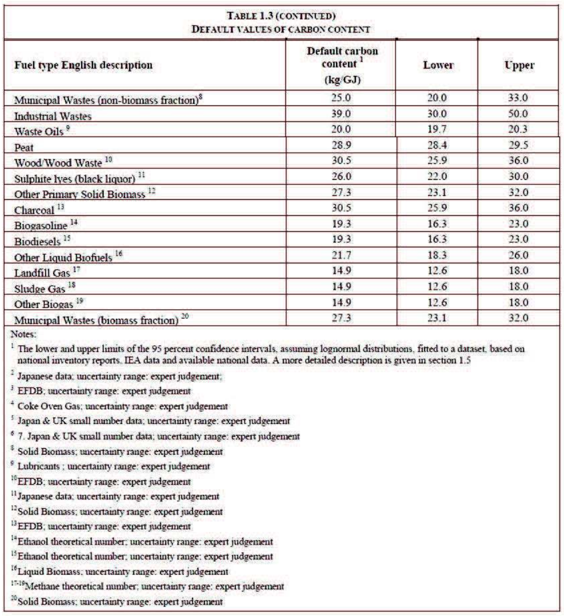

TABLE 1.3 (CONTINUED)
DEFAULT VALUES OF CARBON CONTENT

Fuel type English description	Default carbon content [1] (kg/GJ)	Lower	Upper
Municipal Wastes (non-biomass fraction)[8]	25.0	20.0	33.0
Industrial Wastes	39.0	30.0	50.0
Waste Oils [9]	20.0	19.7	20.3
Peat	28.9	28.4	29.5
Wood/Wood Waste [10]	30.5	25.9	36.0
Sulphite lyes (black liquor) [11]	26.0	22.0	30.0
Other Primary Solid Biomass [12]	27.3	23.1	32.0
Charcoal [13]	30.5	25.9	36.0
Biogasoline [14]	19.3	16.3	23.0
Biodiesels [15]	19.3	16.3	23.0
Other Liquid Biofuels [16]	21.7	18.3	26.0
Landfill Gas [17]	14.9	12.6	18.0
Sludge Gas [18]	14.9	12.6	18.0
Other Biogas [19]	14.9	12.6	18.0
Municipal Wastes (biomass fraction) [20]	27.3	23.1	32.0

Notes:

[1] The lower and upper limits of the 95 percent confidence intervals, assuming lognormal distributions, fitted to a dataset, based on national inventory reports, IEA data and available national data. A more detailed description is given in section 1.5

[2] Japanese data; uncertainty range: expert judgement;

[3] EFDB; uncertainty range: expert judgement

[4] Coke Oven Gas; uncertainty range: expert judgement

[5] Japan & UK small number data; uncertainty range: expert judgement

[6] 7. Japan & UK small number data; uncertainty range: expert judgement

[8] Solid Biomass; uncertainty range: expert judgement

[9] Lubricants ; uncertainty range: expert judgement

[10] EFDB; uncertainty range: expert judgement

[11] Japanese data; uncertainty range: expert judgement

[12] Solid Biomass; uncertainty range: expert judgement

[13] EFDB; uncertainty range: expert judgement

[14] Ethanol theoretical number; uncertainty range: expert judgement

[15] Ethanol theoretical number; uncertainty range: expert judgement

[16] Liquid Biomass; uncertainty range: expert judgement

[17-19] Methane theoretical number; uncertainty range: expert judgement

[20] Solid Biomass; uncertainty range: expert judgement

Figure 3.7: Default values of carbon content - Table 1.3 (Continued) in IPCC Guidelines for National Greenhouse Gas Inventories (2006), Volume 2: Energy [6].

$$
\begin{aligned}
Q_{(t)} &= a_1 I_{(t)} + a_2 TB_{(t)} + a_3 C_{(t)} + a_4 Eimp_{(t)} + a_5 RN_{(t-1)}, && (3.11)\\
E_{j(t)} &= \sum_i S_{i(t)} \cdot EI_{i(t)} \cdot M_{ij(t)} \cdot GDP_{(t)}, && (3.12)\\
RN_{(t)} &= E_{4(t)} + E_{5(t)}, && (3.13)\\
y_{(t)} &= y_{(t-1)} \cdot (1 + r_y), && (3.14)
\end{aligned}
$$

where $S_{i(t)}, EI_{i(t)}, M_{ij(t)}, I_{(t)}, TB_{(t)}, C_{(t)}$, and $Eimp_{(t)}$ evolve following Equation 3.14 while the parameters a_i have constant values. Note that index j runs over the type of energy sources, while i on the industrial sectors; $j = 4$ and $j = 5$ corresponds to renewable and alternative energy, respectively. $t = 0$ corresponds to the base year and t is given in number of years since 1980. The value of r_y is fixed through the definition of the used scenario,

$$r_y = \left(\frac{y_{(tf)}}{y_{(0)}}\right)^{1/tf} - 1, \tag{3.15}$$

where tf is the future time for which we establish the goal ($y_{(tf)}$), and y_0 is the starting value of the function. According to Rowland (2003) [179] and Jin et al., [180], to extrapolate the trend of the period 1980-2010 in the base scenario (trend), one should use a value of r_y that depends on the time,

$$r_{y(t)} = \left(\frac{y_{(t-1)}}{y_{(t-n)}}\right)^{1/n} - 1, \tag{3.16}$$

where n is the number of years of the dataset period, ***i.e.***, 30 in our case. The feedback mechanism is provided through the inclusion of $RN_{(t-1)}$ in the calculation of the income (Q) (Equation 3.11). As $a_5 < 0$ (see Table 3.2) the feedback mechanism is negative. This fact induces a decrease of the GDP for the *SC-3* and *SC-4* scenarios with respect to *SC-2* (see section 3.10.1 in this Chapter) for increasing of renewable energy use. In general, any increase of the terms $\sum_i S_{i(t)} \cdot EI_{i(t)} \cdot M_{ij(t)}$ for $j = 4$ and $j = 5$ will induce a reduction, though moderate, of the income.

In Figure 3.8 we present the schematic view of the whole model. It is worth noting the *feedback* mechanism between renewable energy and GDP. This is one of the keys of the model, which allows us to generate a non-trivial evolution of the system. In this Figure, we can identify the economic submodel, the energy consumption and productive sectoral submodel, as well as the CO$_2$ intensity and energy matrix submodel.

3.8 Causal diagram of CO$_2$ emissions

To understand why and how CO$_2$ emissions change over time, we need to know the factors that separately affect or control CO$_2$ emissions. In particular, it is extremely useful to represent the driving forces of CO$_2$ emissions in a hierarchical way, showing the causality relationship between the different variables. All this information constitutes the causal diagram. In this work the variables that will determine the amount of CO$_2$ emissions are: GDP (formation components), share of

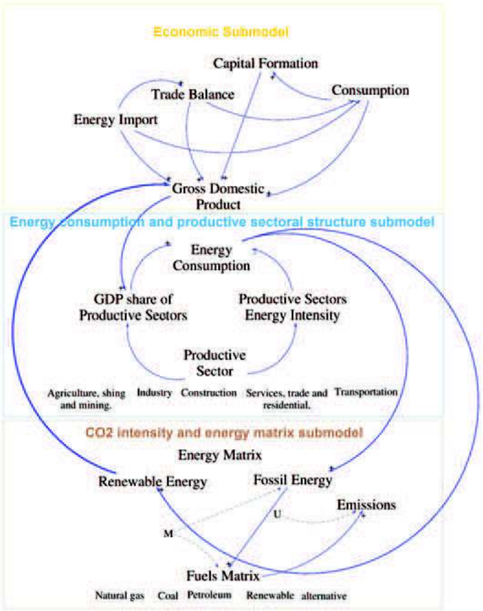

Figure 3.8: Causal diagram for the model. Continuous lines stand for the relationship between variables, while dashed ones correspond to control terms (S:*productive sectoral structure*, M: *energy matrix*, U:*emission factors*). Bold line represents a feedback mechanism.

the different productive sectors in the GDP, energy intensity of each sector, energy consumption, energy matrix, and carbon dioxide intensity. They are all represented schematically in Figure 3.8. It can be observed that the CO_2 emitted into the atmosphere has several connections with the variables of the model: economic growth and its different productive activities demand more energy, this increase in energy consumption induces higher CO_2 emissions that could be regulated by changes in the energy matrix and in the productive sectoral structure of the country.

It is worth to note the presence of a feedback mechanism associated to the influence of renewable energy on the GDP (see bold line in Figure 3.8).

3.9 Model validation and verification

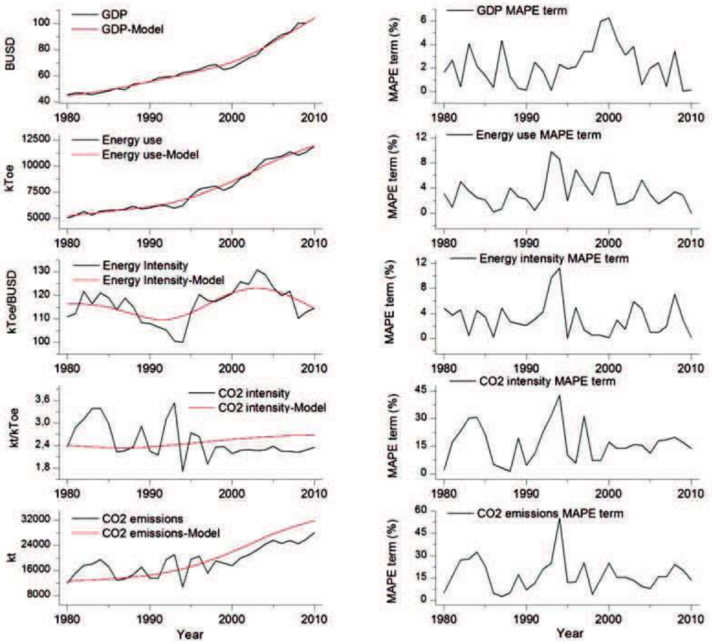

Figure 3.9: Left: Comparative of model result vs. historical data. Right: Time series of MAPE term at time t, see Ecuation 3.17.

Official dataset from 1980 to 2010 and the output of the model for the same period can be compared to test the reliability and robustness of the model. This analysis can be carried out calculating the mean absolute percentage error (MAPE) that is a measure of accuracy of a method for constructing fitted time series values in statistics, specifically in trend estimation. MAPE is most commonly used to evaluate cross-sectional forecasts (Ahlburg, 1995 [195]; Campbell, 2002 [196]; Hyndman and Koehler, 2006 [197]; Isserman, 1977 [198]; Miller, 2001 [199]; Murdock et al., 1984 [200]; Rayer, 2007 [201]; Sink, 1997 [202]; Smith, 1987 [203];

Smith and Sincich, 1990 [204]; Smith and Sincich, 1992 [205]; Smith, Tayman, and Swanson, 2001 [206]; Tayman, Schaffer, and Carter, 1998 [207]; Wilson, 2007 [208]).

It usually expresses accuracy as a percentage, and is defined by the formula:

$$\text{MAPE}(\%) = \frac{1}{n}\sum_{t_1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \times 100, \tag{3.17}$$

where, A_t, F_t, and n are the real data, the calculated values, and the number of data, respectively.

Table 3.3: Mean absolute percentage error (MAPE) for selected variables.

VARIABLE	MAPE(%)
GDP	2.2
Energy consumption	3.3
Energy intensity	3.2
CO_2 intensity	16
CO_2 emission	17

In table 3.3 the corresponding MAPE values for some selected variables are given. These results indicate the robustness of the model.

Note that in this work, we consider that CO_2 emissions come only from the burning of fossil fuels and we do not include the contribution coming from the production of cement, because the lack of official data. Therefore, our projections will consider CO_2 emissions only. This fact, together with the process of smoothing (HP filter) of the raw dataset and the use of general emission factors [42] justify the somehow large deviations observed in table 3.3 for the CO_2 intensity and CO_2 emissions (see Figure 3.9).

3.10 Scenarios

3.10.1 Scenario analysis for income, energy and emissions

As mentioned in Section 1.7 in Chapter 1, scenario analysis is used in a wide range of purposes in the literature. The primary function of the scenario approach in economy growth, energy consumption and emission in this research is to respond to uncertainty and potentially to develop strategic insights for policy.

Sometimes the terminology used to describe possible future conditions in the context of income, energy and emissions is often interchangeable in the literature. Holmes (2007) [209] notes some important distinctions. Whereas projections, forward historical data or past trends and forecasts, all of them are predictive and seek to determine the most likely future, scenarios look at diverging trends and the potential unfolding of new dynamics.

Rather than prediction, scenario approach seeks to describe a *spectrum of possibilities*. This is a bounded package of probability that could cover the range of plausible outcomes. Economic and environmental scenarios are used in contexts where dynamic complex systems are subject to uncertainties.

These uncertainties include inadequate scientific understanding, data gaps and inherent uncertainties on future events (Nakicenovic, 2000) [64]. Sometimes forecasts and projections are based on producing *Business As Usual* (BAU) or central *best guess* estimates and the high/low or optimistic/pessimistic variants of these.

According to Nakicenovic (2000) [64], the formulation of a range of emission scenarios is an appropriate technique to encompass uncertainties and deliver policy insights. With the use of scenario approach, some concern of *decision-makers* about the quantitative point forecasts of single *most likely* estimates arises. While this can reflect an ease of understanding of single estimates, or simply what decision-makers are accustomed to, these forecasts can also reflect a particular set of values or interests promoted as *objective* information. This concern with forecasts may not be appropriate to either scientific inquiry or to strategic thinking in decision-making, but it is a practice issue for scenarios.

Nielsen and Karlsson (2007) [40] note a science-policy nexus issue as technological and economic rationalities are implicitly embedded in models. This opens the question of the worldview, values and philosophy underpinning supposedly *objective* scientific information. This information can reflect specific futures that are profitable or preferable to certain interests or can be used to legitimise results rather than guide policy. The use of scenarios offers an approach to make world views more explicit, through the description of underlying themes in narratives. It can also be used to document assumptions used in modelling.

3.10.2 **Proposal of scenarios for Ecuador 2010-2025**

The goals that will be considered to define the different scenarios that will be proposed, under the general purpose of *improve the quality of life of people with the least environmental impact* are:

- *Goal 1*, by 2025 the GDP per capita will reach the international average (≈ 15000 USD according to our estimates based on World Bank data) through a process of industrialization and improvement of the productive sectoral structure of the country;
- *Goal 2*, in regard to the *Goal 1*, the use of renewable energy will be increased up to almost 30% of the total energy consumption;
- *Goal 3*, in regard to *Goal 1* and *Goal 2*, the energy efficiency will be enlarged by a reduction of the energy intensity and by changes in the productive sectoral structure.

Taking into account the latter goals, we propose four scenarios concerning the growth of the income, the evolution of the energy matrix and of the productive sectoral structure for the period 2011-2025.

1. *Baseline scenario* (*BS*): the GDP, the energy matrix and the productive sectoral structure will evolve through the smooth trend of the period 1980-2010 extrapolated to 2011-2025 using the geometric growth rate method.
2. *Increasing GDP scenario* (*SC-2*): GDP will increase approximately up to be double of reference GDP (2010) by 2025. To generate this scenario a constant annual growth of GDP formation components (I, TB, C, $Eimp$,

see Section 3.3.3 in this Chapter) of 7% per year between 2011 to 2025 will be assumed and a structural change in the productive sectoral structure will be implemented through a growth of 1% per year in the GDP share (S_i) in the sectors with more profit in the country economy: industry sector (sec-2) and trade and public service sector (sec-4). The rest of the variables will evolve as in the *BS* scenario. This scenario clearly corresponds to a situation where the economy is growing rapidly and no mitigation measurements to reduce the CO_2 emissions are carried out.

3. *Increasing GDP and share of renewable energies scenario* (*SC-3*): increasing GDP and change in productive sectoral structure as in the *SC-2* scenario is considered, however the share of fossil energy, will be reduced approximately one point per year, passing from a 88% in 2011 to 67% in 2025 due to a constant annual growth of share in renewable and alternative energy (M_4 and M_5). This scenario shows a first measure of environmental responsibility in order to try to reduce dependence of fossil energy.

4. *Increasing GDP and share of renewable energies and improvement in energy efficiency scenario* (*SC-4*): increasing GDP, change in productive sectoral structure and change in share of fossil energy as in *SC-3* scenario is carried out. Moreover, an improvement in energy efficiency is implemented with a 1% reduction of energy intensity in industry sector (sec-2), in trade and public services sector (sec-4) and in transportation sector (sec-5). This scenario takes a step towards improving the country's environmental responsibility and sustainable development by supporting their energetic saving measures and energy efficiency.

Both *SC-3* and *SC-4* scenarios goals are realistic considering the state of development and evolution of energy technology in various energy projects implemented by the Ecuadorian government, and the trends in the use of renewable energies in the country [154] (see Section 2.5 and Section 2.6 in Chapter 2).

3.11 Empirical findings and discussion of the model

This section includes the estimations and respective discussion for the period 2011-2025 in each studied scenarios of the main considerate variables, such as: income and income per capita, energy consumption and CO_2 emissions, among others.

3.11.1 Economic estimates

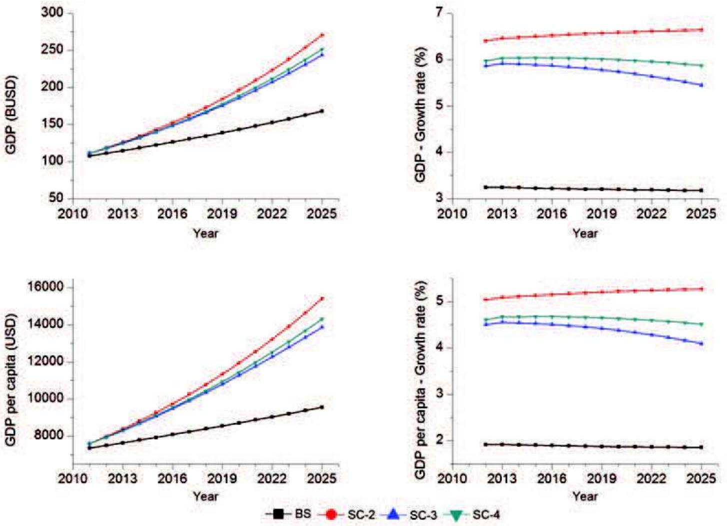

Figure 3.10: Left: Estimation of GDP and GDP per capita for the period 2011-2025 in Ecuador. Right: Growth rate.

GDP estimates for the two economic scenarios considered (on the one hand the *BS* and on the other hand *SC-2*, *SC-3* and *SC-4*) are presented in Figure 3.10, where one can see that the estimated GDP for the *SC-2* scenario will be around 271 billion USD in 2025 (61% higher than for *BS* scenario) and its average growth rate is 6.6% while in *BS* scenario is 3.2%. Note that the projected GDP is not a forecast but a consequence of the considered scenarios. Assuming an annual increase of the population of 1.2%, the population will pass from 14.5 million in 2010 to 17.6 million in 2025, thus GDP per capita in 2025 will be around 15000 USD (see Figure 3.10), which is roughly the prevision that has been considerate as the international average of GDP per capita.

In *SC-3* and *SC-4* scenarios, GDP would be lower than in *SC-2* scenario with a reduction of 27 and 20 billion USD, reaching 244 and 251 billion USD (BUSD) in 2025, respectively, due to the promotion of renewable energy and energy efficiency (see Figure 3.10). The nexus between GDP and renewable energy is obtained through the feedback mechanism of the model (see Section 3.7 in this Chapter). In *SC-4* scenario the reduction in GDP is slightly smaller (about 7 billion USD regarding the reduction in *SC-3*) because of the improvement in the energy intensity. Note that the tiny deviations between *SC-2*, *SC-3* and *SC-4* scenarios are due to the feedback mechanism between GDP and renewable energy. This can be seen in the different average growth rates for these scenarios, *SC-2* with 6.6%, *SC-3* with 5.8% and *SC-4* with 6.0% (see Figure 3.10).

Regarding the evolution of each sector, in sec-1 a very similar growth is observed in all scenarios (see Figure 3.11), about 3.8%. The reason is that its growth is not primarily affected by changes in the energetic matrix since this sector is less energetically intensive and its revenues depend greatly on the oil production of the country (see Section 2.2 in Chapter 2).

In sec-2 and sec-4, a significant increase is observed in the growth rate of the *SC-2*, *SC-3* and *SC-4* scenarios with respect to the growth rate of the BS scenario (see Figure 3.11). In the case of sec-2, *BS* grows at a rate of 3.3% while *SC-2* average growing is 7.6%. This growth is diminished in the remaining two scenarios, *SC-3* with 6.5% and *SC-4* with 6.9%. Similarly, in the sec-4, *BS* grows at a rate of 2.4% while the *SC-2* grows at a rate of 7.6%, this growth also is diminished in *SC-3* with a rate of 6.9% and in *SC-4* with a rate of 7.1%. The reason for this decrease is the application of the policy of reducing the use of fossil fuels and the improvement of energy efficiency.

In the case of sec-3 and sec-5, an increase in the growth rate is also observed in the *SC-2*, *SC-3* and *SC-4* scenarios with respect to *BS* but with less intensity. Note that the sec-5 (transport), in the *BS*, grows with a rate of 3.4% and the *SC-2*, *SC-3* and *SC-4* grow with an average value of 6.4% (see Figure 3.11).

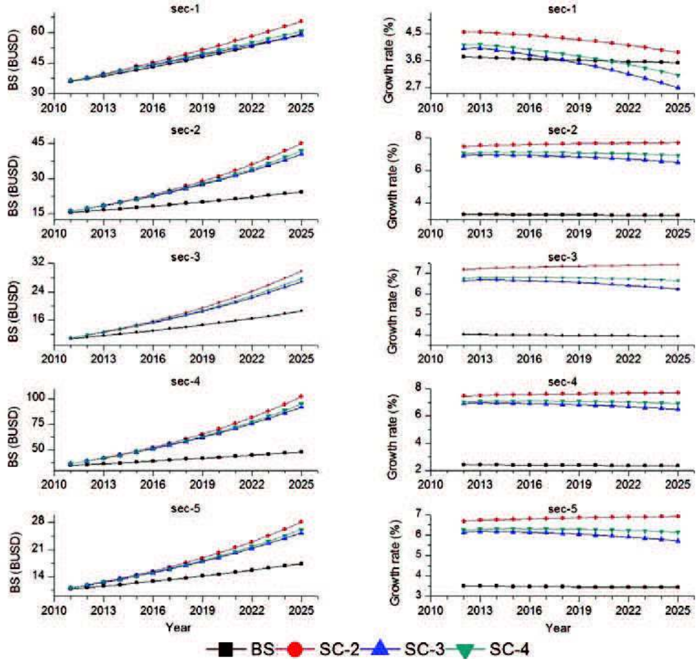

Figure 3.11: Left: Estimation of GDP by sector for the period 2011-2025 in Ecuador. Right: Growth rate.

Figure 3.12 shows the estimation of the Productive Sectorial Matrix (PSM) for the *BS* and for the alternative scenarios (*SC-2*, *SC-3* and *SC-4*). In *BS* case, we can observe that the largest sector is sec-1 (includes income from petroleum) that represented around 34% of GDP in the period 2011-2025, reinforcing the country's oil dependence, followed by sec-4 (31%), sec-2 (14%), sec-3 (11%) and sec-5 (10%). In the alternative scenarios, we can observe a change in the shares of PSM and Sec-4 is now the largest sector (35%), following by sec-1 but with a less share that in previous case (28%), sec-2 (industry) growth up to 16%, sec-3 (11%) and sec-5 (10%). Note that the share of sec-5 (transportation) keeps constant.

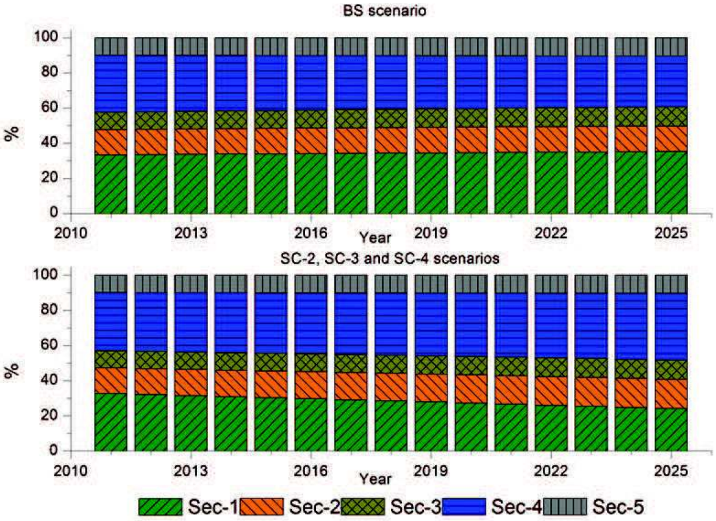

Figure 3.12: Estimation of Productive Sectorial Matrix in Ecuador 2011-2025.

3.11.2 Energy estimates

Energy consumption is calculated through the product of the energy intensity of each productive sector (EI_i) and the corresponding share of the GDP (Q_i) of every sector. The values of the energy consumption for the period 2011-2025 are represented in Figure 3.13. In 2025 the *BS* scenario generates a consumption of 20520 ktoe, the *SC-2* scenario about 36040 ktoe (76% higher than the *BS* scenario), and the *SC-3* scenario generates a consumption of 32425 ktoe (58% higher than the *BS* scenario). These two last scenarios show the growth of the energy consumption due to the increase of GDP and to the changes of the productive sectoral structure. Finally, *SC-4* scenario generates a consumption of 26740 ktoe (only 30% higher than in the *BS* scenario). It clearly shows the benefits of the reduction of the energy intensity.

In Figure 3.13, we can see that there are three pathways followed by the different proposed scenarios, the most energetically intensive is the path followed by

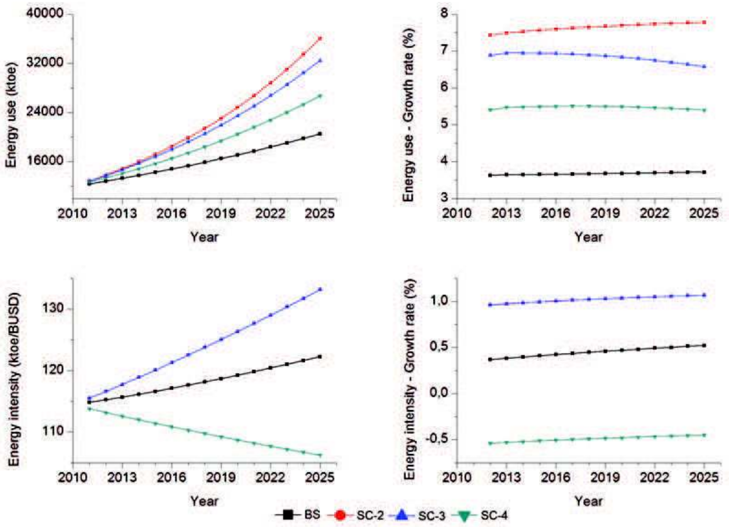

Figure 3.13: Lefth: Estimation of energy consumption and energy intensity for the period 2011-2020 in Ecuador. Right: Growth rate.

SC-2 and *SC-3* (indistinguishable in the used scale) , due to its larger energy consumption and low energy efficiency goal. Indeed, in these scenarios the energy intensity increases more than 15% (period 2011-2025). The path taken by *SC-4* is clearly the most energetically efficient, with a reduction of 6% in energy efficiency, while *BS* follow the trend path with a increase of 7% in the whole period.

The estimated values of energy intensity and energy consumption in each productive sector till 2025 are shown in Figure 3.14 and Figure 3.15, respectively to illustrate the differences between sectors. In Figure 3.14, one can clearly see the results of the implementation of energy efficiency goals set for each sector (especially for sec-2, sec-4 and sec-5) in scenario SC-4 (see Section 3.10.2 in this Chapter). Indeed, sec-5 in *SC-4* scenario has a reduction in its energy intensity value of almost 165 points (ktoe/BUSD) respect to the value in the rest of scenarios

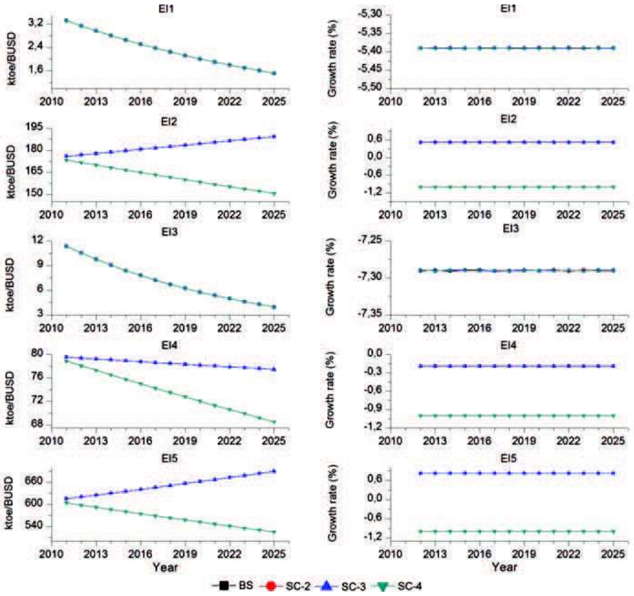

Figure 3.14: Left: Estimation of energy intensity in each productive sector for the period 2011-2025 in Ecuador. Right: Growth rate.

in 2025[1], while sec-2 and sec-4 reach a reduction of 40 and 10 points, respectively, in the same case[2].

Regarding energy matrix, two types of evolution have been taken into account in the calculations, in particular, for the share of fossil energy inside of the energy matrix and its components (M_1, M_2, and M_3). In the first case (scenarios *BS* and *SC-2*), the evolution of fossil energy keeps the tendency of the period 1980-2010. In the second case (scenarios *SC-3* and *SC-4*), a continuous drop of the use of fuel energy down to 67% in 2025 due to an increase of one point per year, approximate,

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[1] Note that, in *SC-4* sec-5 sector there is a reduction in the energy consumption of more than 5600 ktoe in 2025 respect to *SC-2* (see Figure 3.15).

[2] Note that, in *SC-4* scenario there are more than 2200 and 1400 ktoe of reduction in the energy consumption in 2025 for sec-2 and sec-4, respectively with respect to *SC-2* (see Figure 3.15).

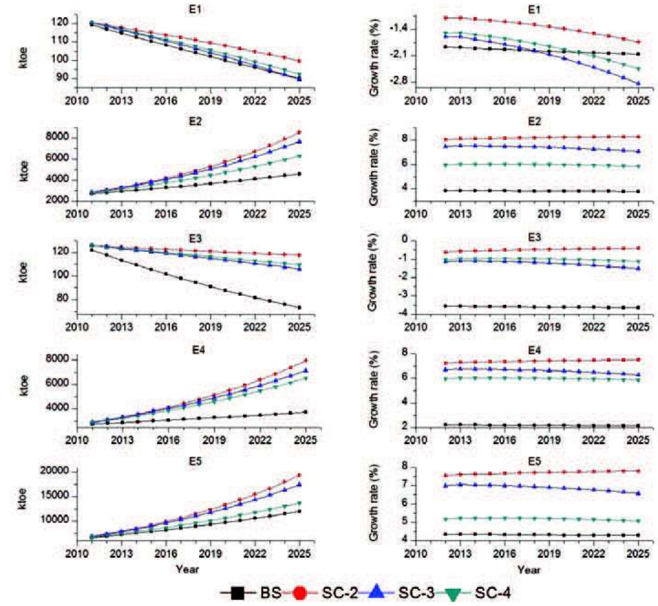

Figure 3.15: Left: Estimation of energy consumption in each productive sector for the period 2011-2025 in Ecuador. Right: Growth rate.

of renewable energy share (see Figure 3.16).

3.11.3 **Emission estimates**

A very important result is that the reduction of the global CO_2 intensity is twofold, on one hand, it is due to the use of a more efficient fossil fuel technology (lower CO_2 intensity) and, on the other hand, due to the reduction of the fossil energy share in the energy matrix. Both contributions are equally important. Note that the $2011 - 2025$ period presents different evolution of the global CO_2 intensity. In both *BS* and *SC-2* scenarios the value CO_2 intensity was almost constant (2.7 kt/ktoe) and in *SC-3* and *SC-4* scenarios a decreasing trend was shown, going from 2.7 to

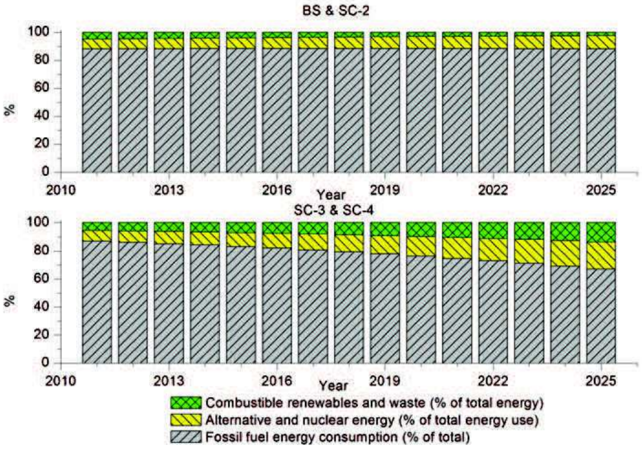

Figure 3.16: Estimation of energy matrix for the period 2011-2025 in Ecuador.

2.1 kt/ktoe between 2011 and 2025 (see Figure 3.17).

Figure 3.17 shows CO_2 emissions as a function of time for the period 2011-2025, under the four considered scenarios. In 2025 the highest CO_2 emission corresponds to the *SC-2* scenario, while the lowest corresponds to the *SC-4* scenario. The *SC-3* and *SC-4* scenarios, which imply the continuous growth of the GDP and the application of attenuation measures, with a reduction of the fossil energy contribution to the energy matrix and changes in the productive sectoral structure, present a clear reduction of CO_2 emissions with respect to the *SC-2* scenario. In particular, in 2025 CO_2 emissions would reach 97 thousand kt in *SC-2* scenario, and only 55 thousand kt in *BS* scenario. With the reduction of fossil energy, down to 67% in *SC-3* scenario, without modifying the energy intensity, one reaches 66 thousand kt, while implementing energy efficiency measures in the productive sectoral structure (*SC-4* scenario) emissions are reduced down to 54 thousand kt.

The *BS* scenario presents CO_2 emissions in 2025, 1.7 times higher than in 2010, while the *SC-2* scenario gives rise to an increase of 2.8 times. This implies that the amount of CO_2 emissions in the *SC-2* scenario during the period 2011-2020 will

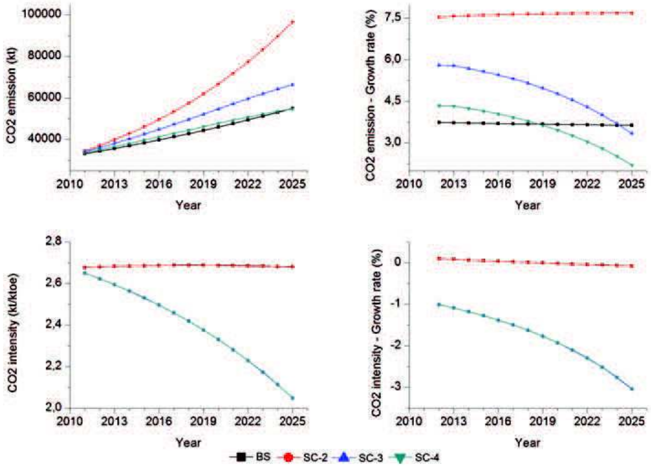

Figure 3.17: Left: Estimation of CO$_2$ and CO$_2$ intensity for the period 2011-2025 in Ecuador. Right: Growth rate.

be 260 thousand kt higher than in the *BS* scenario. Scenarios where renewable energy and efficiency goals are implemented show that it is possible to increase the GDP in a constant way, mitigating, at the same time, the CO$_2$ emissions, therefore reducing the rise of the emissions due to the higher economic activity. In particular, the most efficient scenario, *SC-4*, presents a remarkable reduction. In 2025 CO$_2$ emissions will be 43% lower than in the *SC-2* scenario. Furthermore, the *SC-3* scenario generates 115 thousand kt more than *BS* scenario during the 2011-2025 period, which supposes a reduction of 30 thousand kt with respect to *SC-2* scenario. Finally, the *SC-4* scenario generates 300 kt less than *BS* scenario during the same period, which supposes a large reduction of 41 thousand kt with respect to the *SC-2* scenario.

The estimated values of CO$_2$ intensity and CO$_2$ emissions in each productive sector till 2025 are shown in Figure 3.18 and Figure 3.19 respectively to illustrate the differences between sectors. In Figure 3.18, we can see the results of the im-

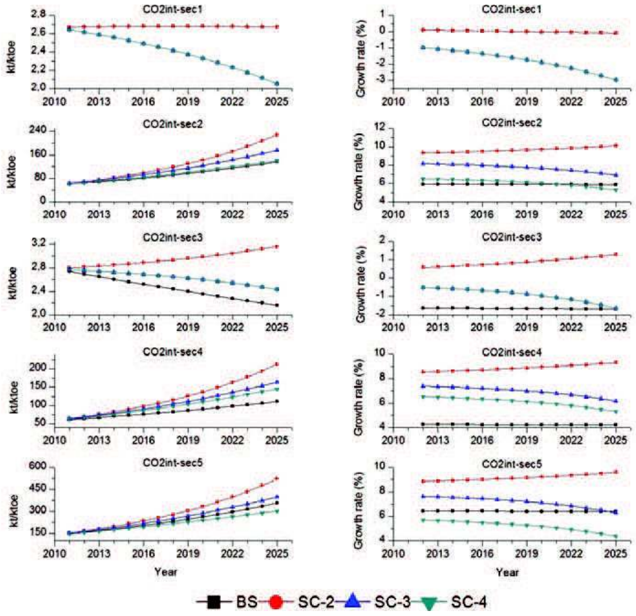

Figure 3.18: Left: Estimation of CO_2 intensity in each productive sector for the period 2011-2025 in Ecuador. Right: Growth rate.

plementation of green goals set for each sector (especially for sec-2 and sec-5) in scenario SC-4 (see Section 3.10.2 in this Chapter). Indeed, sec-5 in *SC-4* scenario presents a reduction in its CO_2 intensity value of 55, 220 and 95 points (kt/ktoe) respect to the value of *BS*, *SC-2* and *SC-3* in 2025, respectively. Note that, in *SC-4* scenario there are more than 4, 24 and 7 thousand kt of reduction in emissions of transport sector (sec-5) in 2025 respect to *BS*, *SC-2* and *SC-3* scenarios, respectively (see Figure 3.19). While sec-2 in *SC-4* reach a reduction of 88 and 136 points with respect to *SC-2* and *SC-3*, respectively, and only has 4 point more than the value of CO_2 intensity in *BS* scenario. Note that, in *SC-4* scenario there are almost 10 and 3 thousand kt of reduction in emissions of industry sector (sec-2) in 2025 respect to *SC-2* and *SC-3*, respectively, and only 600 kt more than in the *BS* scenario

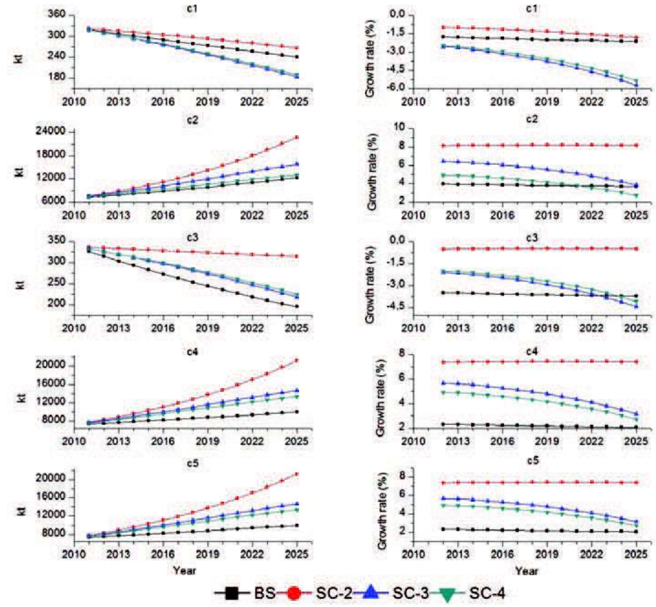

Figure 3.19: Left: Estimation of CO_2 in each productive sector for the period 2011-2025 in Ecuador. Right: Growth rate.

(see Figure 3.19).

3.12 Summary and conclusions of the chapter

This Chapter presents a model based on a variation of the Kaya Identity and on an approach of GDP formation which is supported with the use of renewable energy. The official data set (1980-2010) was used to parameterize the model, while with the second part of the period (2011-2025) an estimation of different variables, including the CO_2 emissions, was carried out. To this end, the GDP and the energy intensity have been modeled. Moreover, different scenarios that present the evolution of the energy matrix and the productive sectoral structure have been defined.

First, a *BS* scenario (baseline scenario) has been defined, in which the variables of the model were parameterized according to the observed tendency during the period 1980-2010, assuming a geometric growth rate during the period 2011-2025. The second scenario, called *SC-2*, is characterized by the increasing (relative to 2010) of the GDP during the period 2011-2025 (with the goal of reaching the estimated international average GDP per capita in 2025). In the third scenario, called *SC-3* scenario, besides assuming the increasing of the GDP, we impose the decreasing of the fossil energy share (ES_1) up to 67%. Finally, in the fourth one, *SC-4* scenario, we complement the *SC-3* scenario including changes in the productive sectoral structure to achieve a reduction of energy intensity, which supposes a lower CO_2 intensity.

The main outcome of this chapter are the estimates of CO_2 emissions by the period 2011-2025 in each scenario (see Section 3.11.3 in this Chapter). By 2025 the *BS* scenario reaches 55 thousand kt, in the *SC-2* scenario it corresponds to 97 thousand kt, in *SC-3* scenario to 66 thousand kt, and in the *SC-4* scenario to 55 thousand kt of CO_2. Note that the *BS* scenario corresponds to a modest GDP increase, while in the others the GDP increases heavily. The highest emissions are for the *SC-2* scenario where no mitigation measures are taken. The other two scenarios show us that it is possible a sizable reduction of the emissions, promoting the renewable energy (*SC-3* scenario) and on top of that modifying the productive sectoral structure, therefore, reducing the energy and the CO_2 intensities, as in the *SC-4* scenario. It is worth to note that both promotion of renewable energy and improvement of the energy intensity are equally effective attenuating CO_2 emissions.

Adapt or perish, now as ever, is nature's inexorable imperative.

H. G. Wells

CHAPTER

4

Decomposition analysis in income and energy consumption related with CO_2 emissions in Ecuador (1980-2025)

4.1 Overview

In the present chapter, we discuss the decomposition analysis (DA) methodology applied within this research. This section presents the used technique, the applied mathematical methodology and the construction of an appropriate identity to measure the change of CO_2 emission in Ecuador during the period 1980-2025. Change is measured at both macro and disaggregated sectoral level. Specific aspects related to the application of DA to both the historical period (1980-2010) and in medium term prevision (2011-2025) for the proposed scenarios are discussed.

DA is widely applied in understanding changes in economic, energy consumption, environmental, employment and other socio-economic indicators (Hoekstra and van den Bergh, 2003) [210]. Several DA methodologies have been developed specifically to analyze changes in energy and emissions. Two main streams of inquiry have evolved under the concept of DA: $i)$ Index Decomposition Analysis (IDA) and $i)$ Structural Decomposition Analysis (SDA).

These techniques have been used for both temporal and cross country/region analysis. IDA is formulated using concepts similar to the *index numbers* used in economics and statistics. This technique is more popular in the literature than SDA which is based on an input-output model (Ang, 2004a) [211]. At first sight, the advantages of IDA over SDA include the requirement for less data (Hatzigeorgiou et al., 2008) [212]. In IDA, absolute, structural and elasticity indicators have been analysed in contrast to SDA which has generally been restricted to absolute indicators. In many countries input-output tables are not constructed annually. IDA also permits the exploration of a share effect in industry or transport, indeed, this methodology has a great development and application studies in the literature. In contrast, SDA can distinguish between technological and demand effects which is not possible in IDA. Zhou and Ang, (2008) [213] propose that IDA is more flexible for aggregate data studies, Hatzigeorgiou (2008) [212] points the requirement for less data and the use of three indicator forms as comparative advantages of IDA approach, while Ang (2004a) [211] states its simplicity and flexibility.

Since late 1970s IDA methods have undergone several deep changes in scope of application. The reason is the expanding from applications in industry to energy demand and emission analysis across various sectors. Key to the application of IDA is the decomposition of change as an indicator, using a governing function to a number of predefined factors of interest to the analysis (Zhou, 2008) [213]. This idea can be used to get insight into the effect of the driving forces[1] or determinants that underlie changes. IDA approach is now a widely accepted analytical tool for energy and carbon emissions analysis (Ang, 2004) [52]. The technique has direct policy implications as it can be used to accurately quantify effects including evaluation of energy conservation programs and the outcome may provide a basis for

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[1] In DA, the driving forces are determined by the governing function designed and are quantitative. In scenario analysis, driving forces can potentially overlap with those described by the DA approach, but they also encompass qualitative aspects that sometimes cannot be captured by modelling.

forecasting (Ang, 2004a) [211].

4.2 Decomposition techniques in explanatory factors. Aggregate data decomposition

Proops et al (1993) [214] decompose the growth rate of CO_2 emissions considering an aggregate economic activity, that is, without taking into account the relative weights of the different productive sectors. They identified three variables that influence the temporal evolution of CO_2 emissions, which are:

- The ratio of $CO_2(C)$ and energy used (E): $\frac{C}{E}$,
- The ratio of energy used in the economy (E) and the GDP (Q): $\frac{E}{Q}$,
- The GDP of the economy (Q).

These variables are related in the following identity:

$$C = \left(\frac{C}{E}\right)\left(\frac{E}{Q}\right)Q. \tag{4.1}$$

Taking logarithms of the identity 4.1 and differentiating[1] respect to time:

$$\frac{C'}{C} = \left(\frac{(C/E)'}{C/E}\right) + \left(\frac{(E/Q)'}{E/Q}\right) + \frac{Q'}{Q}. \tag{4.2}$$

Considering that time series are in discrete time and taking into account that $x' = \frac{dx}{dt} \approx \frac{\Delta x}{\Delta t}$ and assuming that $\Delta t = 1$, then $\frac{x'}{x} \approx \frac{\Delta x}{x}$, Equation 4.2 can be approached as,

$$\frac{\Delta C}{C} \approx \frac{\Delta(C/E)}{C/E} + \frac{\Delta(E/Q)}{E/Q} + \frac{\Delta Q}{Q}. \tag{4.3}$$

As Equation 4.3 is a discrete approximation, the result in both sides of the equation do not match and always will exist a residue.

Therefore, according to equation 4.3, the variation of CO_2 will be influenced by the following variables:

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[1] Wherein the $'$ represents the first derivative with respect to time, $x' = \frac{dx}{dt}$.

- The variation of the ratio $\frac{C}{E}$: this variation would be picking the modification of the fuel mix, so as to provide the same amount of energy a different quantity of CO_2 is emitted. Another possibility is that technologies that reduce emissions at the end of the process are applied.

- The variation of the ratio $\frac{E}{Q}$: it is the modification of the energy requirements to produce one unit of GDP. The variation of the ratio $\frac{E}{Q}$ could take place either because it increases the efficiency of energy production or because the structure is modified to sectors with lower energy requirements.

- The variation of Q: is the change in the GDP of the economy.

If we consider the three effects of first level mentioned in Grossman and Krueger (1991) [131] (effect scale, composition and technology, see Section 5.2.2 in Chapter 4), CO_2 change in Equation 4.3 can be explained through tree terms: $i)$ the first is the technological effect, $ii)$ the second refer to the rest of the technological effect (related to the improved efficiency in the use of resources), and the composition effect, $iii)$ the third is the scale effect. Although Proops et al (1993) [214] proposed this decomposition to be used for CO_2, it could be used for any contaminant associated with energy use.

This decomposition, some times called *aggregate* data decomposition, precisely because it does not incorporate information neither on the behavior of the different sectors nor introduce specific information on the fuel mix used, this approach represent the economic system as a whole. Since we need to incorporate information about productive sectors and energy mix to understand their behavior and effect on emission (disaggregated data) and because this will introduce a *sum term* inside Equation 4.3, a new approach is needed.

4.3 Index decomposition analysis (IDA)

These methods began to be used to decompose the energy consumption and energy intensity but later extended its use to the decomposition of pollutant emissions related to energy (notably CO_2, SO_2 and NO_x).

According to Ang and Zhang (2000) [55], the two most used IDA methods in the literature have been the Laspeyres and arithmetic mean Divisia index. Following Ang and Zhang (2000) [55] and Ang (1994) [215], we choose as an indicator the *energy intensity* of the industry, to *shorten the explanation*, since it involves only two factors decomposition whereas if we decompose, *e.g.*, emissions related to energy, we have to work with four factors. Also, we will introduce some reference to the decomposition of CO_2 emissions that will be used in the case of study in Section 4.5 in this Chapter.

We define the following variables for year t:

- E_t: total energy consumption in the industry.
- E_{it}: energy consumption in the industrial sector i.
- Y_t: total industry output.
- Y_{it}: production of industrial sector i.
- S_{it}: share of the industrial sector i (Y_{it}/Y_t).
- I_t: aggregate energy intensity (E_t/Y_t).
- I_{it}: energy intensity of sector i (E_{it}/Y_{it}).

The aggregate energy intensity can be expressed as:

$$I_t = \sum_i S_{it} I_{it}, \tag{4.4}$$

where the sum is taken over all industrial sectors (i). In Equation 4.4 the aggregate energy intensity is expressed in terms of the production structure and the sectoral energy intensities.

To analyze the variation of I_t as a funtion of changes of its components, *i.e.*, S_{it} and I_{it}, we will differentiate Equation 4.4 with respect to time,

$$I'_t = \sum_i \left(I_{it} S'_{it} + I'_{it} S_{it} \right). \tag{4.5}$$

Following Ang and Zhang (2000) [55], if we assume that the aggregate energy intensity varies from I_0 at time 0 to I_T at time T, this change can be expressed in two ways: $D_{tot} = \frac{I_T}{I_0}$ and $\Delta I_{tot} = I_T - I_0$. The first is called multiplicative decomposition since the estimated impact of structural change (D_{str}) and sectoral intensity (D_{int}) appear as multiplicative:

$$D_{tot} = D_{str} D_{int}. \tag{4.6}$$

The second form is called additive decomposition, the same two effects now called I$_{str}$ (structural change) and I$_{int}$ (sectoral intensity), appear additively:

$$\Delta I_{tot} = \Delta I_{str} + \Delta I_{int}. \tag{4.7}$$

4.3.1 Laspeyres index

This method isolates the impact of one variable, allowing it to vary while keeping the rest of the variables at their base year values (Ang and Zhang, 2000) [55].

Returning to Equation 4.5, which was in continuous time and converting it into a discrete time, keeping the variables that do not vary in their base year values, we approach the variation of I from year 0, to year T with the following expression:

$$I_T - I_0 = \sum_i I_{i0}(S_{iT} - S_{i0}) + \sum_i (I_{iT} - I_{i0}) S_{i0}. \tag{4.8}$$

The effects shown in the second member of Equation 4.8 can also be expressed as:

$$\Delta I_{str} = \sum_i S_{iT} I_{i0} - \sum_i S_{i0} I_{i0}, \tag{4.9}$$

$$\Delta I_{int} = \sum_i S_{i0} I_{iT} - \sum_i S_{i0} I_{i0}, \tag{4.10}$$

$$\Delta I_{rsd} = (I_T - I_0) - (\Delta I_{str} + \Delta I_{int}), \tag{4.11}$$

where ΔI_{rsd} is the residual that has been produced by the above discretization of time.

4.3.2 Arithmetic mean divisia index

The Divisia index can be defined as a weighted average of growth rates in which the components are weighted in proportion to their share to the total value.

Following Ang (1994) [215], we integrate Equation 4.5 on both sides with respect to time t, from year 0 to year T, Ang (1994) obtained the following expression:

$$\Delta I_{tot} = \int_0^T \sum_i I_{it} S'_{it} dt + \int_0^T \sum_i I'_{it} S_{it} dt. \tag{4.12}$$

Taking into account that:

$$I_{it} = \frac{E_{it}}{Y_{it}} = \frac{E_{it}}{Y_t}\frac{Y_t}{Y_{it}} = \frac{E_{it}}{Y_i}\frac{1}{S_{it}}. \tag{4.13}$$

Now, we reformulate Equation 4.12 to obtain the following expression[1],

$$\Delta I_{tot} = \int_0^T \sum_i \frac{E_{it}}{Y_t}\frac{S'_{it}}{S_{it}} dt + \int_0^T \sum_i \frac{E_{it}}{Y_t}\frac{I'_{it}}{I_{it}} dt = \Delta I_{str} + \Delta I_{int} \tag{4.14}$$

The integral of Equation 4.14 is converted into a parametric problem. To do this, we consider the first term of Equation 4.14 under the following conditions,

$$min\left\{E_{i0}/Y_0, E_{iT}/Y_T\right\} \leq E_{it}/Y_t \leq max\left\{E_{i0}/Y_0, E_{iT}/Y_T\right\}, \tag{4.15}$$

$$min\left\{S_{i0}, S_{iT}\right\} \leq S_{it} \leq max\left\{S_{i0}, S_{iT}\right\}. \tag{4.16}$$

One can find a set of parameters, β_i, satisfying the following equation [215]:

$$\Delta I_{str} = \sum_i \left[\frac{E_{i0}}{Y_0} + \beta_i\left(\frac{E_{iT}}{Y_T} - \frac{E_{i0}}{Y_0}\right)\right] \times \ln\left(\frac{S_{iT}}{S_{i0}}\right). \tag{4.17}$$

The same can be done with the second term of Equation 4.14,

$$\Delta I_{int} = \sum_i \left[\frac{E_{i0}}{Y_0} + \tau_i\left(\frac{E_{iT}}{Y_T} - \frac{E_{i0}}{Y_0}\right)\right] \times \ln\left(\frac{I_{iT}}{I_{i0}}\right), \tag{4.18}$$

where $0 \leq \beta, \tau \leq 1$

If we take $\beta_i = \tau_i = 0.5$, Equations 4.17 and 4.18 would be as follows,

$$\Delta I_{str} = \sum_i \left[\frac{\frac{E_{iT}}{Y_T} + \frac{E_{i0}}{Y_0}}{2}\right] \times \ln\left(\frac{S_{iT}}{S_{i0}}\right), \tag{4.19}$$

---

[1] Indeed, Ang (1994) [215] obtained two different expressions for the same decomposition, allowing to deduce two parametric Divisia methods for additive decomposition. The presented here is the so called method of parametric Divisia 1 for additive decomposition. The expression from where starts the method of parametric Divisia 2 is simply the Equation 4.12 without restating. It also has two parametric Divisia methods for multiplicative decomposition.

$$\Delta I_{int} = \sum_i \left[\frac{\frac{E_{iT}}{Y_T} + \frac{E_{i0}}{Y_0}}{2} \right] \times \ln \left(\frac{I_{iT}}{I_{i0}} \right), \tag{4.20}$$

$$\Delta I_{rsd} = \Delta I_{tot} - (\Delta I_{str} + \Delta I_{int}). \tag{4.21}$$

Equations 4.19 to 4.21 constitue the arithmetic mean Divisia index formulas in its additive form as they appear in the work by Ang and Zhang (2000) [55]. The term ΔI_{rsd} includes the residual resulting from the discrete approximation made. The expression in brackets in Equations 4.19 and 4.20 would act as a weight for sector i in the summation.

To obtain the multiplicative form, Equation 4.5 is divided between I_t and then integrated, as in the additive form, between year 0 to year T, obtaining:

$$\ln \left(\frac{I_T}{I_0} \right) = \int_0^T \left(\sum_i \frac{I_{it} S'_{it}}{I_t} \right) dt + \int_0^T \left(\sum_i \frac{I'_{it} S_{it}}{I_t} \right) dt. \tag{4.22}$$

If we set $D_{tot} = \frac{I_T}{I_0}$, Equation 4.22 can be expressed as:

$$D_{tot} = exp \left\{ \int_0^T \sum_i \left(\frac{E_{it}}{E_t} \right) \left(\frac{S'_{it}}{S_{it}} \right) dt \right\} \times exp \left\{ \int_0^T \sum_i \left(\frac{E_{it}}{E_t} \right) \left(\frac{I'_{it}}{I_{it}} \right) dt \right\}, \tag{4.23}$$

$$D_{tot} = D_{str} \times D_{int}, \tag{4.24}$$

where:

$$D_{str} = exp \left\{ \int_0^T \sum_i \left(\frac{E_{it}}{E_t} \right) \left(\frac{S'_{it}}{S_{it}} \right) dt \right\}, \tag{4.25}$$

$$D_{int} = exp \left\{ \int_0^T \sum_i \left(\frac{E_{it}}{E_t} \right) \left(\frac{I'_{it}}{I_{it}} \right) dt \right\}, \tag{4.26}$$

In Equation 4.23, we can transform the integrated problem into a parametric problem in the same way that was done in the additive case (see Ang, 1994 [215]).

In contrast to Ang and Zhang (2000) [55][1], we used the general parametric Divisia methods to arrive at the Equations 4.19 - 4.24 in the manner described by

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[1] These authors use the theorem of the instantaneous growth rate and discrete approach based on call Törnqvist formula to arrive at the same equations.

Ang (1994) [215]. We selected the parametric Divisia methods because they allowed Ang (1994) [215] to classify all decomposition methods used until 1995, both additives and multiplicative, simply by varying the value given to the parameters β_i and τ_i. As has been mentioned in Ang (1994) [215]: *The values of the parameters can also be treated as weights assigned to the corresponding variables in year 0 and year T in the decomposition.* Because the weights can be assigned in an infinite number of ways, there may be an infinite number of decomposition methods, each corresponding to a specific set of weights.

For example, if we take $\beta_i = \tau_i = 0.5$, the equations of the method of arithmetic mean Divisia index are obtained, as we have shown for the additive form. By giving the value of 0.5 to the parameters, it is being assigned the same weight (0.5) at year 0 and year T. But if $\beta_i = \tau_i = 0$, then we would be in the case of Laspeyres index because all weights are assigned to year 0[1].

Ang (1994) [215] states that the term *adaptive* in the adaptive mean Divisia method, indicate that the parameters are not fixed a priori by the researcher but are determined, in the energy intensity case by the energy consumption and by the industrial production levels in the year 0 and in the year T [215].

The methods described can be applied to the decomposition between two given years, but may be also applied to a time series so that the decomposition will take place between t and $t+1$, with t varying from 1 to N. As will be $(N-1)$ decomposition sets which are used to calculate the cumulative effect [215].

Note that, all the methods used until 1995 and classified by Ang (1994) [215] presents as major drawback that they leave a residue on decomposition. Also note that the presence of logarithms, create a problem of zero, *i.e.*, problems that appear when the data set values are equal to zero.

In Ang and Zhang (2000) [55] accurate methods were proposed and solved the above problems. Those methods are: the logarithmic mean Divisia index (LMDI) method and refined Laspeyres index method. Note that these new methods can not be integrated in the general framework of parametric Divisia methods that allowed Ang (1994) [215] to classify the methods used until 1995.

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[1] The equations that we presented for the Laspeyres index decomposition, Equations 4.9 and 4.10, are obtained exactly by the method of parametric Divisia 2 for the additive case (see Ang,1994 [215]) when a value of 0 is given to the parameters.

4.3.3 Logarithmic mean divisia index (LMDI)

This method does not give residue in the decomposition, but still have the problem of zero, it can be solved by replacing zero values with small positive numbers (Ang, 2000) [55]. This method weights using the logarithmic mean rather than the arithmetic mean, *i.e.,* the arithmetic mean in brackets in Equations 4.19 and 4.20 is replaced by the logarithmic mean. It applies to both additive and multiplicative form.

Following Ang (2005) [216], let V be an energy-related aggregate composed of n factors contributing to changes in V over time and each one is associated with a quantifiable variable, x_1, x_2,..., x_n. Let subscript i be a sub-category of the aggregate for which structural change is to be studied. At the sub-category level the relationship $V_i = x_{1,i}x_{2,i}\cdots x_{n,i}$ holds. Then, the general index decomposition analysis (IDA) for V is given by:

$$V = \sum_i V_i = \sum_i x_{1,i}x_{2,i}\cdots x_{n,i}, \tag{4.27}$$

the aggregate changes from $V^0 = \sum_i x^0_{1,i}x^0_{2,i}\cdots x^0_{n,i}$ in time 0 to $V^T = \sum_i x^T_{1,i}x^T_{2,i}\cdots x^T_{n,i}$ in time T.

In additive decomposition we decompose the difference as,

$$\Delta V_{tot} = \Delta V^T - \Delta V^0 = \Delta V_{x1} + \Delta V_{x2} + \cdots + \Delta V_{xn}. \tag{4.28}$$

While in multiplicative decomposition as,

$$D_{tot} = \frac{V^T}{V^0} = D_{x1}D_{x2}\cdots D_{xn}. \tag{4.29}$$

The subscript tot represents the total or overall change and the terms on the right-hand side give the effects associated with the respective factors in Equation 4.27.

In the logarithmic mean Divisia index (LMDI) approach[1], the general formula for the effect of the kth factor on the right hand side of Equations 4.28 and 4.29 are respectively:

$$\Delta V_{x_k} = \sum_i L\left(V_i^T, V_i^0\right) \ln\left(\frac{x^T_{k,i}}{x^0_{k,i}}\right). \tag{4.30}$$

---

[1] The LMDI is used here to refer to the logarithmic mean Divisia method I (LMDI I). A related version, the LMDI II, has a weighting scheme slightly more complex than LMDI I (Ang et al., 2003) [217].

$$D_{x_k} = exp\left[\sum_i \frac{L\left(V_i^T, V_i^0\right)}{L\left(V^T, V^0\right)} \ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right)\right], \tag{4.31}$$

where $L(a, b) = (a - b)/(\ln a - \ln b)$ as defined in Ang (2004) [52].

4.3.4 **Refined Laspeyres index**

In the case of methods based on the Laspeyres index, the problem of zero does not exist, but as Ang and Zhang (2000) shown, these methods leave large residues after decomposition. To address these residues, Sun (1998) proposed the method called the refined Laspeyres index, in which residues (interactions) are equally distributed between the different effects (structural effect and intensity effect) decomposition. This method can only be applied to the additive form. Following Laspeyres index method, Equations 4.19 and 4.20 would be replaced by [55]:

$$\Delta I_{str} = \sum_i \left(S_{iT} - S_{i0}\right) I_{i0} + \frac{1}{2} \sum_i \left(S_{iT} - S_{i0}\right) \left(I_{iT} - I_{i0}\right), \tag{4.32}$$

$$\Delta I_{int} = \sum_i \left(I_{iT} - I_{i0}\right) S_{i0} + \frac{1}{2} \sum_i \left(S_{iT} - S_{i0}\right) \left(I_{iT} - I_{i0}\right), \tag{4.33}$$

were $\sum_i \left(S_{iT} - S_{i0}\right)$ is the residue of the decomposition.

Ang and Zhang (2000) [55] conclude that residues obtained by the employment of basic Laspeyres approach are far from the ideal values (1 in the multiplicative form and 0 in the additive form), whereas the arithmetic mean Divisia method is very close to these ideal values. The two Divisia methods (arithmetic and logarithmic mean) would provide similar results when changes in the variables between year 0 and year T are not so important. In the event that this does not happen, the arithmetic mean Divisia method in its additive form has significant residue.

4.4 **Structural decomposition analysis (SDA)**

Rose and Chen defined the SDA as *the analysis of economic change through a set of comparative static changes in key parameters in an input-output table* (Rose and Chen, 1991) [218]. According to Rose and Casler (1996) [219], the basic rationale of the SDA is to break an identity into its components. This division can be as simple as three parts or as complex as desired. For these authors, the reasons that may explain the popularity of this methodology are:

- This methodology overcomes many of the features of the static input-output models and allows us to examine changes over time in the technical coefficients and sectoral participation. Although it has been used mainly for historical analysis, this technique can also be used as a predictive tool. It also allows examine the responses to changes in prices, which are only implicit even in the input-output tables based on values.
- Another reason is that it is a pragmatic alternative to the econometric estimation. To analyze the same issues, econometric studies require time series of fifteen years or more and not just the outputs and primary factors of production, but also the intermediate inputs. The SDA only require two input-output tables: one for the initial year and one for the final one.
- An additional reason is that it allows to consider all inputs used in production, including intermediate. This is especially interesting for studies related to the environment and natural resources, and to analyze the causes of pollution and resource depletion.

Hoekstra and van den Bergh (2002) [220] conducted a review of the literature on the implementation of the SDA to the physical flows in an economy (*e.g.*, emissions). These authors consider that the input-output framework is suitable for environmental analysis because it is able to integrate data on the economic situation and data on physical flows. They point to two methods of input- output analysis that combine monetary and physical data that are relevant to the SDA:

- The input-output analysis using the method of ”hybrid units”. This method allows the use of different units in different rows of the input-output table (for example, replace the monetary units in the sectors of primary energy production by corresponding physical unit of CO$_2$ emissions). Thus, the data from the monetary input-output table and physical input-output table can be integrated into a hybrid units input-output table.

- The input-output analysis using the method of factor intensity. In this method the monetary input-output model is associated (multiplying) a vector of material intensity per unit of output (or value added) in each sector. This method requires less data than the previous one. According to Miller and Blair (1985) [221], this method is equivalent to the hybrid units only if the prices of the products are uniform for all industries and consumers. If prices are not uniform, the method of hybrid units works better. For example, if the price of fuel varies between sectors, a monetary unit of fuel purchased by different sectors may result in different amounts of fuel and also in different emissions, so that the correct variation in emissions would not result. This does not happen in the method of hybrid units.

Following Hoekstra and van den Bergh (2002) [220], the input-output model can be written as,

$$x = L \cdot y \tag{4.34}$$

where $L = (I - A)^{-1}$ is the Leontief inverse matrix[1] and y is the vector of final demand. This equation can be decomposed into two effects: $i)$ *the effect coefficients input-output*, which is produced by changes in the structure of the intermediate inputs and $ii)$ *the final demand effect*, which reflects the changes in y:

$$\Delta x = \Delta L \cdot y + L \cdot \Delta y. \tag{4.35}$$

These two effects may in turn be analyze separately:

$i)$ On one hand, the input-output coefficients can be decomposed into the change due to the technological substitution of inputs (changes between inputs) and productivity changes (changes in the efficiency with which an input is used).

Following Hoekstra and see Bergh (2002) [220], the decomposition of the input-output coefficients can be:

- Additive: $\Delta L = (I - \Delta A)^{-1}$.
- Multiplicative: $\Delta L = L \cdot \Delta A \cdot L$.

---

[1] Note that, If the inverse $(I - A)^{-1}$ exists, then a unique solution to the Equation 4.34 exists.

The next step in the decomposition is to break down changes in the coefficient matrix, A, into changes in the underlying structure of the inputs. To do this there are two ways:

- Divide the matrix into individual coefficients: $\Delta A = \Delta A_{11} + \Delta A_{12} + ... + \Delta A_{ij} + \Delta A_{nn}$.
- Use a method based on the RAS [1] approach: $\Delta A = \Delta r \cdot \Delta A^{t-1} \cdot s + r \cdot A^{t-1} \cdot \Delta s + \epsilon$, where r and s are RAS multipliers.

$ii)$ On the other hand, final demand can be decomposed into several effects: the effect of product participation (changes in the participation of n-products consumed); the effect category (changes between p-categories in final demand) and the effect of the level of final demand (the effect of growth in total final demand). If sufficient information is available, the decomposition of final demand is able to determine the impact on environmental indicators of changes in domestic consumption or changes in foreign transactions.

Final demand can be decomposed into (Hoekstra and van den Bergh, 2002) [220]:

$$\Delta Y = \Delta B \cdot c \cdot f + B \cdot \Delta c \cdot f + B \cdot c \cdot \Delta f, \tag{4.36}$$

where B is a matrix whose elements are equal to the elements of the matrix in final demand divided by the corresponding column sums; coefficients c indicate the share of each category in final demand in total final demand; the scalar f represents the total final demand.

Taking reference exposed decomposition, the decomposition model of hybrid units would be identical to the Equation 4.35 except that the variables would be hybrid units.

In the case of the method of factor intensity, we should calculate the total physical flow m:

$$m = i \cdot L \cdot y, \tag{4.37}$$

---

[1] The RAS method is an iterative method of biproportional adjustment of rows and columns that has been independently developed by various researchers, such as Kruithoff and Sheleikhovski in the 1930s. In 1961, Stone adapted the technique for use in updating IO tables from the work of Deming and Stephan [222].

where i collect the intensity (physical use per unit of output) for each sector.

The decomposition of the Equation 4.35 would lead to the following expression:

$$\Delta m = \Delta i \cdot L \cdot y + i \cdot \Delta L \cdot y + i \cdot L \cdot \Delta y, \tag{4.38}$$

where the second and third term would be the effects of input-output coefficients and final demand and the first term is the intensity effect, that would include the influence of changes in the physical flows per unit of output (the output in monetary terms).

SDA requires choosing an index to carry out the decomposition since each index produces different results and residues. No conclusive results have been reached on what is the most appropriate index (Hoekstra and van den Bergh, 2002) [220].

Hoekstra and van den Bergh (2003) [210] conducted a comparative analysis between SDA and IDA methods. The main advantage of the IDA is that it requires less data than SDA. However, the SDA allows a more detailed breakdown, in which a set of technological effects and final demand is included that can not be obtained with the IDA. In addition, SDA can capture the indirect effects of demand.

Hoekstra and van den Bergh (2003) [210] pointed out the different effects that can be captured with each of the two methods:

- Production effect (SDA and IDA), measures the effect of the change in total output on indicator.
- Structure effect (IDA), pick up the effect of a change in the share of the productive sectors in the economy.
- Leontief effect (SDA) assesses the effects of changes in the Leontief inverse matrix and can be interpreted as a technological effect of changes in the structure of intermediate inputs.
- Intensity effect (SDA and IDA) estimates changes in the use of the indicator in each sector per unit of output.
- Final demand effect (SDA), measures the effect of changes in final demand products of each sector.

Therefore, each method allows to estimate different effects but the SDA enables a more detailed analysis of demand and technological effects while IDA study allows to study the structure effects together with the intensity effect.

Since one of the goals of this research is to analyze the effects of scale, structure and intensity on CO$_2$ emissions in Ecuador, LMDI approach for this case study has been selected. Another reason for this choice is because the kind and level of desegregation of the data available for the country.

4.5 LMDI analysis for Ecuador 1980-2025

As was already explained, Ang (2004) [52] compared various index decomposition analysis methods and concluded that the multiplicative and additive logarithmic mean Divisia index (LMDI) method is the preferred method due to their theoretical foundation, adaptability, ease of use and result interpretation, and some other desirable properties in the context of decomposition analysis..

In this section we will carry out a decomposition analysis based on the LMDI (Ang, 2005) [216]. This analysis will allow us to determine the relative importance of each term conforming the CO$_2$ emission (see Equation 3.1). Indeed, it is very enlightening to write down the increase on CO$_2$ emission relative to the value of a given period, and to decompose it as the sum or product of the terms corresponding to the different driving forces that conform the CO$_2$ emission. Therefore we can use (Ang, 2005) [216]:

In the case of the additive decomposition:

$$\Delta C_{tot} = C^T - C^0 = \Delta C_{act} + \Delta C_{str} + \Delta C_{int} + \Delta C_{mix} + \Delta C_{emf}, \qquad (4.39)$$

where C_{tot} is the CO$_2$ emission (relative to the base year), C^0 and C^T represent the emission in the base and final year respectively, C_{act} is the GDP term, C_{str} is the structure term (the share of the different sectors to the GDP), C_{int} the energy intensity term, C_{mix} the energy mixing term, and C_{emf} the emission factor term. Note that because the emission factors, given by the IPCC, do not change over the time, $C_{emf} = 0$ all the time and therefore it will not be shown in the tables. The other option is, In the case of the multiplicative decomposition:

$$D_{tot} = C^T/C^0 = D_{act} \times D_{str} \times D_{int} \times D_{mix} \times D_{emf}, \tag{4.40}$$

where D_{tot} is the CO_2 emission (relative to the base year), D_{act} is the GDP term, D_{str} is the structure term (the share of the different sectors to the GDP), D_{int} the energy intensity term, D_{mix} the energy mixing term, and D_{emf} the emission factor term. As said before $D_{emf} = 1$ all the time and therefore it will not be shown in the tables.

Applying as indicated in Section 4.3.3 of this Chapter for the case of CO_2 emissions (see Equation 4.39 and 4.40) the following formulas are obtained for decomposing changes in each of the terms involved in Equation 3.1, for both additive and multiplicative forms:

LMDI formula additive decomposition are,

$$\Delta C_{act} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{Q^T}{Q^0}\right), \tag{4.41}$$

$$\Delta C_{str} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{S_i^T}{S_i^0}\right), \tag{4.42}$$

$$\Delta C_{int} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{EI_i^T}{EI_i^0}\right), \tag{4.43}$$

$$\Delta C_{mix} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{M_{ij}^T}{M_{ij}^0}\right), \tag{4.44}$$

$$\Delta C_{emf} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{U_{ij}^T}{U_{ij}^0}\right). \tag{4.45}$$

LMDI formula multiplicative decomposition are,

$$D_{act} = exp\left(\sum_{ij} \frac{(C_{ij}^T - C_{ij}^0)/(\ln C_{ij}^T - \ln C_{ij}^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln\left(\frac{Q^T}{Q^0}\right)\right), \tag{4.46}$$

$$D_{str} = exp\left(\sum_{ij} \frac{(C_{ij}^T - C_{ij}^0)/(\ln C_{ij}^T - \ln C_{ij}^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln\left(\frac{S_i^T}{S_i^0}\right)\right), \tag{4.47}$$

$$D_{int} = exp\left(\sum_{ij} \frac{(C_{ij}^T - C_{ij}^0)/(\ln C_{ij}^T - \ln C_{ij}^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln\left(\frac{EI_i^T}{EI_i^0}\right)\right), \tag{4.48}$$

$$D_{mix} = exp\left(\sum_{ij} \frac{(C_{ij}^T - C_{ij}^0)/(\ln C_{ij}^T - \ln C_{ij}^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln\left(\frac{M_{ij}^T}{M_{ij}^0}\right)\right), \tag{4.49}$$

$$D_{emf} = exp\left(\sum_{ij} \frac{(C_{ij}^T - C_{ij}^0)/(\ln C_{ij}^T - \ln C_{ij}^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln\left(\frac{U_{ij}^T}{U_{ij}^0}\right)\right), \tag{4.50}$$

Table 4.1: Aggregate data for Ecuador for the period 1980-2025.

Year	CO$_2$ emissions (Mt)	Income (BUSD)	Energy consumption (ktoe)
Data $_{1980}$	11.9	45.4	5032
Data $_{1995}$	19.6	63.4	7143
Data $_{2010}$	28.1	104	11930
BS $_{2025}$	55.0	167	20520
SC-2 $_{2025}$	96.6	271	36040
SC-3 $_{2025}$	66.5	244	32430
SC-4 $_{2025}$	54.7	251	26700

Table 4.2: Results of the CO$_2$ emission additive decomposition factors for the period 1980-2025.

Scenario	Δ C$_{tot}$ (kt)	Δ C$_{act}$	Δ C$_{str}$	Δ D$_{int}$	Δ C$_{mix}$
Data $_{1980\text{-}1995}$	5470	4780	194	196	292
Data $_{1995\text{-}2010}$	14800	12300	-637	1160	1990
BS $_{2010\text{-}2025}$	22600	20100	-82	2500	96
SC-2 $_{2010\text{-}2025}$	62100	55600	3020	3300	192
SC-3 $_{2010\text{-}2025}$	32500	39900	2400	2640	-12400
SC-4 $_{2010\text{-}2025}$	23200	37100	2200	-5040	-11100

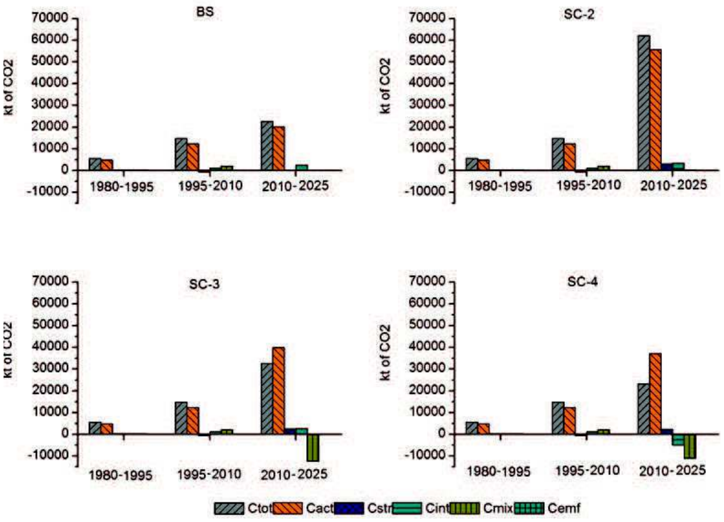

Figure 4.1: Bar view of the CO_2 emission additive decomposition factors for the period 1980-2025 in Ecuador.

We will use three periods of 16 years to perform the analysis, two within the set of historical data (1980-1995 and 1995-2010) and the last one corresponding to the forecast period (2010-2025). This analysis will allow us to determine the relative importance of each term related with CO_2 emission. The aggregate CO_2 emissions in million tonnes of CO_2 (Mt), income in billion of USD (BUSD) and energy consumption (ktoe) are shown in Table 4.1.

The findings (see Figures 4.1 and 4.2) show that in the period 1980-1995 there was an increase in emissions by 35% (see Table 4.3) or equivalently of more than 5400 kt (see Table 4.2). The LMDI analysis show that the activity effect led to an increases just 3 percent points (38%) that the margin in emission increase. The effect of structural change ($D_{str} = 1.01$) in productive sectors and change in energy mix ($D_{mix} = 1.02$) does not have significant impact over the emission in this period. Actual growth in emissions was lower because of the reduction of the

Table 4.3: Results of the CO$_2$ emission multiplicative decomposition factors for the period 1980-2025.

Scenario	D$_{tot}$	D$_{act}$	D$_{str}$	D$_{int}$	D$_{mix}$
Data *1980-1995*	1.35	1.38	1.01	0.95	1.02
Data *1995-2010*	1.85	1.68	0.98	1.04	1.09
BS *2010-2025*	1.72	1.61	1.00	1.07	1.00
SC-2 *2010-2025*	3.03	2.59	1.09	1.07	1.00
SC-3 *2010-2025*	2.08	2.33	1.09	1.07	0.77
SC-4 *2010-2025*	1.71	2.41	1.09	0.85	0.77

sectoral energy intensity ($D_{int} = 0.95$), see a pictorial view in Figure 4.3. Note that the ratio D_{tot}/D_{act} is almost 1 and is a proxy of that country emissions in this period grow in the same factor that the income (see Figures 4.1).

The period 1995-2010 reflected a greater increase in emissions (85%) or equivalently of more than 14800 kt (see Tables 4.2 and 4.3). The LMDI analysis show that the activity effect led to an increase of 0.80 times (68%) that the margin in emissions increase. In addition, changes in energy intensity ($D_{int} = 1.04$) and in energy mix ($D_{int} = 1.09$) led to an additional increase in emissions. The impact of structural change ($D_{str} = 0.98$) in productive sectors has a reduction effect in emission. Note that the ratio D_{tot}/D_{act} equal to 1.10 is a proxy of that the higher economic growth in this period (regarding to the previous one) accelerated the emission growth of the country (see Figures 4.3).

Regarding the forecast period, the findings shows that in 2025 the CO$_2$ emissions increase by 72% or equivalently of more than 22000 kt in the *BS* scenario. The LMDI analysis show that the activity effect led to an increase of 0.85 times (61%) that the margin in emissions increase. The effect of structural change ($D_{str} = 1.00$) in productive sectors and change in energy mix ($D_{mix} = 1.00$) does not have impact on the emission in this period. Actual growth in emissions was higher because of increase in sectoral energy intensity ($D_{int} = 1.07$), as an pictorial view of Figure 4.3. Note that the ratio D_{tot}/D_{act} is almost the same that for the previously period (1.07) (see Figure 4.4) and is a proxy of that the grow in emissions depends mainly

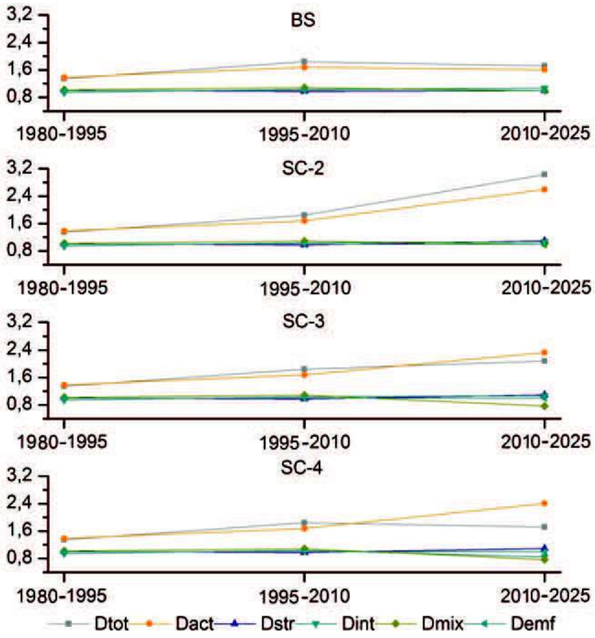

Figure 4.2: View of the CO_2 emission multiplicative decomposition factors for the period 1980-2025 in Ecuador.

on the scale term (D_{act}) in *BS* scenario.

The *SC-2* scenario presents an amount of emissions in 2025 that is more than 3 times that in 2010 (3.03 times) or equivalently of more than 62000 kt. The LMDI analysis show that the activity effect led to an increase of 0.57 times (2.49 times) that the margin in emissions increase. The effect of energy mix ($D_{mix} = 1.00$) does not have impact on the emission during this period. As in *BS* scenario, actual growth in emissions was higher because the increase in sectoral energy intensity ($D_{int} = 1.07$) and by the impact of the structural change ($D_{str} = 1.09$), as an in the pictorial view of Figure 4.3. Note that the ratio D_{tot}/D_{act} is 1.17 (higher than *BS* scenario) (see Figure 4.4) and is a proxy of that the higher economic growth

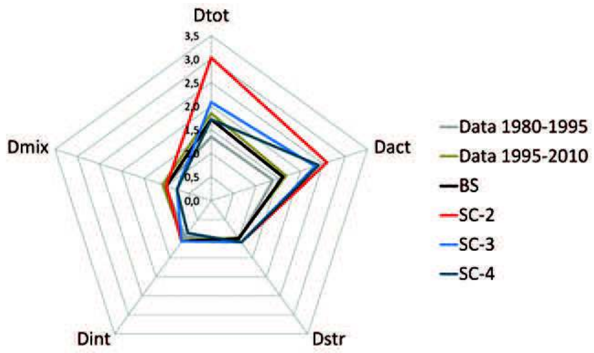

Figure 4.3: Pictorial view of the CO$_2$ emission multiplicative decomposition factors for the period 1980-2025 in Ecuador.

achieved in this scenario is because an increase in the economic scale and in the energy intensity, arising from the shift in the composition of industry output towards energy-intensive sectors of the country as has been considered in this scenario (see Section 3.10.2 in Chapter 3).

The *SC-3* scenario presents an amount of emissions in 2025 that is more than 2 times in 2010 (2.08 times) or equivalently of more than 32000 kt. The LMDI analysis show that the activity effect led to an increase of 1.23 times ($D_{tot} = 2.33$) that the margin in emissions increase. In addition, impact of structural change ($D_{str} = 1.09$) in productive sectors changes and in energy intensity ($D_{int} = 1.07$) led to a increase in emissions. The impact of energy mix ($D_{str} = 0.77$) used in productive sectors has a reduction effect in emissions as has been considered in this scenario (see Section 3.10.2 in Chapter 3), see a pictorial view in Figure 4.3. Note that the ratio D_{tot}/D_{act} is lower than 1 (0.89) (see Figure 4.4) and is a proxy of that for first time in the country (in the analyzed period), the economic growth is higher than emission growth. The reason is that in addition of the growth in the economic scale, the impact of energy mix change leads to a reduction of this ratio.

Finally, in the *SC-4* scenario the emissions just increase by a factor of 1.71 or equivalently more than 23000 kt. The LMDI analysis shows that the activity

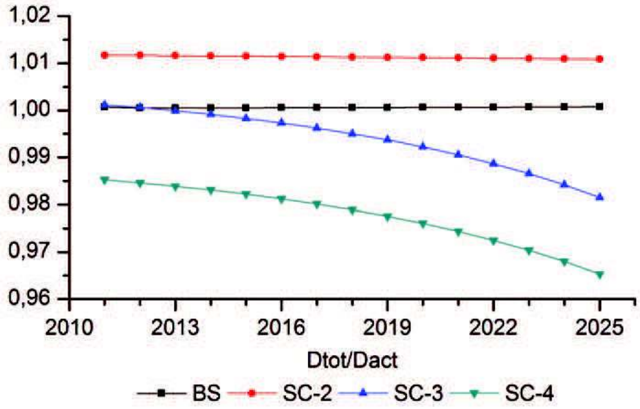

Figure 4.4: D_{tot}/D_{act} for the period 2011-2025 in Ecuador.

effect led to an increase almost 2 times ($D_{tot} = 2.33$) that the margin in emission increase. As in previous scenarios, the impact of structural change ($D_{str} = 1.09$) in productive sectors changes led to an increases in emissions. However, actual growth in emissions was lower than in rest of scenarios because the impact of energy mix ($D_{str} = 0.77$) and the reduction in sectoral energy intensity ($D_{int} = 0.85$) has a reduction effect in emission as has been considered in this scenario (see Section 3.10.2 in Chapter 3), see a pictorial view in Figure 4.3. Note that in this scenario the ratio D_{tot}/D_{act} is the lowest (0.71) (see Figure 4.4) and as in the *SC-3* scenario, in addition to the growth in the economic scale, the impact energy mix are present and adding the impact of the reduction of energy intensity considered in this scenario (see Section 3.10.2 in Chapter 3) is reducing even more this ratio.

All the coefficients are summarized in Table 4.2 and 4.3 and in a pictorial way in Figure 4.3. In this figure five axes are depicted corresponding to the five columns appearing in table 4.3. The value of the vertical axis, D$_{tot}$, corresponds to the product of the five remaining variables, D$_{act}$, D$_{str}$, D$_{int}$, D$_{mix}$ and D$_{emf}$.

4.6 Summary and conclusions of the chapter

This Chapter presents a decomposition analysis of CO_2 related to income growth and energy consumption bases on LMDI (see Section 4.5 in this Chapter) for Ecuador in the period 1980-2025. For this purpose three periods have been selected, the first sub-period is 1980-1995 where the LMDI analysis findings suggest that the country emissions in this period almost grow (38%) in the same factor that the income (35%), see Figures 4.1. The second sub-period is 1995-2010 and the evidence suggest that a higher economic growth (68%) led to even greater emissions growth (85%) in the country.

The third sub-period is 2010-2025 and includes the analysis for the different scenarios proposed in Chapter 3. To see more clearly how the income-CO_2 relationship behaves as a function of time, it is very enlightening to depict the ratio D_{tot}/D_{act} as a function of the time (see Figure 4.4). The first striking thing is the very different behaviour for each scenario. On one hand, it is somehow surprising the almost flat curve corresponding to the *BS* scenario which implies a *trend-growth* GDP scenario, however the CO_2 emission increases steadily because of the absence of attenuation measurements. A similar behaviour, although slightly sloping down, is observed for *SC-2*, where a rapid growth of the GDP is assumed without any attenuation action regarding CO_2 emission. It is worth noting a certain decrease of the ratio D_{tot}/D_{act} in the final part of the period under study. The other two scenarios, *SC-3* and *SC-4*, show a steady reduction of the ratio D_{tot}/D_{act} due to the changes in the sectoral structure and in the energy mix, which allows compensation of rapid GDP growth.

This preliminary analysis suggests that, with the appropriate changes in the energy mix, the sectoral structure, and the share of renewable energies, Ecuador can move into a more environmentally sustainable situation. All these results encourages us to perform a more rigorous analysis in regard to income and emission relationship. The EKC analysis to study in which stage of the process Ecuador is currently in, and will be in the coming future is carried out in Chapter 5.

You must be the change you wish to
see in the world.
Mahatma Gandhi

CHAPTER
5

System dynamics modelling and the environmental Kuznets curve in Ecuador (1980-2025)

5.1 Overview

Kuznets (1955) stated that the changing relationship between per capita income and income inequality is an *inverted-U-shaped* curve. As per capita income increases, income inequality also increases at first and then starts declining after a *turning point* (TP). In other words, the distribution of income becomes more unequal in early stage of income growth and then the distribution moves towards greater equality as economic growth continues (Kuznets, 1955) [88]. This observed empirical phenomenon is popularly known as the Kuznets curve. In the 1990s and onwards, the Kuznets curve took a new existence. There were evidences that the level of environmental degradation and the per capita income follows the same inverted-U-shaped relationship as does income inequality and per capita income in the original

Kuznets curve. Now, Kuznets curve has become a tool for describing the relationship between measured levels of environmental quality (for example, emissions of CO_2) and per capita income. This inverted-*U*-shaped relationship between economic growth and measured pollution indicators (environmental quality) is known as the Environmental Kuznets curve (EKC).

First empirical EKC studies appeared independently in three working papers: an NBER[1] working paper as part of a study of the environmental impacts of NAFTA[2] (Grossman and Krueger, 1991) [131], the World Bank's 1992 World Development Report (Shafik and Bandyopadhyay, 1992) [92] and a Development Discussion paper as part of a study for the International Labour Organisation (Panayotou, 1993) [223]. Grossman and Krueger which was later published in 1993 (Grossman and Krueger, 1993) [131], first pointed out an inverted-*U* relationship between pollutants (SO_2 and smoke) and income per capita. The name of Kuznets was attached to the inverted-U relationship between pollution and economic development later due to its resemblance with the inverted-*U* relationship between income inequality and economic development proposed by Kuznets. However, Panayotou (1993) [223] first coined it as the Environmental Kuznets curve or EKC. At this point we will follow the review that Dinda (2004) [93] conducted about the EKC hypothesis.

5.2 Explanations for the EKC

EKC hypothesis actually summarizes an essentially dynamic process of change. As income of an economy grows over time, emission level grows first, reaches a peak and then starts declining after a threshold level of income has been crossed. However, the statement of the hypothesis makes no explicit reference to time. Dinda (2004) [93] states that EKC can be considerate as a long run phenomenon. In other words, it is a development trajectory for a single economy that grows through different stages over time. Empirically, this development trajectory can be observed in *cross-country* or *cross-sectional* data, which represents countries with different

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[1] The National Bureau of Economic Research is an American private nonprofit research organization committed to undertaking and disseminating unbiased economic research among public policymakers, business professionals, and the academic community.

[2] North American Free Trade Agreement.

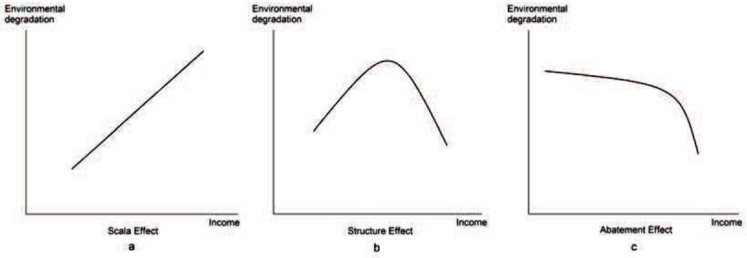

Figure 5.1: Different effects of income on environmental degradation as presented in Islam et al. (1999) [7]

level of income (low, middle and high) groups corresponding to their emission levels. The author also said that assuming that all countries follow one EKC, then at any cross-section of time, it should be observed that some countries are poor, shaping the initial stage of EKC, some others are developing countries approaching towards the peak or starting to decline and others are rich, lying on the final stage of the EKC. Evidently, thus, under the null hypothesis of EKC and under the assumption of invariance of the *income–emission* relationship, for a given set of cross-country or cross-sectional data on income and emission, the emission on income regression line should be an *inverted-U-shaped* empirical EKC [93].

Therefore, according to the EKC hypothesis the relationship between income per capita and some types of pollution is approximately an inverted-U. This behaviour states that as the per capita income growths, environmental damage increases, reaches a maximum, and then declines. The reason for this behaviour is that when income reaches a certain threshold the economy moves into a different regime, where the rate of emissions with respect to income can be reduced with respect to the initial regime.

There is thus a unidirectional causality running from income to environmental degradation. The theoretical explanations of the EKC hypothesis are based on three effects: the scale effect, the structure effect and the abatement effect (Grossman and Krueger,1991; Islam etal.,1999) [7, 131] (see Figure 5.1).

5.2.1 Environmental quality demand and income elasticity

As income grows, society achieve a higher standard of living and care more for the quality of environment they live in and demand for better environment induces structural changes in economy that tends to reduce environmental degradation. The most common explanation for the shape of an EKC (see Figure 5.2) is the notion that when a country achieves a sufficiently high standard of living, people attach increasing value to environmental amenities (Pezzey, 1989 [224]; Selden and Song, 1994 [225]; Baldwin, 1995 [226]). When a particular level of income is reached, the willingness to pay for a clean environment rises by a greater proportion than income (Roca, 2003) [227]. This will be reflected through changes in habits and in choice of less environmentally damaging products by people. Thus, people with a high standard of living can value and pay (at the same time) for a cleaner environment and to preserve it. Generally, it is recognized that income elasticity of environmental quality demand and resource goods is in excess of unity, *i.e.*, clean environment and preservation are *luxury goods* [93]. But major indicators of environmental degradation are monotonically rising in income though the income elasticity is less than one and is not a simple function of income alone [93]. However, Dinda (2004) survey [93] states that most of the EKC models have emphasized the role of income elasticity of environmental quality demand (Beckerman, 1992 [91]; Carson et al., 1997 [228]; Chaudhuri and Pfaff, 1998 [229]; McConnell, 1997 [230]) and this elasticity is often invoked in the literature as the main reason to explain the reduction of emission level. An adequate explanation of observed EKC relationships for some pollutants, are consistent with the high-income elasticity of environmental quality demand (McConnell, 1997 [230]; Shafik, 1994 [231]). Poor countries have little demand for environmental quality, however, as a society reaches high levels of living , its members may intensify their demands for a more healthy and cleaner environment. Societies with higher incomes are not only willing to spend more for green products but also create pressure for environmental protection and regulations. In most cases where emissions have declined with rising income, the reductions have been due to local and national institutional reforms, such as environmental legislation and *market-based* incentives to reduce environmental degradation.

5.2.2 Scale, technological and composition effects

There are three different channels where economic growth affects the quality of environment: scale effects, technological effects and composition effects (Grossman and Krueger, 1991) [131]. Increasing output requires more input and thus more natural resources are used in production process. More output also implies more wastes and emissions by product, which also contributes to degrade environmental quality. Therefore, economic growth exhibits a scale effect that has a negative impact on environment. However, economic growth also has a positive impact on environment through the composition effect: income grows, the structure of the economy tends to change and gradually cleaner activities increase with reduces pollution [93].

Environmental degradation tends to increase as structure of the economy changes from rural to urban, or from agricultural to industrial, but it starts to fall with another structural change from energy intensive industry to services and knowledge based technology intensive industry. As a wealthy nation can afford to spend more on research and technical development (Komen et al., 1997) [135], technological progress occurs with economic growth and the dirty and obsolete technologies are replaced by upgraded new and cleaner technology, which improves environmental quality. This is the so called technique effect of economic growth. Vukina et al., (1999) [132] state that EKC suggests that the negative impact on environment of the scale effect, that tends to prevail in initial stages of growth, will be eventually outweighed by the positive impact of the composition and technique effects that will tend to lower the emission level.

5.2.3 International trade

International trade is one of the most important factors that envelope the EKC [93]. Trade leads to increase the size of the economy increasing pollution, thus, trade can be considerate as a cause of environmental degradation. However, many authors have long argued that trade is not the root cause of environmental damage (Birdsall and Wheeler, 1993 [232]; Lee and Roland-Holst, 1997 [233]; Jones and Rodolfo, 1995 [234]). Free trade has the contradictory impacts on environment, on one hand, increasing pollution and, on the other hand, motivating reductions in it. Environmental quality could decline through the scale effect as increase the trade volume (especially export) up to the size of the economy, which increases pollution. On the other hand, trade can improve the environment through the composition effect and/or the technique effect (*i.e.*, as income rises through trade, environmental regulation is tightened whith spurs pollution reducing innovation) [93].

Pollution from the production of pollution-intensive goods declines in a given country as it increases in an other via international trade. This composition effect is attributed to two related hypotheses: $i)$ Displacement Hypothesis and $ii)$ Pollution Haven Hypothesis. These hypotheses are basically the same with respect to comparative advantage in international trade. ***Displacement Hypothesis*** expects that trade liberalization or openness will lead more rapid growth of pollution- intensive industries in less developed economies as developed economies enforce strict environmental regulations (Harrison, 1996 [235]; Rock, 1996 [236]; Tobey, 1990 [237])[1]. ***Pollution Haven Hypothesis*** refers to the possibility that multinational industries, particularly those engaged in highly polluting activities, relocate to countries with lower environmental standards. Also this hypothesis argues that low environmental standards become a source of comparative advantage, and thus shifts in trade patterns. This theory suggests that high regulation countries will lose all the *dirty industries* and low regulation countries will get them all.

Most of the developing countries rely on technology transfer through foreign direct investment from developed countries as a primary means of technology acquisition. In the case of Pollution Haven Hypothesis, these clean and upgraded technologies could reduce pollution level. Also the diffusion of technology prevents economic latecomers from requiring the same levels of materials and energy inputs per unit of income than older industrialized countries needed in past. Some authors suggest that international trade enhances diffusion of clean technology (Martin and Wheeler, 1992 [238]; Reppelin-Hill, 1999 [239]) and another authors have suggested that this might allow developing countries to *dive through* the EKC.

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[1] Note that, the changes in the structure of production in developed economies are not accompanied by equivalent changes in the structure of consumption, therefore, EKC actually records displacement of dirty industries to less developed economies (Copeland and Taylor, 1995) [123].

Other scenario could be the so called *race to bottom*: relatively high environmental standards in developed economies impose high costs on polluters. Therefore, polluting activities in high-income economies face higher regulatory costs than their counterparts in developing countries (Wheeler, 2000 [240] and Jaffe et al., 1995 [241]; Mani, 1998 [242]). Wheeler (2000) [240] states that globalization could trigger the environmental *race to bottom*, in which competition increases for investment and jobs. Indeed, the bottom rises with economic growth. Less developed economies improve their environmental quality as investment increases income and employment. This has led some authors to argue that globalization is compatible with pollution reduction (Robinson, 1988 [243]; Dessus and Bussolo, 1998 [244]; Grether and Melo, 2002 [245]).

5.3 Theoretical analysis of EKC

A basic comparative static analysis of the costs and benefits associated with a better environmental quality provides an interesting conceptual insight as to how the EKC may arise. The EKC is derived from the interaction points of marginal cost (MC) and marginal benefit (MB) curves (Munasinghe, 1999) [140]. An EKC can be derived directly from the technological link between consumption of a desired good and abatement of its undesirable by product (Andreoni and Levinson, 2001) [246]. It is also consistent with either Pareto[1] efficient policy or a decentralized market economy. If pollution is not priced, companies will use it until its marginal product is zero, when pollution is considered as a factor of production, but not the stock of environmental capital. Extending this model, stock of environmental quality is included as a factor of production (Lopez, 1994) [247], then the predictions of this model depend crucially on the existence of property rights. The EKC emerges from a dynamic process, as a part of capital goes for development of the environmental sectors. Total capital is divided into two parts, one is used in production process that creates pollution and damage the existing environment and the other is used to clean up environment or improve it (Dinda, 2002) [114].

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[1] Pareto efficiency, or Pareto optimality, is a state of allocation of resources in which it is impossible to make any one individual better off without making at least one individual worse off.

The role of abatement expenditure is crucial to reduce the pollution in production side (Selden and Song, 1994 [225]; Dessus and Bussolo, 1998 [244]; Jaeger, 1998 [248]). But the abatement expenditure may not be a determining factor behind the EKC for long-lived pollutants like hazardous waste sites that are neither easily abated nor shifted elsewhere. A theoretical model of the EKC based on perfect mobility of household and labour is developed, and a general equilibrium model that emphasizes spatial separation on the consumer side as the reason behind the EKC for hazardous waste sites (Gawande et al., 2001) [249]. Under various conditions, the EKC relationship between pollution and income can be obtained theoretically (John and Pecchenino, 1994 [250]; Jones and Rodolfo, 1995 [234]; Selden and Song, 1995 [103]; Beltratti, 1997 [251]; Stokey, 1998 [252]; Kadekodi and Agarwal, 1999 [253]; Bulte and van Soest, 2001 [254]; Dinda, 2002 [114]). Note that the EKC relationship may also take shape from the interaction between ecological and economic factors (Ezzati et al., 2001) [110].

The empirical evidence for the existence of an EKC has been found in various studies. These studies share some common characteristics with respect to the data and methods employed. Most of the data used in these studies are cross-sectional panel data [93]. The following reduced form model is used to test the various possible relationships between pollution level/environmental pressure and income:

$$y_i = \alpha_i + \beta_1 x_{it} + \beta_2 x_{it}^2 + \beta_3 x_{it}^3 + \beta_4 z_{it} + \epsilon_{it}, \tag{5.1}$$

where y is an environmental indicator, x is income and z relates to other variables of influence on environmental degradation. The subscript i stands for the country, t for time, α_i is a constant, β_k are the coefficient of the k explanatory variables. Equation 5.1 allows us to test several forms of environment–economic development/growth relationships:

- (i) $\beta_1 = \beta_2 = \beta_3 = 0$.
  A flat pattern or no relationship between x and y.
- (ii) $\beta_1 > 0$ and $\beta_2 = \beta_3 = 0$.
  A monotonic increasing relationship or a linear relationship between x and y.

- (iii) $\beta_1 < 0$ and $\beta_2 = \beta_3 = 0$.
  A monotonic decreasing relationship between x and y.
- (iv) $\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 = 0$.
  An inverted-U-shaped relationship, i.e., EKC.
- (v) $\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 = 0$.
  A U-shaped relationship.
- (vi) $\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 > 0$.
  A cubic polynomial or N-shaped figure.
- (vii) $\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 < 0$.
  Opposite to the N-shaped curve.

5.4 Empirical findings of EKC in Ecuador

The inverted *U*-shaped relationship between CO_2 emissions and GDP is an empirical observation. In this respect there are many studies where quadratic and cubic models are used to fit the emissions to income (Canas, 2003 [255]; Shen, 2004 [256]; Cole, 2005 [257]; Galeotti, 2006 [258]; Esteve, 2012a [259]). However, in many cases the evidences of the EKC hypothesis is weak. Another way to test the validity of the EKC assumption is to compare the long and the short run impact of income on emissions (Nara, 2010 [260], Jaunky, 2011 [145]). Whatever approach is used or set of countries studied, analysis always uses past data and there are no studies where the EKC hypothesis has been tested in a forthcoming period. To do this, a detailed model of the connection between GDP and CO_2 emissions is needed, as well as a set of plausible scenarios that could describe a possible evolution (income, energy matrix, and sectoral structure) of a given country.

As the theory predicts a long-run relationship linking emissions and economic growth, there is a wide stream of recent research that has assessed this relationship employing co-integration techniques. The empirical evidence suggests that pollution levels and GDP may be jointly determined, so that any constraint put on energy consumption, to help in reducing emissions, will have effects on economic growth. In the initial stage, as in the developing countries, CO_2 emissions

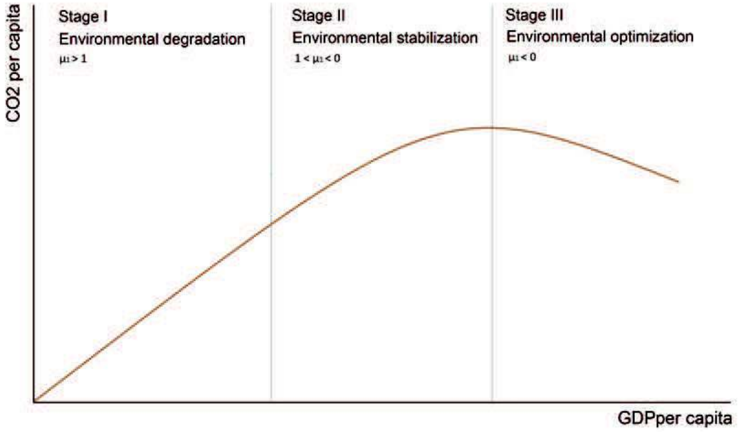

Figure 5.2: Schematic plot of the relationship between the per capita income and the CO_2 emission: 1) linear growth of the pollution with the GDP, 2) stabilization, and 3) reduction of the emissions with the increase of the income. Figure adapted from Iglesias et al. (2013) [8].

scale with the *size* of the economy because the industries are relatively rudimentary, unproductive, and polluting. In the second stage, the impact of the economy in environmental degradation is reduced through the *structure and composition effect*, because the economy growth induces structural changes. In particular, that happens as an agricultural based economy shifts into a manufacturing services based economy. Finally, the third stage appears when nations invest intensively in research and development and the dirty and obsolete technologies are replaced by clean ones. At this point the pollution starts to decrease as a function of the income. The different phases of the EKC are depicted schematically in Figure 5.2.

Some authors, (Soytas, 2001 [261]; Soytas, 2003 [262]; Lee, 2005 [263]; Lise, 2006 [264]; Chontanawat, 2008 [265]; Halicioglu, 2009 [266]; Ozturk, 2010 [267]; Esteve, 2012a [259]; Esteve, 2012b [268]; Fosten, 2012 [269]) among others, use cointegration procedures to examine the CO_2 and GDP nexus, however these studies analyze past evidence. Our proposal goes a step further and intends to see under what conditions a country could approach the fulfilment of the EKC hypothesis in the medium term.

To this end, we will use the model proposed in Chapter 3 and the findings of Chapter 4 ((see Section 4.6 in Chapter 4) as starting point (see Section 3.10.1 in Chapter 3).

The following sections are an effort to fill the gap in the literature of studies on the relationship between emissions and GDP in Latin American countries in general, and in Ecuador in particular. In addition, studies of a single country help policy makers improve comprehensive policies to control environmental degradation. Moreover, it represents a step forward in the study of the EKC hypothesis following Jaunky's specification [145], due to the inclusion of a forthcoming (2011-2025) and not a past period of time.

In Jaunky (2011) the author tries to test the EKC hypothesis in a set of high-income countries for the period 1980-2005. The lower long-run income elasticity does not provide evidence for the EKC, but it indicates that CO_2 emissions are stabilizing in developed countries. Therefore, the extension of this work to other countries and to a forthcoming period is of interest.

5.4.1 **EKC hypothesis verification**

The EKC hypothesis supposes that from a given moment onward the relationship between CO_2 emission and income is no longer proportional and that, even the first can be reduced as GDP increases. To get the first insight about the relationship between GDP and CO_2 we plot the per capita GDP and CO_2 emission as a function of the year in Figure 5.3, using the data set of the period 1980-2010 and the model calculation for the four considered scenarios (2011-2025). To calculate the value of the population, needed for any per capita quantity, we use the geometric-growth rate (Equation (3.14)) to extrapolate its value into the forecast period. Regarding GDP, one can observe two clearly distinct behaviours in the forecast period, on one hand the *BS* scenario, with a moderate increase of the GDP per capita, and on the other hand, the rest of scenarios that present a large increase of the GDP. For CO_2 emissions *BS* and *SC-4* scenarios show the same value, while *SC-3* shows a slightly

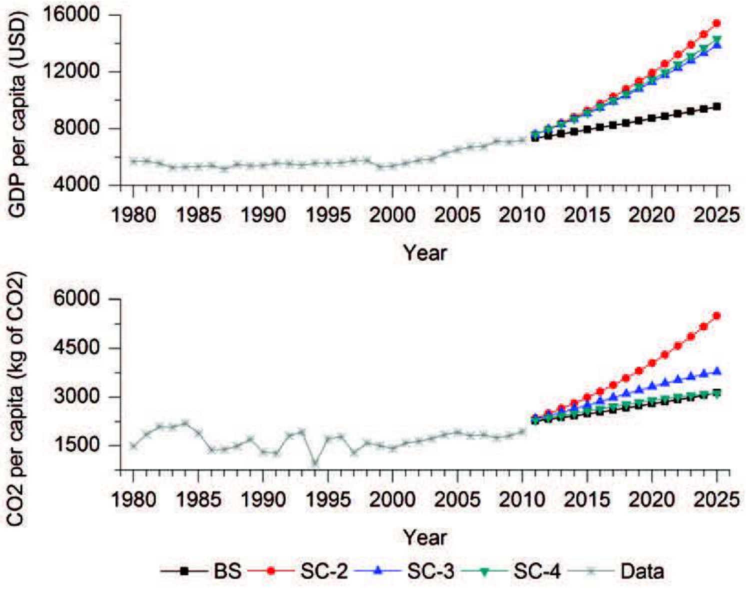

Figure 5.3: Top: Estimation of GDP per capita for the period 2011-2025 in Ecuador. Bottom: Estimation of CO_2 emission per capita for the period 2011-2025 in Ecuador.

higher one, and *SC-2* scenario presents, by far, the largest increase of CO_2 emissions. In Figure 5.4 we combine both pieces of information into a single picture, where we plot CO_2 emission per capita as a function of GDP per capita. According to this figure it seems that the different scenarios generate different regimes and the environmental impact is attenuated in some cases, specially for *SC-3* and *SC-4* scenarios.

We follow the Jaunky's specification [145] for testing the EKC hypothesis in Ecuador. A reduced form equation for the relationship between the per capita income and the CO2 emission is assumed:

$$LCO2_t = \mu_0 + \mu_1 LGDP_t + \epsilon_t, \tag{5.2}$$

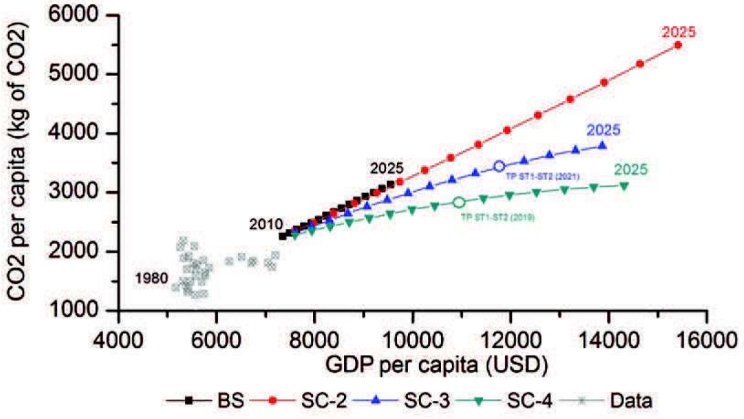

Figure 5.4: GDP per capita *versus* CO_2 emission per capita for the period 2011-2025 in Ecuador. Marks TP-ST1-ST2 stand for the year of the turning points (the scenario passes from stage 1 to state 2) of the EKC (see Figure 5.5).

where $LCO2$ is the natural logarithm of the CO_2, $LGDP$ is the natural logarithm of the GDP, ϵ is the error term, μ_0 is the term constant, and μ_1 estimates the CO_2-GDP elasticity.

In the first region of the simplified Kuznets curve (Figure 5.2), as the elasticity $\mu_1 > 1$ there is a high responsiveness of GDP to changes in CO_2 emissions. Therefore, a change in GDP generates a more than proportional increase in CO_2 emission. This phase involves little environmental responsibility and also implies that the country is in the early stage of environmental sustainability (*environmental degradation*). If $0 < \mu_1 < 1$, then an income increase leads to a less than proportional increase in CO_2 emissions and, as a consequence, it implies that the country enters into the second stage of the EKC with *environmental stabilization*[1] . Finally, for $\mu_1 < 0$ a negative relationship occurs between GDP and CO_2 emission. This is the final stage of the EKC and mean that the country enters into a phase with

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[1] Note that, we define turning point of change from the first to the second stage (TP-ST1-ST2(t) as the time t where $\mu_1 > 1$ pass to $0 < \mu_1 < 1$).

intensive use of green technology and *environmental optimization*.

5.4.2 **EKC verification**

We start the analysis by testing the order of integration of both variables $LGDP_t$ and $LCO2_t$ using the tests of Ng and Perron (2001) [270]. These authors proposed using test statistics which are a efficient modified versions of Phillip-Perron (PP) and Augmented Dickey-Fuller (ADF) tests. Such modifications that improve the tests do not exhibit the severe size distortions of the PP tests for errors with large negative MA (moving average) or AR (auto-regression) roots, and they can have substantially higher power than the PP tests.

Using the GLS detrended data y_T^d, the efficient modified PP tests are defined as:

$$\bar{M}Z_{\alpha}^{GLS} = \left(T^{-1}y_T^d - \lambda^2\right)\left(2T^{-2}\sum_{t=1}^{T} y_{t-1}^d\right)^{-1}, \tag{5.3}$$

$$\bar{M}SB^{GLS} = \left(T^{-2}\sum_{t=1}^{T}\frac{y_{t-1}^d}{\lambda^2}\right)^{1/2}, \tag{5.4}$$

$$\bar{M}Z_t^{GLS} = \bar{M}Z_{\alpha}^{GLS} \times \bar{M}SB^{GLS}, \tag{5.5}$$

$$\bar{M}SB^{GLS} = \left[T^{-2}\left(y_{t-1}\frac{2}{s^2}\right)\right]^{1/2}, \tag{5.6}$$

where $[y_t]_1^T$ represents the realization of the time series, T denotes the sample size, λ^2 is a consistent estimate of the long-run variance parameter λ^2 and s^2 are the variances.

The statistics $\bar{M}Z_{\alpha}^{GLS}$ and $\bar{M}Z_t^{GLS}$ are efficient versions of the PP and Z_α and Z_t tests that have much smaller size distortions in the presence of negative moving average errors. Note that those tests should be performed for the whole dataset.

The results are shown in Table 5.1, and according to them, the null hypothesis of no stationarity cannot be rejected, independently of the statistic used, for both series, $LGDP_t$ and $LCO2_t$. Accordingly, both series would be concluded to be I(1).

Table 5.1: Ng-Perron unit root test.

Variable	$\bar{M}Z_{\alpha}^{GLS}$	$\bar{M}Z_{t}^{GLS}$	$\bar{M}SB^{GLS}$	$\bar{M}P_{T}^{GLS}$
$LGDP_t$	-3.488	-1.268	0.364	25.197
$LCO2_t$	-4.827	-1.532	0.317	18.750

Once the order of integration of the series is analyzed, we will estimate the long-run regression model [145] using the Dynamic Ordinary Least Squares (DOLS)[1] estimation method of Stock and Watson (2010) [144], following the methodology proposed by Shin (1994)[2] [271]. This approach is similar to the KPSS[3] tests, which are implemented in two stages for the case of cointegration.

The first step in our estimation strategy would therefore consist of the estimation of the coefficients of a long-run dynamic equation [145] including leads and lags of the explanatory variables (GDP) in the long-run regression model, *i.e.,* the so-called DOLS regression:

$$LCO2_t = \mu_0 + \mu_1 LGDP_t + \sum_{j=-q}^{q} \mu_j \Delta LGDP_{t-j} + \epsilon_j. \tag{5.7}$$

The second step is to use the statistic C_{μ}[4] that is a LM-type[5] test designed by Shin (1994) [271], to test the null hypothesis of cointegration against the alternative

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[1] Least squares estimation of equation might suffer two problems: endogeneity bias in the explanatory variables and nuisance parameter dependencies due to serial correlation in the residuals.

[2] In order to overcome the problem of the low power of the classical cointegration tests in the presence of persistent roots in the residuals of the cointegration regression, Shin (1994) [271] suggests a new test where the null hypothesis is that of cointegration.

[3] These tests are called the Kwiatkowski et al. (1992) [272] tests, and assume the null hypothesis of stationarity.

[4] C_{μ} is the test statistic for deterministic cointegration, *i.e.*, when no trend is present in the regression.

[5] Lagrange multiplier (LM) test is a statistical test of a simple null hypothesis that a parameter of interest θ is equal to some particular value θ_0. It is the most powerful test when the true value of θ is close to θ_0. The main advantage of this test is that it does not require an estimate of the information under the alternative hypothesis or unconstrained maximum likelihood. This makes testing feasible when the unconstrained maximum likelihood estimate is a boundary point in the parameter space.

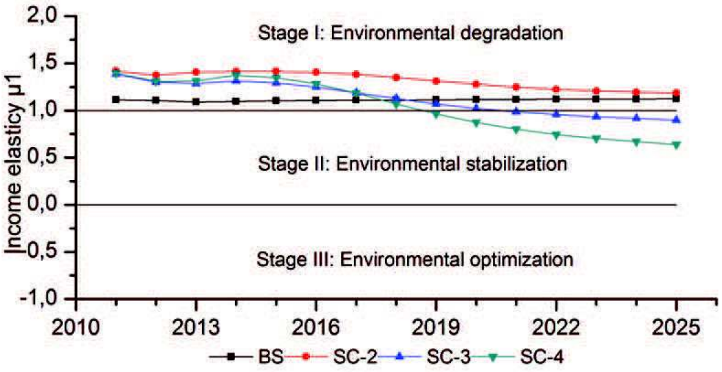

Figure 5.5: Evolution of CO_2-GDP elasticity for the period 2010-2025 in Ecuador.

of no cointegration in a DOLS regression.

$$C_\mu = T^{-2} \sum \frac{\tilde{S}^2_{\mu t}}{\tilde{s}^2_\mu(l)}, \tag{5.8}$$

where $\tilde{S}^2_{\mu t}$ and $\tilde{s}^2_\mu$ are semiparametric consistent estimators of the long-run variance.

In table 5.2 (Full sample column), we report the estimates from the DOLS regression and the results from Shin's test (Shing, 1994) [271]. Results show evidence of linear cointegration between CO_2 emissions and GDP, because we cannot reject the null hypothesis of cointegration, being the estimated value of the income elasticity of CO_2 emissions, $\mu_1 = 1.19$ which denotes little environmental responsibility, *i.e.*, Ecuador in 2010 is still in the first stage of the EKC.

Our final aim is to verify whether the EKC applies to Ecuador in the medium term (up to 2025), or to know the EKC stage that the country fulfills. To carry out this task, we perform the same process described above using the time series obtained in our model (see Chapter 3). The results are shown in table 5.2. The results show that in any scenario Ecuador fulfills the EKC hypothesis. However, in *SC-3* and *SC-4* scenarios the income elasticity of CO_2 emissions is below 1, which means, that in these cases, Ecuador has reached a new stage of environmental responsibility. In particular, stage 2 of the EKC is closer in the 2020s decade than

Table 5.2: Stock -Watson-Shin's DOLS ^{a,b,c,d} estimation of linear cointegration.

Parameter estimates	Full sample 1980-2010	BS 1980-2025	SC-2 1980-2025	SC-3 1980-2025	SC-4 1980-2025
μ_0	-19.9***	-18.4***	-19.7**	-12.7	-6.50
	(1.7)	(0.2)	(2.5)	(2.4)	(3.5)
μ_1	1.19***	1.123***	1.19***	0.898***	0.641***
	(0.07)	(0.009)	(0.10)	(0.099)	(0.056)
R^2	0.998	0.999	0.995	0.989	0.982
Test: C_μ^c	0.132	0.071	0.113	0.131	0.152
σ^2	0.013	0.011	0.046	0.053	0.071

[a] Standard Errors (in brackets) are adjusted for long-run variance. The long-run variance of the cointegrating regression residual is estimated using the Barlett window which is approximately equal to INT($T^{1/2}$) as proposed in Newey and West (1987) [273].

[b] We choose q=INT($T^{1/3}$) as proposed by Stock and Watson (2010) [144].

[c] C_μ is a LM statistic for cointegration using the DOLS residuals from deterministic cointegration, as proposed Shin (1994) [271]. *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively.

[d] The critical values are taken from table 1 and $m = 1$ of Shin (1994) [271]: C_μ 0.231 (10%) 0.314 (5%) 0.533 (1%)

in first decade of the 21th century. Figure 5.5 clearly illustrates this, where the μ_1 elasticity is plotted as a function of the year for the four scenarios under investigation. It is important to point out that Ecuador switches from the first to the second stage in 2019 and 2021 for scenarios *SC-4* and *SC-3*, respectively.

In conclusion, the changes introduced in the *SC-3* and *SC-4* scenarios, which suppose an increase in energy efficiency, changes in the energy matrix, the productive sectoral structure, and in the share of renewable energy to the total consumption (see Section 3.10.2 in Chapter 3), have induced a more environmentally sounding scenario. The impact of GDP growth is somehow attenuated and the country moves towards a situation where the increase of the GDP will not lead to an unavoidable and uncontrolled increase of CO_2 emissions.

5.5 Summary and conclusions of the chapter

In this Chapter we have studied the EKC hypothesis for Ecuador in a forthcoming period, 2011-2025, using the model propoused in Chapter 3 under four different scenarios (see Section 3.10.1 in Chapter 3). The model allows us to estimate the CO_2 emission as a function of global productive activity, the energy mix and industry sectoral structure, using the system dynamics (SD) methodology. In addition we use a GDP formation presented in Chien and Hu (2008) [5] that depends on the renewable energy which creates a *feedback* mechanism that makes the model more reliable and allows us to obtain *non-trivial* conclusions in the analysis. The generated data under four different scenarios closely followed Jaunky's specification [145] and allowed us to see whether the EKC is fulfilled, or not, in Ecuador and to calculate the elasticity between GDP and CO_2 emission.

In the analysis of the EKC hypothesis we conclude that in any case Ecuador fulfills this hypothesis, but the value of the CO_2-GDP elasticity allows us to separate the proposed scenarios in two families, on one hand *BS* and *SC-2*, and, on the other, *SC-3* and *SC-4* scenarios. In the first case, the elasticity is larger than one, while in the second case it is lower than one. Therefore, the first family implies little environmental respect, while the second family corresponds to a situation where the impact of the GDP growth is attenuated.

Our estimates do indeed show that Ecuador will be able to enter the area of environmental stability (second stage of the EKC) in the medium term (2019-2021). Therefore, to achieve this goal it is essential to implement policies that allow the diversification of energy sources and to increase energy efficiency in the productive sectors in order to get more sustainable development.

This Chapter intended to fill the gap in the literature of studies on energy and CO_2 emissions in Latin American countries in general, and in Ecuador in particular. On the other hand, this kind of study may help policymakers create more comprehensive and reliable policies for control of environmental degradation. Moreover this work contributes to the EKC literature with a case study of Ecuador using time series data for the period 1980-2010 and goes a step further with the study of a forthcoming period, up to 2025.

Our species needs, and deserves, a citizenry with minds wide awake and a basic understanding of how the world works.

Carl Sagan

CHAPTER 6

Summary and conclusions

Globally, CO_2 is by far the main contributor to anthropogenic greenhouse gas (GHG) emissions (IPCC, 2007) [156, Fig. 2.1]: CO_2 represents 76.7% of the GHG emissions (approximately 56.6% is from fossil fuels, 17.3% from deforestation, and 2.8% from other sources). Ecuador has a relatively low level of CO_2 emissions (2200 kg per capita) while Qatar, the world's largest CO_2 emitter per capita in 2010, emitted 40300 kg per capita. At the same time Venezuela, the largest CO_2 emitter in Latin America (LA), emitted annually 6900 kg per capita (WB, 2014) [151]. It is expected that social and economic development in the coming years could significantly increase Ecuador's emissions. Observations show that global CO_2 emissions, far from stabilizing, have experienced significant growth in recent years.

Several international organizations, notably, the Intergovernmental Panel on Climate Change (IPCC), are warning about the need of stabilizing the CO_2 and others anthropogenic GHG emissions in order to avoid a catastrophic warming of the climatic system during this century (IPCC, 2007) [156]. The IPCC has developed several methods to estimate GHG emissions, such as the *Reference Method* (IPCC, 2006) [42], which is a *top-down* technique that uses data from the country's energy supply (mainly from the burning of fossil fuels), land use, and deforestation rate, among others, to calculate CO_2 emissions. It is a straightforward method that can be applied on the basis of the available energy supply statistics (IPCC, 2006) [42]. However, the problem arises when it is necessary to conduct more detailed studies and find the driving forces that are behind the emissions, but the data is not available or is not sufficiently disaggregated for use with this method.

A key factor of economic development in countries and the transition from subsistence agricultural economies to modern industrial societies which are oriented to services, is to have an adequate supply of *affordable energy*. Energy is essential to enhance the social and economic welfare and, in most cases, it is essential to attract industrial and commercial wealth. It is a condition, *sine qua non.* of poverty alleviation, generalize social protection and raise living standards. Note that no matter how essential energy can be for the development, energy is just a medium, it is not the *final goal*, and the *final goal* of sustainable development is to achieve good health, a high standard of living, sustainable energy and a clean environment.

As already mentioned, energy consumption is one of the greatest measures of progress and well-being of a society. The concept of *energy crisis* appears when the energy sources of the society supplies are depleted. An economic model like the present one, whose operation depends on continued growth, also requires an equally growing demand for energy. Since fossil energy sources are finite, it is inevitable that at some point the demand can not be supplied and all system will collapse; unless new sources of energy would be discovered or new techniques are developed, as would be the case of renewable energy.

The potential of renewable energy has a great capacity to help meet global energy demand. Furthermore, this type of clean energy has a rapidly growing due to the remarkable technical advances that have taken place in recent years and by the strong support of the various national governments and the enormous social support.

The commitment to promote this type of development and the rational use of energy, involves setting goals at national and regional levels and define a policy according with these goals.

The general objective of this research was create to a useful methodology to estimate CO_2 emissions of a given country, in particular for Ecuador, and to understand the driving forces that guide this process, such as economic growth, energy use, energy mix structure, and fuel use in the productive sectors. The proposed methodology tries to be easily transferable to other countries, regions, and time periods and to be used as a *pedagogical tool* for explaining to policymakers the possible ways to design a policy for reducing CO_2 emissions in a medium term horizon.

This study combines decomposition analysis with scenario modelling to create a baseline prevision as guidance for possible new policies. This allowed the development of a model with a set of integrated exploratory scenarios about income growth, energy use and CO_2 emissions for Ecuador in a medium term (2025). The scenarios show plausible more *environmental-friendly* pathways that the country could take to get closer to a sustainable development.

The application of *scenario analysis-modelling* in the short-to-medium term is intended to develop insights into plausible future changes with additional green goals in the driving forces in national policies. While the decomposition analysis gives insights into historical change. The study offers potential *longer-term insights* through the exploration of changes in to the driving forces to evaluate the fulfillment of the Environmental Kuznets Curve (EKC) hypothesis.

The thesis was organized into six chapters and seven appendices. Chapter 1 presents the introduction of the most important aspects of the methodology and objectives of the research. Chapter 2 introduce the main figures in economy, productive sectors, energy use, etc., about Ecuador from 1980 to 2010; also it discusses about critical factors for the adoption of renewable technologies in the country.

Chapter 3 presents a model approach of CO_2 emissions in Ecuador in the upcoming years, up to 2025. The main goal here is to study in detail the way the changes in the energy matrix and in the Gross Domestic Product (GDP) will affect the CO_2 emissions in the country. In particular, special attention to the effect of a reduction of the share of fossil energy will be paid, as well as of an improvement in the efficiency of the fossil energy use. In this chapter, we have developed a System Dynamic (SD) model based on a relationship, which is a variation of the *Kaya identity* (Kaya, 1993) [169], and on a formation of GDP approach that depends on renewable energy (Chien and Hu) [5], which introduces a *feedback mechanism* in the model and allows us to generate a *non-trivial* evolution of the system. Therefore, the GDP and the energy intensity have been modeled with different scenarios that present the evolution of the energy matrix and the productive sectoral structure have been defined. First, a *BS* scenario (baseline scenario) has been defined, in which the variables of the model were parameterized according to the observed tendency during the period 1980-2010 (see Chapter 2), assuming a geometric growth rate during the period 2011-2025. The second scenario, called *SC-2*, is characterized by the increasing (relative to 2010) of the GDP during the period 2011-2025 (with the goal of reaching the estimated international average GDP per capita in 2025). In the third scenario, called *SC-3* scenario, besides assuming the increasing of the GDP, we impose the decreasing of the fossil energy share (ES_1) up to 67%. Finally, in the fourth one, *SC-4* scenario, we complement the *SC-3* scenario including changes in the productive sectoral structure to achieve a reduction of energy intensity, which supposes a lower CO_2 intensity.

The main outcome of this chapter are the estimates of CO_2 emissions for the period 2011-2025 in each scenario (see Section 3.11.3 in this Chapter). By 2025 the *BS* scenario reaches 55 thousand kt, in the *SC-2* scenario it corresponds to 97 thousand kt, in *SC-3* scenario to 66 thousand kt, and in the *SC-4* scenario to 55 thousand kt of CO_2. Note that the *BS* scenario corresponds to a modest GDP increase, while in the others the GDP increases heavily. The highest emissions are for the *SC-2* scenario where no mitigation measures are taken. The other two scenarios show us that it is possible a sizable reduction of the emissions, promoting the renewable energy (*SC-3* scenario) and on top of that modifying the productive sectoral structure, therefore, reducing the energy and the CO_2 intensities, as in the *SC-4* scenario. It is worth to note that both promotion of renewable energy and improvement of the energy intensity are equally effective attenuating CO_2 emissions.

After the study that has been carried out in this chapter, the main conclusions are:

- Energy and emissions analysis, the development of policy and the reporting of progress require insight into the driving forces of change and potential future evolution.
- Energy and emissions are both dependent on, and influenced by, a wider development domain which is complex in evolution and uncertain in outcome.

- Qualitative and quantitative exploratory scenario analysis was implemented for baseline quantification of future CO_2 emissions as *scientific inquiry* to improve the *strategic planning*.

- The exploratory scenarios are not predictions but are plausible descriptions of alternative future worlds. These involve not only technical and economic parameters but explicitly represent the evolution of social, political and cultural aspects.

- The emissions increase under all scenarios studied but the composition of this growth and the total growth by 2025 are divergent and suggest that it is possible to control the CO_2 emissions even under a scenario of continuous increase of the income. To do this, it is needed an increase of both the use of renewable energy and the support of use of more efficient fossil fuel technologies.

- The methodology presented is useful to estimate the CO_2 emissions of a given country and to understand the driving forces that guide this process.

- This methodology is easily transferable to other countries, regions, and time periods. Moreover, it can be pedagogically useful for explaining to *policy-makers* the possible ways to design a policy for reducing CO_2 emissions in a medium term horizon.

- This study offers useful lessons for developing countries, and it could be used as a *policy-making* tool.

The results obtained with the model are the starting point for the decomposition analysis in Chapter 4 and for the study of Environmental Kuznets Curve (EKC) in Chapter 5.

In Chapter 4, a decomposition analysis of CO_2 related to income growth and energy consumption bases on LMDI (see Section 4.5 in this Chapter) for Ecuador in the period 1980-2025 is carried out. For this purpose three periods have been selected, the first period is 1980-1995 where the LMDI analysis findings suggest that the country emissions in this period almost grow (38%) in the same factor that the income (35%). The second period is 1995-2010 and the evidence suggests that a higher economic growth (68%) led to even greater emissions growth (85%) in the country.

The third period is 2010-2025 and includes the analysis for the different scenarios proposed in Chapter 3. To see more clearly how the income-CO$_2$ relationship behaves as a function of time, it is very enlightening to depict the ratio D_{tot}/D_{act}[1] as a function of the time. The first striking thing is the very different behaviour of each scenario. On one hand, it is somehow surprising the almost flat curve corresponding to the *BS* scenario which implies a *trend-growth* GDP scenario, however the CO$_2$ emission increases steadily because of the absence of attenuation measurements. A similar behaviour, although slightly sloping down, is observed for *SC-2*, where a rapid growth of the GDP is assumed without any attenuation action regarding CO$_2$ emission. It is worth noting a certain decrease of the ratio D_{tot}/D_{act} in the final part of the period under study. The other two scenarios, *SC-3* and *SC-4*, show a steady reduction of the ratio D_{tot}/D_{act} due to the changes in the sectoral structure and in the energy mix, which allows compensation of the rapid GDP growth.

The main conclusions of this chapter are:

- The application of decomposition analysis was implemented to get insight at macro and sectoral level both historically and for alternative future evolution in the different scenarios. This can enhance knowledge of the driving forces that control in CO$_2$ emissions.

- In general, economic growth is the most significant in determining future emissions, thus the scale growth in economic output of the sectors induce an increase of the emissions. Patterns of energy intensity saw a deeper decrease in industry, trade and public service sector as well as in transport in the greener scenario (*SC-4*). One can clearly see the results of the implementation of energy efficiency goals set for each sector in this scenario.

- The key of the alternative evolution scenarios is the complex array of driving forces in the development path, which can be driven by governance and society. These driving forces, in particular, can influence the evolution of

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[1] Terms of the LMDI formula in Multiplicative decomposition case (see Figure 4.4).

technological change and the development models applied but can also be represented by lifestyles and societal preferences.

- This preliminary analysis suggests that, with the appropriate changes in the energy mix, the sectoral structure, and the share of renewable energies, Ecuador can move into a more environmentally sustainable situation.

In Chapter 5 we try to respond *if is it possible for a country in the process of development to comply with the EKC hypothesis in the medium term?*. This chapter has studied the EKC hypothesis in Ecuador in a forthcoming period, 2011-2025, under four different scenarios (see Section 3.10.1 in Chapter 3). We used co-integration techniques (Stock and Watson) [144] to test the existence of the EKC hypothesis in Ecuador in the medium term using the Jaunky's specification (Jaunky, 2011) [145]. Our proposal goes a step further than previous contributions, and intends to see under which conditions a country could approach the fulfilment of this hypothesis in the medium term. Results do not support the fulfilment of the EKC, nevertheless, our estimations show that Ecuador could be on the way to achieving environmental stabilization in the near future if economic growth is combined with an increase in the use of renewable energies, an improvement of the productive sectoral structure, and the use of a more efficient fossil fuel technology.

After the analysis that has been carried out in this chapter we can conclude that:

- Lower emissions are not necessarily associated with lower economic growth: as the economy expands demand for the supply of energy and energy intensive goods increases, but at the same time, economic growth can drive technological change, increases efficiency, institutional change and preferences towards a reduction of the emissions.

- In no case, Ecuador fulfills this hypothesis, but the value of the CO_2-GDP elasticity allows us to separate the proposed scenarios into two families, on one hand *BS* and *SC-2*, and, on the other, *SC-3* and *SC-4* scenarios. In the first case, the elasticity is larger than one, while in the second case it is lower than one. Therefore, the first family implies little environmental respect, while the second one corresponds to a situation where the impact of the GDP growth over environment is attenuated.

- Our estimates do indeed show that Ecuador will be able to enter the area of environmental stability (second stage of the EKC) in the medium term (2019-2021). Therefore, to achieve this goal it is essential to implement policies that allow the diversification of energy sources and to increase energy efficiency in the productive sectors in order to get more sustainable development.
- This chapter intended to fill the gap in the literature of studies on energy and CO_2 emissions in Latin American countries in general, and in Ecuador in particular. On the other hand, this kind of study may help policymakers to create more comprehensive and reliable policies for control of environmental degradation. Moreover this work contributes to the EKC literature with a case study of Ecuador using time series data for the period 1980-2010 and goes a step further with the study of a forthcoming period, up to 2025.

In summary, the influence of policy and *decision-making* on the development path and the complex array of driving forces show that governance represents, a more broad conception than *government*. Ultimately, the evolution of governance is dependent on society. The development path arising from governance and society can involve stronger or weaker processes of *sustainability* that encourage stronger or weaker processes of immaterialisation, dematerialisation and decarbonisation (Tapio et al., 2007) [274]. Emissions can evolve on higher or lower emissions trajectories based not only on the evolution of economic growth but on the evolution of the development path. Within the development path, economic growth interacts with governance and societal choices and the other driving forces. This can drive potential lock-in to a higher emissions trajectory.

6.1 Limitations

As with most research, the lack of data, poor quality and level of detail as well as the little disaggregation and accessibility have been the main limitation of this study. The data used to build the model has been taken from published sources and additional estimates have been made on base of the literature. In completing the data set for different variables, data are probably underestimate or overestimate.

The lack of more disaggregated data has avoided a more developed division in sub-systems, such as the productive sectors. The lack of this *sectoral-vision* weakens the *macro-vision* and the insight about the dynamics of the system that may provide the model. In addition, the decomposition analysis framework does not explicitly consider the effect of price on energy consumption. The general level of prices is also important in explaining growth in GDP but cannot be explicitly considered in the analysis. It also cannot explore how high inflation reduces growth in output. Goodwin et al. (2003) [275] suggests that income is a stronger determinant of fuel consumption than fuel price and consumption is price inelastic. Despite these limitations, in the scenarios, a range of income growth rates are explored which allows the analysis of alternative evolutions of the economy and its relationship with energy and emissions.

Scenario analysis is a method for structuring thinking on the future but the future is by its nature complex and uncertain. Known factors can evolve in unknown ways and unknown factors can have a substantial impact and alter outcomes. In general, the scenarios attempt to bound uncertainty of the known factors while unknown factors or wildcards have been excluded and would be the subject of strategic planning exercises (Nakicenovic et al., 2000) [64]. Note that the scenario analysis has been made based on assumptions and generalizations used in the literature.

The top-down methodology for building models maybe have a bias in the estimation and analysis at sector level. In addition, the identity that has been used (an extension of Kaya identity) may suggest direct causality and simple linear relationships between variables. The factors described in the identity maybe are not directly driving forces in themselves.

Due to the high complexity involved in environmental, economic and energy systems, there is no methodology or model to make an accurate forecast and as mentioned above, the scenario analysis not even tries to make a prediction, therefore, our study outcomes should be taken as estimates of potential future for the accomplishment of policies.

6.2 Areas for further research

In order to get more accurate estimates and realistic scenarios, future research would expand the model within different sectors and economic activities of the country. Each sector could contain their own causal relationships and driving forces, in order to achieve deeper insight on their dynamics. The priority should be to develop transport and construction sectors, as these are the most energetically intensive and therefore they are calls for achieving improved in energy intensity and in emissions reduction.

In responding to data gaps, further research both on transport and industry activity data for Ecuador would be beneficial to both policy and analysis. Further data research could also examine the disaggregation of energy data for different types of transport (passenger/freighter) or industrial activity. For the residential sector, further disaggregation could be extended to different branches of housing by including by age and dwelling type or by energy service or technology type *e.g.* lighting, space heating etc. where data permits.

The use of the model with other indicators (economic and environmental) and another type pollutants (SO_2, CH_4, etc.) could also be recommended for future research. Note that, the use of the model and the methodology can also be transferred to other countries or similar zones.

The most comprehensive and holistic vision of growth, energy consumption and emissions issue is another line that future research should continue. In light of the results, insights into convergence processes at local and regional level, about income, energy use and emissions are necessary for the development of new and more effective policies. The long-term impact of energy infrastructure investment and alternative approaches to curb future demand is meritorious of further analysis.

CHAPTER

7

Appendix

7.1 Appendix A

Appendix A presents the historical data that was used to build and validate the model. The considered data corresponds to the period 1980-2010 and it has been extracted from the official data sources such as: Ecuadorian Institute of Statistics and Census (INEC, 2012) [172], Central Bank of Ecuador (BCE) [152], World Bank[1] (WB) [146], and International Energy Agency (IEA) [153].

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[1] Economic official data set used is given in constant 2005 PPP international dollars.

Appendix A Historical Data (1980-2010)

Year	Population (Total)	GDP, PPP (constant 2005 international $)	GDPpc (USD)	Agriculture, Fishing and Mining Sector (% of GDP)	Industrial Sector (% of GDP)
1980	7957811	45348387571	5698,60	28,66	14,13
1981	8178948	46874315322	5731,09	28,65	14,14
1982	8403034	46607486519	5546,51	28,64	14,15
1983	8629832	45427603706	5264,02	28,63	14,15
1984	8859125	47170328792	5324,49	28,62	14,16
1985	9090592	48546166408	5340,26	28,61	14,16
1986	9323745	50522364562	5418,68	28,60	14,16
1987	9557974	49438373617	5172,47	28,60	14,16
1988	9792658	53574220063	5470,86	28,60	14,16
1989	10027109	54099539802	5395,33	28,62	14,15
1990	10260587	55550422486	5413,96	28,65	14,14
1991	10493498	58435507851	5568,73	28,70	14,12
1992	10725281	59319377193	5530,80	28,77	14,08
1993	10953182	59494485196	5431,71	28,88	14,04
1994	11173647	62292016560	5574,90	29,02	13,98
1995	11384506	63384349640	5567,60	29,19	13,90
1996	11584074	64906106323	5603,05	29,38	13,82
1997	11774005	67536871819	5736,10	29,59	13,73
1998	11959586	68963769795	5766,40	29,83	13,63
1999	12148188	64619429726	5319,26	30,09	13,52
2000	12345023	66430642294	5381,17	30,36	13,40
2001	12552036	69975853579	5574,86	30,61	13,30
2002	12767415	73552710360	5760,97	30,88	13,22
2003	12987992	75960473417	5848,52	31,15	13,19
2004	13208869	82663204609	6258,16	31,43	13,21
2005	13426402	87411173006	6510,39	31,70	13,29
2006	13639708	91564517585	6713,08	31,98	13,43
2007	13849721	93430326328	6746,01	32,26	13,62
2008	14056740	100196254255	7127,99	32,57	13,84
2009	14261566	100558832906	7051,04	32,89	14,09
2010	14465000	104160450566	7200,86	33,22	14,35

7. APPENDIX

Appendix A Historical Data (1980-2010)

Year	Construction Sector (% of GDP)	Trade and Public services Sector (% of GDP)	Transportation Sector (% of GDP)	Energy use (kt of oil equivalent)	Agriculture, Fishing and Mining Sector (% of Energy use)	Industrial Sector (% of Energy use)
1980	8,35	39,46	9,39	5032,22	3,00	17,00
1981	8,35	39,47	9,39	5259,13	3,00	18,00
1982	8,35	39,48	9,38	5677,75	4,00	18,00
1983	8,36	39,49	9,38	5293,44	4,00	19,00
1984	8,36	39,49	9,37	5708,26	5,00	19,00
1985	8,36	39,50	9,37	5775,48	5,00	19,00
1986	8,35	39,51	9,37	5750,92	5,00	19,00
1987	8,35	39,51	9,38	5874,32	5,00	19,00
1988	8,33	39,51	9,39	6169,54	5,00	19,00
1989	8,31	39,51	9,40	5869,94	2,00	20,00
1990	8,29	39,50	9,43	5997,20	1,50	20,00
1991	8,25	39,47	9,46	6221,86	1,50	20,00
1992	8,20	39,44	9,51	6244,76	1,50	20,00
1993	8,14	39,38	9,57	5979,53	1,50	20,00
1994	8,07	39,30	9,64	6228,28	1,38	24,77
1995	7,99	39,20	9,72	7143,29	1,25	23,33
1996	7,91	39,08	9,81	7806,35	1,25	23,33
1997	7,84	38,94	9,89	7954,64	1,21	22,58
1998	7,80	38,78	9,97	8095,33	1,21	22,58
1999	7,80	38,57	10,03	7693,42	1,29	24,14
2000	7,85	38,32	10,07	8033,32	1,21	22,58
2001	7,96	38,04	10,09	8800,79	1,21	22,58
2002	8,11	37,69	10,10	9169,46	1,21	22,58
2003	8,29	37,27	10,09	9933,56	1,21	22,58
2004	8,49	36,78	10,08	10653,78	1,00	25,64
2005	8,71	36,22	10,07	10782,45	1,00	20,73
2006	8,95	35,59	10,06	10970,65	1,00	20,00
2007	9,19	34,89	10,04	11383,24	1,08	22,31
2008	9,42	34,14	10,02	11030,69	1,06	22,25
2009	9,65	33,36	10,01	11351,79	1,03	22,19
2010	9,87	32,56	9,99	11931,70	1,03	21,50

Appendix A Historical Data (1980-2010)

Year	Construction Sector (% of Energy use)	Trade and Public services Sector (% of Energy use)	Transportation Sector (% of Energy use)	Energy Intensity (kToe/BUSD)	Energy Intensity in Agriculture, Fishing and Mining Sector (kToe/BUSD)	Energy Intensity inIndustrial Sector (kToe/BUSD)
1980	11,00	33,00	36,00	110,97	11,61	133,47
1981	10,00	32,00	37,00	112,20	11,75	142,82
1982	9,00	31,00	38,00	121,82	17,01	155,01
1983	8,00	30,00	39,00	116,52	16,28	156,45
1984	7,00	29,00	40,00	121,01	21,14	162,43
1985	7,00	29,00	40,00	118,97	20,79	159,63
1986	7,00	29,00	40,00	113,83	19,90	152,71
1987	7,00	29,00	40,00	118,82	20,77	159,39
1988	7,00	29,00	40,00	115,16	20,13	154,51
1989	2,00	29,00	47,00	108,50	7,58	153,33
1990	1,50	27,00	50,00	107,96	5,65	152,72
1991	1,50	27,00	50,00	106,47	5,56	150,86
1992	1,50	27,00	50,00	105,27	5,49	149,50
1993	1,50	27,00	50,00	100,51	5,22	143,19
1994	1,38	24,77	47,71	99,99	4,74	177,20
1995	1,25	26,67	47,50	112,70	4,83	189,15
1996	1,25	26,67	47,50	120,27	5,12	203,03
1997	1,21	25,81	49,19	117,78	4,81	193,68
1998	1,21	25,81	49,19	117,39	4,76	194,46
1999	1,29	27,59	45,69	119,06	5,12	212,58
2000	1,21	25,81	49,19	120,93	4,82	203,76
2001	1,21	25,81	49,19	125,77	4,97	213,56
2002	1,21	25,81	49,19	124,67	4,88	212,88
2003	1,21	25,81	49,19	130,77	5,08	223,85
2004	1,00	22,36	50,00	128,88	4,10	250,14
2005	1,00	23,00	54,27	123,35	3,89	192,39
2006	1,00	23,00	55,00	119,81	3,75	178,44
2007	1,08	23,99	51,53	121,84	4,09	199,59
2008	1,06	23,63	52,00	110,09	3,58	176,95
2009	1,03	23,20	52,56	112,89	3,53	177,71
2010	1,03	23,36	53,07	114,55	3,57	171,61

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Appendix A Historical Data (1980-2010)

Year	Energy Intensity in Construction Sector (kToe/BUSD)	Energy Intensity in Trade and Public services Sector (kToe/BUSD)	Energy Intensity in Transportation Sector (kToe/BUSD)	Fossil fuel energy consumption (% of total)	Alternative and nuclear energy (% of total energy use)	Combustible renewables and waste (% of total energy)
1980	146,20	92,80	425,44	79,04	1,22	19,74
1981	134,34	90,96	442,32	78,57	1,95	19,49
1982	131,24	95,66	493,44	78,09	2,68	19,24
1983	111,55	88,53	484,61	77,63	3,40	18,96
1984	101,35	88,86	516,34	77,24	4,11	18,65
1985	99,65	87,34	507,71	76,94	4,78	18,28
1986	95,38	83,55	485,73	76,76	5,39	17,85
1987	99,65	87,21	506,83	76,73	5,93	17,35
1988	96,72	84,52	490,72	76,85	6,38	16,76
1989	26,10	79,64	542,34	77,15	6,76	16,10
1990	19,54	73,80	572,58	77,58	7,05	15,37
1991	19,37	72,83	562,62	78,13	7,27	14,61
1992	19,26	72,07	553,62	78,74	7,42	13,83
1993	18,53	68,90	525,34	79,42	7,51	13,06
1994	17,05	63,02	494,89	80,15	7,55	12,30
1995	17,63	76,67	550,55	80,92	7,53	11,55
1996	19,02	82,07	582,37	81,68	7,48	10,85
1997	18,17	78,05	585,73	82,41	7,41	10,18
1998	18,21	78,12	579,47	83,11	7,33	9,56
1999	19,75	85,15	542,60	83,78	7,23	8,99
2000	18,63	81,43	590,85	84,44	7,12	8,44
2001	19,11	85,33	613,16	85,09	6,99	7,92
2002	18,59	85,36	607,35	85,70	6,87	7,42
2003	19,08	90,54	637,30	86,27	6,77	6,96
2004	15,17	78,35	639,02	86,74	6,71	6,55
2005	14,16	78,33	664,68	87,12	6,69	6,19
2006	13,39	77,43	655,30	87,40	6,72	5,88
2007	14,38	83,78	625,34	87,61	6,79	5,61
2008	12,37	76,20	571,09	87,77	6,88	5,35
2009	12,03	78,50	592,86	87,92	6,97	5,11
2010	12,00	82,19	608,43	88,08	7,06	4,86

Appendix A Historical Data (1980-2010)

Year	Gaseous fuel consumption (% Total Fosil Energy)	Solid fuel consumption (% Total Fosil Energy)	Liquid fuel consumption (% Total Fosil Energy)	CO2int (kt/kToe)	CO2pc- (kgCO2)	CO2-Total
1980	0,01	0,00	0,78	2,36	1491,63	11870,08
1981	0,01	0,00	0,78	2,89	1855,70	15177,71
1982	0,01	0,00	0,77	3,10	2095,11	17605,27
1983	0,01	0,00	0,77	3,39	2077,87	17931,63
1984	0,01	0,00	0,77	3,40	2188,00	19383,76
1985	0,01	0,00	0,76	2,98	1893,89	17216,57
1986	0,01	0,00	0,76	2,23	1372,61	12797,83
1987	0,01	0,00	0,76	2,26	1391,91	13303,88
1988	0,01	0,00	0,76	2,37	1493,36	14624,00
1989	0,01	0,00	0,77	2,91	1706,03	17106,56
1990	0,01	0,00	0,77	2,26	1318,76	13531,23
1991	0,01	0,00	0,77	2,15	1272,01	13347,88
1992	0,01	0,00	0,78	3,10	1806,27	19372,76
1993	0,01	0,00	0,79	3,53	1928,05	21118,25
1994	0,01	0,00	0,80	1,71	952,39	10641,63
1995	0,01	0,00	0,80	2,74	1717,46	19552,44
1996	0,01	0,00	0,81	2,64	1776,51	20579,20
1997	0,01	0,00	0,82	1,91	1289,09	15177,71
1998	0,01	0,00	0,82	2,36	1594,10	19064,73
1999	0,01	0,00	0,83	2,37	1503,85	18268,99
2000	0,01	0,00	0,84	2,19	1422,54	17561,26
2001	0,01	0,00	0,84	2,27	1592,77	19992,48
2002	0,01	0,00	0,85	2,29	1644,02	20989,91
2003	0,01	0,00	0,86	2,26	1728,47	22449,37
2004	0,01	0,00	0,86	2,28	1838,65	24286,54
2005	0,01	0,00	0,86	2,38	1912,10	25672,67
2006	0,01	0,00	0,87	2,25	1810,69	24697,25
2007	0,01	0,00	0,87	2,25	1846,25	25569,99
2008	0,01	0,00	0,87	2,22	1744,19	24517,56
2009	0,01	0,00	0,87	2,28	1815,81	25896,35
2010	0,01	0,00	0,87	2,35	1941,11	28078,22

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Appendix A Historical Data for Economic Model (1980-2010)

Indicator Name	GDP (USD-2005)	Investment (% GDP)	Trade balance (% GDP)	Consumption (% GDP)	Energy Use (ktoe)	Energy import(% Energy Use)	Renewables (% Energy Use)
1980	49062851650	25,37	-0,73	57,06	5032,22	-133,54	19,50
1981	51816682846	25,83	-0,68	58,98	5259,13	-129,14	18,05
1982	52135275313	21,76	-3,10	64,00	5677,75	-110,26	18,60
1983	51959647851	20,67	0,24	63,70	5293,44	-157,95	19,91
1984	53323730597	18,78	1,69	63,32	5708,26	-161,81	19,22
1985	55422020148	18,95	3,65	62,64	5775,48	-176,65	18,37
1986	57342272613	23,57	-1,85	62,67	5750,92	-185,70	17,56
1987	57193699525	25,41	-7,00	66,31	5874,32	-79,71	18,40
1988	60562675687	26,11	-4,65	62,27	6169,54	-177,34	18,01
1989	61171801723	27,09	-4,55	63,78	5869,94	-173,12	18,35
1990	63422871451	24,07	0,93	62,69	6021,20	-173,60	13,71
1991	66144564024	22,05	2,15	64,46	6343,80	-172,47	13,55
1992	67543065602	22,67	3,46	63,93	6499,21	-182,42	12,71
1993	68875837583	21,08	-3,10	71,42	5992,01	-228,60	13,87
1994	71808743259	21,29	-3,22	70,98	6380,95	-236,77	12,26
1995	73426270226	19,82	-3,34	72,30	7162,49	-208,93	10,89
1996	74697827835	18,54	0,33	70,26	7787,15	-181,13	10,21
1997	77930648806	20,31	-1,95	70,37	7888,39	-178,55	8,35
1998	80476276364	24,00	-7,61	72,52	8320,97	-157,66	9,54
1999	76662195157	19,63	3,55	65,05	7801,91	-174,85	10,28
2000	77499194203	21,28	4,79	64,58	8034,28	-181,94	8,68
2001	80611275017	22,35	-4,30	72,50	8800,79	-161,21	8,29
2002	83913738916	23,70	-6,39	72,86	9206,90	-141,14	7,91
2003	86198607096	19,59	-2,04	71,74	9927,80	-138,81	6,49
2004	93276392755	20,20	-1,56	70,47	10349,74	-183,17	5,59
2005	98211934236	21,64	-0,86	68,51	10986,88	-167,77	5,21
2006	102536722721	22,46	0,96	65,98	10922,56	-173,64	5,30
2007	104782342544	22,70	1,28	65,09	11332,31	-155,15	6,42
2008	111443492905	26,39	0,27	61,51	11027,43	-158,87	5,93
2009	112074810922	25,64	-1,61	62,24	11461,86	-138,39	5,37
2010	115268445163	26,98	-3,98	63,88	12096,90	-126,22	5,35

7.2 **Appendix B**

Appendix B presents the outcomes of the model in the period 1980-2010. We use this results in the model validation.

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Appendix B Model Outcomes (1980-2010)

Year	Population (Total)	GDP, PPP (constant 2005 international $)	GDPpc (USD)	Energy use (kt of oil equivalent)	
1980	7946890	44600000000	5612,26	5189,16	
1981	8178140	45628900000	5579,37	5307,11	
1982	8409590	46418100000	5519,66	5394,86	
1983	8640850	47268300000	5470,33	5482,41	
1984	8872430	48192300000	5431,69	5568,89	
1985	9104000	49206000000	5404,89	5653,96	
1986	9336150	50342400000	5392,21	5741,98	
1987	9567680	51575500000	5390,59	5831,78	
1988	9798260	52882700000	5397,15	5923,81	
1989	10028500	54241600000	5408,73	6021,75	
1990	10256200	55614600000	5422,55	6129,50	
1991	10481800	56973300000	5435,45	6250,26	
1992	10704000	58289300000	5445,56	6392,86	
1993	10923500	59564900000	5452,94	6564,17	
1994	11138600	60839900000	5462,06	6766,50	
1995	11350300	62152800000	5475,89	7001,93	
1996	11559100	63537300000	5496,72	7266,77	
1997	11764900	65219500000	5543,58	7577,54	
1998	11969600	66634200000	5566,96	7862,07	
1999	12173100	68488600000	5626,24	8196,14	
2000	12377600	70607300000	5704,46	8546,77	
2001	12583000	73059600000	5806,19	8920,27	
2002	12789400	75827500000	5928,93	9313,19	
2003	12997900	78877000000	6068,46	9706,86	
2004	13207100	82183000000	6222,62	10092,60	
2005	13417100	85680400000	6385,90	10459,40	
2006	13627800	89311900000	6553,66	10802,60	
2007	13837600	93015000000	6721,88	11118,30	
2008	14048000	96745800000	6886,81	11406,70	
2009	14258700	100509000000	7048,96	11677,80	
2010	14468300	104288000000	7208,06	11931,70	

Appendix B Model Outcomes (1980-2010)

Year	Energy Intensity (kToe/BUSD)	Energy Intensity in Agriculture, Fishing and Mining Sector (kToe/BUSD)	Energy Intensity in Industrial Sector (kToe/BUSD)	Energy Intensity in Construction Sector (kToe/BUSD)	Energy Intensity in Trade and Public services Sector (kToe/BUSD)	Energy Intensity in Transportation Sector (kToe/BUSD)
1980	116,35	15,79	144,16	147,11	94,46	446,10
1981	116,31	16,17	146,25	136,83	92,83	457,44
1982	116,22	16,51	148,24	126,54	91,18	468,55
1983	115,98	16,72	149,98	116,21	89,49	479,09
1984	115,56	16,72	151,40	105,88	87,74	488,91
1985	114,90	16,43	152,51	95,52	85,96	497,91
1986	114,06	15,80	153,39	85,05	84,15	506,32
1987	113,07	14,84	154,24	74,45	82,33	514,37
1988	112,02	13,59	155,22	63,82	80,54	522,09
1989	111,02	12,14	156,60	53,49	78,84	529,45
1990	110,21	10,66	158,59	44,13	77,34	536,02
1991	109,71	9,28	161,38	35,70	76,16	541,65
1992	109,67	8,06	165,11	29,32	75,40	546,52
1993	110,20	7,03	169,83	25,09	75,11	551,00
1994	111,22	6,21	175,44	21,88	75,31	555,41
1995	112,66	5,58	181,48	19,43	75,95	560,24
1996	114,37	5,13	187,52	17,98	76,85	565,67
1997	116,19	4,81	193,31	17,24	77,85	571,61
1998	117,99	4,60	198,76	16,98	78,88	578,13
1999	119,67	4,46	203,73	16,96	79,84	585,24
2000	121,05	4,37	207,99	16,95	80,37	593,08
2001	122,10	4,31	211,19	16,88	80,65	601,27
2002	122,82	4,26	212,99	16,69	80,93	608,90
2003	123,06	4,19	213,00	16,38	80,98	615,36
2004	122,81	4,11	211,26	15,95	80,83	619,97
2005	122,07	4,02	207,54	15,42	80,58	622,40
2006	120,95	3,93	202,41	14,83	80,32	622,52
2007	119,53	3,83	196,30	14,21	80,10	620,65
2008	117,90	3,72	189,47	13,56	79,92	617,48
2009	116,19	3,61	182,31	12,91	79,80	613,91
2010	114,41	3,50	175,07	12,28	79,69	610,16

Appendix B Model Outcomes (1980-2010)

Year	CO2 in Agriculture, Fishing and Mining Sector (kTons)	CO2 in Industrial Sector (kTons)	CO2 in Construction Sector (kTons)	CO2 in Trade and Public services Sector (kTons)	CO2 in Transportation Sector (kTons)	
1980	485,28	2185,27	1317,22	3997,66	4496,64	
1981	505,32	2255,78	1246,48	3996,49	4686,24	
1982	521,56	2313,32	1166,17	3971,07	4851,44	
1983	534,73	2370,88	1084,86	3947,20	5020,04	
1984	542,41	2428,98	1003,00	3927,37	5194,91	
1985	541,99	2489,66	920,33	3914,81	5379,86	
1986	531,98	2556,75	836,19	3912,76	5584,70	
1987	511,59	2633,02	748,96	3920,88	5812,43	
1988	481,03	2720,72	658,32	3938,73	6065,02	
1989	442,62	2823,87	566,64	3968,50	6342,93	
1990	401,21	2944,99	480,26	4011,97	6638,37	
1991	360,69	3085,62	398,80	4072,12	6945,41	
1992	323,75	3246,90	335,63	4152,17	7261,30	
1993	292,20	3429,99	293,74	4255,38	7591,33	
1994	267,18	3634,84	261,67	4387,36	7947,47	
1995	249,07	3855,70	237,24	4549,73	8340,51	
1996	237,45	4085,56	224,09	4733,95	8766,71	
1997	232,27	4332,16	220,62	4947,90	9251,69	
1998	230,60	4554,32	222,59	5141,78	9713,00	
1999	233,81	4795,49	230,18	5361,55	10248,28	
2000	240,17	5041,18	240,73	5570,74	10837,63	
2001	248,87	5294,65	253,30	5783,42	11481,21	
2002	258,86	5549,27	266,76	6010,27	12163,21	
2003	269,14	5795,00	280,11	6224,97	12865,58	
2004	279,11	6029,38	292,60	6422,21	13566,68	
2005	288,47	6239,25	303,91	6601,09	14242,85	
2006	297,11	6427,98	313,78	6760,10	14874,22	
2007	304,96	6597,89	322,07	6898,42	15455,44	
2008	311,80	6746,53	328,60	7018,09	15997,75	
2009	317,95	6877,05	333,62	7124,76	16526,24	
2010	323,44	6987,95	337,23	7218,57	17045,04	

Appendix B Model Outcomes (1980-2010)

Year	CO2int (kt/kToe)	CO2pc- (kgCO2)	CO2-Total
1980	2,41	1570,69	12482,07
1981	2,39	1551,73	12690,30
1982	2,38	1524,87	12823,56
1983	2,36	1499,59	12957,71
1984	2,35	1476,11	13096,67
1985	2,34	1455,04	13246,64
1986	2,34	1437,68	13422,38
1987	2,34	1424,26	13626,89
1988	2,34	1414,93	13863,82
1989	2,35	1410,43	14144,54
1990	2,36	1411,52	14476,80
1991	2,38	1417,95	14862,65
1992	2,40	1431,22	15319,74
1993	2,42	1452,16	15862,64
1994	2,44	1481,20	16498,53
1995	2,46	1518,22	17232,24
1996	2,48	1561,35	18047,77
1997	2,51	1613,67	18984,63
1998	2,53	1659,40	19862,30
1999	2,55	1714,38	20869,31
2000	2,57	1771,78	21930,44
2001	2,59	1832,75	23061,44
2002	2,60	1895,97	24248,36
2003	2,62	1956,84	25434,81
2004	2,63	2013,31	26589,98
2005	2,65	2062,71	27675,57
2006	2,65	2104,02	28673,19
2007	2,66	2137,57	29578,78
2008	2,67	2164,21	30402,77
2009	2,67	2186,71	31179,62
2010	2,67	2205,67	31912,23

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Appendix B Outcomes of Economic Model (1980-2010)

Year	QT	IT	TBT	CHT	EIMPT	RNT
1980	48,96	11,52	-0,27	28,96	-6502,31	1057,57
1981	50,27	11,71	-0,33	30,18	-6949,82	1113,64
1982	51,57	11,91	-0,39	31,39	-7399,51	1167,91
1983	52,89	12,14	-0,46	32,58	-7851,97	1219,57
1984	54,25	12,43	-0,53	33,78	-8296,42	1266,46
1985	55,67	12,79	-0,63	34,99	-8727,15	1306,45
1986	57,14	13,18	-0,75	36,24	-9147,86	1338,32
1987	58,66	13,58	-0,85	37,54	-9576,98	1361,30
1988	60,25	13,95	-0,90	38,91	-10048,30	1374,62
1989	61,88	14,26	-0,91	40,36	-10546,61	1379,32
1990	63,56	14,49	-0,89	41,91	-11065,68	1377,25
1991	65,26	14,67	-0,88	43,53	-11595,39	1371,02
1992	66,97	14,81	-0,91	45,21	-12119,53	1362,52
1993	68,67	14,94	-0,98	46,89	-12615,32	1353,88
1994	70,38	15,08	-1,05	48,53	-13057,34	1347,09
1995	72,08	15,26	-1,12	50,09	-13431,03	1343,37
1996	73,79	15,49	-1,16	51,56	-13742,29	1343,43
1997	75,53	15,79	-1,19	52,95	-14012,40	1346,34
1998	77,36	16,17	-1,19	54,29	-14266,23	1351,19
1999	79,31	16,62	-1,17	55,64	-14529,42	1355,36
2000	81,49	17,17	-1,17	57,07	-14816,08	1356,80
2001	83,97	17,85	-1,19	58,61	-15131,48	1354,76
2002	86,76	18,66	-1,20	60,23	-15478,90	1350,15
2003	89,86	19,61	-1,16	61,88	-15852,16	1344,46
2004	93,23	20,73	-1,11	63,53	-16220,26	1340,32
2005	96,80	22,01	-1,06	65,14	-16531,47	1339,58
2006	100,49	23,43	-1,06	66,71	-16761,46	1342,91
2007	104,25	24,97	-1,12	68,24	-16904,88	1348,46
2008	108,04	26,57	-1,27	69,76	-16978,46	1352,48
2009	111,83	28,21	-1,47	71,27	-17005,68	1352,29
2010	115,61	29,86	-1,70	72,80	-17015,43	1348,21

7.3 Appendix C

Appendix C presents the outcomes of the model in the forecast period 2011-2025 for the four considered scenarios. We use these results in both decomposition analysis (Chapter 4) and EKC study (Chapter 5).

7. APPENDIX

Appendix C Model Outcomes (2011-2025)

Year	Pop.	GDP, PPP (constant 2005 international $)			
		BS	SC-2	SC-3	SC-4
2011	14656400	107814000000	111344000000	111344000000	111344000000
2012	14846900	111316000000	118476000000	117873000000	117994000000
2013	15039900	114929000000	126125000000	124847000000	125113000000
2014	15235500	118650000000	134295000000	132216000000	132664000000
2015	15433500	122481000000	143024000000	140001000000	140674000000
2016	15634200	126426000000	152350000000	148216000000	149166000000
2017	15837400	130491000000	162312000000	156877000000	158163000000
2018	16043300	134678000000	172953000000	165996000000	167691000000
2019	16251800	138992000000	184319000000	175587000000	177773000000
2020	16463100	143437000000	196459000000	185661000000	188436000000
2021	16677100	148018000000	209424000000	196228000000	199704000000
2022	16893900	152738000000	223270000000	207294000000	211603000000
2023	17113600	157604000000	238054000000	218865000000	224159000000
2024	17336000	162618000000	253841000000	230944000000	237397000000
2025	17561400	167787000000	270696000000	243531000000	251341000000

Appendix C Model Outcomes (2011-2025)

Year	GDPpc (USD)					
	BS	SC-2	SC-3	SC-4		
2011	7356,10	7596,96	7596,96	7596,96		
2012	7497,56	7979,86	7939,22	7947,38		
2013	7641,61	8386,01	8301,04	8318,73		
2014	7787,73	8814,66	8678,19	8707,59		
2015	7936,02	9267,13	9071,22	9114,84		
2016	8086,55	9744,68	9480,29	9541,02		
2017	8239,41	10248,60	9905,47	9986,69		
2018	8394,66	10780,40	10346,80	10452,40		
2019	8552,38	11341,40	10804,20	10938,70		
2020	8712,62	11933,30	11277,40	11445,90		
2021	8875,48	12557,50	11766,30	11974,70		
2022	9041,00	13216,00	12270,30	12525,40		
2023	9209,28	13910,30	12789,00	13098,30		
2024	9380,36	14642,40	13321,60	13693,80		
2025	9554,32	15414,20	13867,40	14312,10		

7.3 Appendix C

Appendix C Model Outcomes (2011-2025)

Year	Agriculture, Fishing and Mining Sector (% of GDP)					
	BS	SC-2	SC-3	SC-4		
2011	33,38	32,65	32,65	32,65		
2012	33,53	32,08	32,08	32,08		
2013	33,68	31,50	31,50	31,50		
2014	33,83	30,92	30,92	30,92		
2015	33,97	30,33	30,33	30,33		
2016	34,11	29,74	29,74	29,74		
2017	34,25	29,14	29,14	29,14		
2018	34,39	28,53	28,53	28,53		
2019	34,52	27,92	27,92	27,92		
2020	34,66	27,30	27,30	27,30		
2021	34,78	26,68	26,68	26,68		
2022	34,91	26,05	26,05	26,05		
2023	35,03	25,42	25,42	25,42		
2024	35,16	24,78	24,78	24,78		
2025	35,27	24,13	24,13	24,13		

Appendix C Model Outcomes (2011-2025)

Year	Industrial Sector (% of GDP)					
	BS	SC-2	SC-3	SC-4		
2011	14,36	14,49	14,49	14,49		
2012	14,37	14,64	14,64	14,64		
2013	14,38	14,78	14,78	14,78		
2014	14,39	14,93	14,93	14,93		
2015	14,40	15,08	15,08	15,08		
2016	14,41	15,23	15,23	15,23		
2017	14,42	15,38	15,38	15,38		
2018	14,43	15,54	15,54	15,54		
2019	14,44	15,69	15,69	15,69		
2020	14,45	15,85	15,85	15,85		
2021	14,46	16,01	16,01	16,01		
2022	14,47	16,17	16,17	16,17		
2023	14,48	16,33	16,33	16,33		
2024	14,49	16,49	16,49	16,49		
2025	14,50	16,66	16,66	16,66		

Appendix C Model Outcomes (2011-2025)

Year	Construction Sector (% of GDP)					
	BS	SC-2	SC-3	SC-4		
2011	9,95	9,95	9,95	9,95		
2012	10,02	10,02	10,02	10,02		
2013	10,10	10,10	10,10	10,10		
2014	10,17	10,17	10,17	10,17		
2015	10,25	10,25	10,25	10,25		
2016	10,32	10,32	10,32	10,32		
2017	10,40	10,40	10,40	10,40		
2018	10,47	10,47	10,47	10,47		
2019	10,55	10,55	10,55	10,55		
2020	10,63	10,63	10,63	10,63		
2021	10,71	10,71	10,71	10,71		
2022	10,79	10,79	10,79	10,79		
2023	10,87	10,87	10,87	10,87		
2024	10,95	10,95	10,95	10,95		
2025	11,03	11,03	11,03	11,03		

Appendix C Model Outcomes (2011-2025)

Year	Trade and Public services Sector (% of GDP)					
	BS	SC-2	SC-3	SC-4		
2011	32,30	32,89	32,89	32,89		
2012	32,04	33,22	33,22	33,22		
2013	31,78	33,55	33,55	33,55		
2014	31,52	33,89	33,89	33,89		
2015	31,27	34,22	34,22	34,22		
2016	31,01	34,57	34,57	34,57		
2017	30,76	34,91	34,91	34,91		
2018	30,51	35,26	35,26	35,26		
2019	30,27	35,61	35,61	35,61		
2020	30,02	35,97	35,97	35,97		
2021	29,78	36,33	36,33	36,33		
2022	29,54	36,69	36,69	36,69		
2023	29,30	37,06	37,06	37,06		
2024	29,06	37,43	37,43	37,43		
2025	28,82	37,81	37,81	37,81		

Appendix C Model Outcomes (2011-2025)

Year	Transportation Sector (% of GDP)					
	BS	SC-2	SC-3	SC-4		
2011	10,02	10,02	10,02	10,02		
2012	10,04	10,04	10,04	10,04		
2013	10,07	10,07	10,07	10,07		
2014	10,09	10,09	10,09	10,09		
2015	10,12	10,12	10,12	10,12		
2016	10,14	10,14	10,14	10,14		
2017	10,17	10,17	10,17	10,17		
2018	10,19	10,19	10,19	10,19		
2019	10,22	10,22	10,22	10,22		
2020	10,24	10,24	10,24	10,24		
2021	10,27	10,27	10,27	10,27		
2022	10,30	10,30	10,30	10,30		
2023	10,32	10,32	10,32	10,32		
2024	10,35	10,35	10,35	10,35		
2025	10,37	10,37	10,37	10,37		

Appendix C Model Outcomes (2011-2025)

Year	Energy use (kt of oil equivalent)					
	BS	SC-2	SC-3	SC-4		
2011	12378,80	12859,80	12859,80	12669,30		
2012	12828,00	13815,10	13744,70	13353,90		
2013	13295,20	14850,00	14699,60	14084,80		
2014	13780,10	15967,60	15720,40	14857,10		
2015	14283,50	17174,60	16811,50	15673,50		
2016	14806,00	18478,10	17976,80	16535,80		
2017	15348,60	19885,80	19219,90	17446,00		
2018	15912,10	21406,00	20545,00	18406,30		
2019	16497,30	23047,60	21955,80	19418,60		
2020	17105,00	24820,20	23456,10	20485,00		
2021	17736,30	26734,30	25049,70	21607,70		
2022	18392,10	28801,00	26740,20	22788,60		
2023	19073,30	31032,40	28530,90	24029,70		
2024	19781,10	33441,40	30425,00	25333,00		
2025	20516,40	36042,20	32425,40	26700,40		

Appendix C Model Outcomes (2011-2025)

Year	Agriculture, Fishing and Mining Sector (% of Energy					
	BS	SC-2	SC-3	SC-4		
2011	0,96	0,94	0,94	0,95		
2012	0,91	0,86	0,86	0,89		
2013	0,86	0,79	0,79	0,83		
2014	0,82	0,73	0,73	0,77		
2015	0,77	0,67	0,67	0,72		
2016	0,73	0,62	0,62	0,67		
2017	0,69	0,56	0,56	0,63		
2018	0,65	0,52	0,52	0,58		
2019	0,62	0,47	0,47	0,54		
2020	0,58	0,43	0,43	0,51		
2021	0,55	0,40	0,40	0,47		
2022	0,52	0,36	0,36	0,44		
2023	0,49	0,33	0,33	0,40		
2024	0,47	0,30	0,30	0,37		
2025	0,44	0,28	0,28	0,35		

Appendix C Model Outcomes (2011-2025)

Year	Industrial Sector (% of Energy use)					
	BS	SC-2	SC-3	SC-4		
2011	22,01	22,08	22,08	22,07		
2012	22,06	22,20	22,20	22,19		
2013	22,10	22,33	22,33	22,31		
2014	22,14	22,45	22,45	22,42		
2015	22,18	22,56	22,56	22,53		
2016	22,22	22,68	22,68	22,65		
2017	22,26	22,80	22,80	22,76		
2018	22,29	22,91	22,91	22,87		
2019	22,32	23,02	23,02	22,98		
2020	22,34	23,13	23,13	23,08		
2021	22,37	23,24	23,24	23,19		
2022	22,39	23,35	23,35	23,30		
2023	22,41	23,46	23,46	23,40		
2024	22,42	23,57	23,57	23,51		
2025	22,44	23,68	23,68	23,61		

Appendix C Model Outcomes (2011-2025)

Year	Construction Sector (% of Energy use)					
	BS	SC-2	SC-3	SC-4		
2011	0,99	0,98	0,98	1,00		
2012	0,92	0,91	0,91	0,93		
2013	0,85	0,84	0,84	0,88		
2014	0,79	0,78	0,78	0,82		
2015	0,74	0,72	0,72	0,77		
2016	0,69	0,66	0,66	0,73		
2017	0,64	0,61	0,61	0,68		
2018	0,59	0,57	0,57	0,64		
2019	0,55	0,52	0,52	0,60		
2020	0,51	0,48	0,48	0,56		
2021	0,48	0,45	0,45	0,53		
2022	0,44	0,41	0,41	0,50		
2023	0,41	0,38	0,38	0,47		
2024	0,38	0,35	0,35	0,44		
2025	0,36	0,33	0,33	0,41		

Appendix C Model Outcomes (2011-2025)

Year	Trade and Public services Sector (% of Energy use)					
	BS	SC-2	SC-3	SC-4		
2011	22,37	22,65	22,65	22,80		
2012	22,07	22,61	22,61	22,92		
2013	21,77	22,58	22,58	23,04		
2014	21,46	22,54	22,54	23,16		
2015	21,16	22,50	22,50	23,28		
2016	20,86	22,45	22,45	23,39		
2017	20,57	22,41	22,41	23,51		
2018	20,27	22,36	22,36	23,62		
2019	19,97	22,31	22,31	23,73		
2020	19,68	22,26	22,26	23,85		
2021	19,39	22,21	22,21	23,96		
2022	19,10	22,16	22,16	24,07		
2023	18,82	22,10	22,10	24,18		
2024	18,54	22,05	22,05	24,28		
2025	18,26	21,99	21,99	24,39		

Appendix C Model Outcomes (2011-2025)

Year	Transportation Sector (% of Energy use)					
	BS	SC-2	SC-3	SC-4		
2011	53,67	53,35	53,35	53,18		
2012	54,04	53,41	53,41	53,06		
2013	54,42	53,46	53,46	52,94		
2014	54,78	53,51	53,51	52,82		
2015	55,14	53,55	53,55	52,69		
2016	55,50	53,59	53,59	52,56		
2017	55,85	53,62	53,62	52,43		
2018	56,20	53,65	53,65	52,29		
2019	56,54	53,67	53,67	52,15		
2020	56,88	53,69	53,69	52,00		
2021	57,21	53,70	53,70	51,85		
2022	57,54	53,71	53,71	51,70		
2023	57,87	53,72	53,72	51,55		
2024	58,19	53,73	53,73	51,40		
2025	58,51	53,73	53,73	51,24		

Appendix C Model Outcomes (2011-2025)

Year	Energy Intensity (kToe/BUSD)					
	BS	SC-2	SC-3	SC-4		
2011	114,82	115,50	115,50	113,79		
2012	115,24	116,61	116,61	113,17		
2013	115,68	117,74	117,74	112,58		
2014	116,14	118,90	118,90	111,99		
2015	116,62	120,08	120,08	111,42		
2016	117,11	121,29	121,29	110,86		
2017	117,62	122,52	122,52	110,30		
2018	118,15	123,77	123,77	109,76		
2019	118,69	125,04	125,04	109,23		
2020	119,25	126,34	126,34	108,71		
2021	119,83	127,66	127,66	108,20		
2022	120,42	129,00	129,00	107,70		
2023	121,02	130,36	130,36	107,20		
2024	121,64	131,74	131,74	106,71		
2025	122,28	133,15	133,15	106,23		

Appendix C Model Outcomes (2011-2025)

Year	Energy Intensity in Agriculture, Fishing and Mining					
	BS	SC-2	SC-3	SC-4		
2011	0,03	0,03	0,03	0,03		
2012	0,03	0,03	0,03	0,03		
2013	0,03	0,03	0,03	0,03		
2014	0,02	0,02	0,02	0,03		
2015	0,02	0,02	0,02	0,02		
2016	0,02	0,02	0,02	0,02		
2017	0,02	0,02	0,02	0,02		
2018	0,02	0,02	0,02	0,02		
2019	0,02	0,02	0,02	0,02		
2020	0,02	0,02	0,02	0,02		
2021	0,02	0,01	0,01	0,02		
2022	0,01	0,01	0,01	0,02		
2023	0,01	0,01	0,01	0,02		
2024	0,01	0,01	0,01	0,02		
2025	0,01	0,01	0,01	0,01		

Appendix C Model Outcomes (2011-2025)

Year	Energy Intensity in Industy Sector (kToe/BUSD)					
	BS	SC-2	SC-3	SC-4		
2011	1,53	1,52	1,52	1,52		
2012	1,54	1,52	1,52	1,52		
2013	1,54	1,51	1,51	1,51		
2014	1,54	1,50	1,50	1,50		
2015	1,54	1,50	1,50	1,49		
2016	1,54	1,49	1,49	1,49		
2017	1,54	1,48	1,48	1,48		
2018	1,54	1,47	1,47	1,47		
2019	1,55	1,47	1,47	1,46		
2020	1,55	1,46	1,46	1,46		
2021	1,55	1,45	1,45	1,45		
2022	1,55	1,44	1,44	1,44		
2023	1,55	1,44	1,44	1,43		
2024	1,55	1,43	1,43	1,43		
2025	1,55	1,42	1,42	1,42		

Appendix C Model Outcomes (2011-2025)

Year	Energy Intensity in Construction Sector					
	BS	SC-2	SC-3	SC-4		
2011	0,10	0,10	0,10	0,10		
2012	0,09	0,09	0,09	0,09		
2013	0,08	0,08	0,08	0,09		
2014	0,08	0,08	0,08	0,08		
2015	0,07	0,07	0,07	0,08		
2016	0,07	0,06	0,06	0,07		
2017	0,06	0,06	0,06	0,07		
2018	0,06	0,05	0,05	0,06		
2019	0,05	0,05	0,05	0,06		
2020	0,05	0,05	0,05	0,05		
2021	0,04	0,04	0,04	0,05		
2022	0,04	0,04	0,04	0,05		
2023	0,04	0,04	0,04	0,04		
2024	0,03	0,03	0,03	0,04		
2025	0,03	0,03	0,03	0,04		

Appendix C Model Outcomes (2011-2025)

Year	Energy Intensity in Trade and Public services Sector					
	BS	SC-2	SC-3	SC-4		
2011	0,69	0,69	0,69	0,69		
2012	0,69	0,68	0,68	0,69		
2013	0,68	0,67	0,67	0,69		
2014	0,68	0,67	0,67	0,68		
2015	0,68	0,66	0,66	0,68		
2016	0,67	0,65	0,65	0,68		
2017	0,67	0,64	0,64	0,67		
2018	0,66	0,63	0,63	0,67		
2019	0,66	0,63	0,63	0,67		
2020	0,66	0,62	0,62	0,66		
2021	0,65	0,61	0,61	0,66		
2022	0,65	0,60	0,60	0,66		
2023	0,64	0,60	0,60	0,65		
2024	0,64	0,59	0,59	0,65		
2025	0,63	0,58	0,58	0,65		

Appendix C Model Outcomes (2011-2025)

Year	Energy Intensity in Transportation Sector					
	BS	SC-2	SC-3	SC-4		
2011	5,36	5,33	5,33	5,31		
2012	5,38	5,32	5,32	5,28		
2013	5,41	5,31	5,31	5,26		
2014	5,43	5,30	5,30	5,23		
2015	5,45	5,29	5,29	5,21		
2016	5,47	5,28	5,28	5,18		
2017	5,49	5,27	5,27	5,16		
2018	5,51	5,26	5,26	5,13		
2019	5,53	5,25	5,25	5,10		
2020	5,55	5,24	5,24	5,08		
2021	5,57	5,23	5,23	5,05		
2022	5,59	5,22	5,22	5,02		
2023	5,61	5,20	5,20	4,99		
2024	5,62	5,19	5,19	4,97		
2025	5,64	5,18	5,18	4,94		

Appendix C Model Outcomes (2011-2025)

Year	Fossil fuel energy consumption (% of total)					
	BS	SC-2	SC-3	SC-4		
2011	88,18	88,18	87,24	87,24		
2012	88,27	88,27	86,35	86,35		
2013	88,35	88,35	85,39	85,39		
2014	88,41	88,41	84,37	84,37		
2015	88,45	88,45	83,28	83,28		
2016	88,49	88,49	82,11	82,11		
2017	88,51	88,51	80,85	80,85		
2018	88,51	88,51	79,51	79,51		
2019	88,51	88,51	78,08	78,08		
2020	88,49	88,49	76,54	76,54		
2021	88,46	88,46	74,90	74,90		
2022	88,42	88,42	73,15	73,15		
2023	88,37	88,37	71,27	71,27		
2024	88,31	88,31	69,25	69,25		
2025	88,24	88,24	67,10	67,10		

Appendix C Model Outcomes (2011-2025)

Year	Alternative and nuclear energy (% of total energy					
	BS	SC-2	SC-3	SC-4		
2011	7,20	7,20	7,55	7,55		
2012	7,35	7,35	8,08	8,08		
2013	7,50	7,50	8,65	8,65		
2014	7,65	7,65	9,25	9,25		
2015	7,81	7,81	9,90	9,90		
2016	7,97	7,97	10,59	10,59		
2017	8,13	8,13	11,34	11,34		
2018	8,30	8,30	12,13	12,13		
2019	8,47	8,47	12,98	12,98		
2020	8,64	8,64	13,89	13,89		
2021	8,82	8,82	14,86	14,86		
2022	9,00	9,00	15,90	15,90		
2023	9,18	9,18	17,01	17,01		
2024	9,37	9,37	18,20	18,20		
2025	9,56	9,56	19,48	19,48		

Appendix C Model Outcomes (2011-2025)

Year	Combustible renewables and waste (% of total					
	BS	SC-2	SC-3	SC-4		
2011	4,61	4,61	5,20	5,20		
2012	4,38	4,38	5,57	5,57		
2013	4,15	4,15	5,96	5,96		
2014	3,94	3,94	6,38	6,38		
2015	3,74	3,74	6,82	6,82		
2016	3,54	3,54	7,30	7,30		
2017	3,36	3,36	7,81	7,81		
2018	3,19	3,19	8,36	8,36		
2019	3,03	3,03	8,94	8,94		
2020	2,87	2,87	9,57	9,57		
2021	2,72	2,72	10,24	10,24		
2022	2,58	2,58	10,96	10,96		
2023	2,45	2,45	11,72	11,72		
2024	2,32	2,32	12,54	12,54		
2025	2,20	2,20	13,42	13,42		

Appendix C Model Outcomes (2011-2025)

Year	Gaseous fuel consumption (% Total Fosil Energy)					
	BS	SC-2	SC-3	SC-4		
2011	0,01	0,01	0,01	0,01		
2012	0,01	0,01	0,01	0,01		
2013	0,01	0,01	0,01	0,01		
2014	0,01	0,01	0,01	0,01		
2015	0,01	0,01	0,01	0,01		
2016	0,01	0,01	0,01	0,01		
2017	0,01	0,01	0,01	0,01		
2018	0,01	0,01	0,01	0,01		
2019	0,01	0,01	0,01	0,01		
2020	0,01	0,01	0,01	0,01		
2021	0,01	0,01	0,01	0,01		
2022	0,01	0,01	0,01	0,01		
2023	0,01	0,01	0,01	0,01		
2024	0,01	0,01	0,01	0,01		
2025	0,01	0,01	0,01	0,01		

Appendix C Model Outcomes (2011-2025)

Year	Solid fuel consumption (% Total Fosil Energy)					
	BS	SC-2	SC-3	SC-4		
2011	0,00	0,00	0,00	0,00		
2012	0,00	0,00	0,00	0,00		
2013	0,00	0,00	0,00	0,00		
2014	0,00	0,00	0,00	0,00		
2015	0,00	0,00	0,00	0,00		
2016	0,00	0,00	0,00	0,00		
2017	0,00	0,00	0,00	0,00		
2018	0,00	0,00	0,00	0,00		
2019	0,00	0,00	0,00	0,00		
2020	0,00	0,00	0,00	0,00		
2021	0,00	0,00	0,00	0,00		
2022	0,00	0,00	0,00	0,00		
2023	0,00	0,00	0,00	0,00		
2024	0,00	0,00	0,00	0,00		
2025	0,00	0,00	0,00	0,00		

Appendix C Model Outcomes (2011-2025)

Year	Liquid fuel consumption (% Total Fosil Energy)					
	BS	SC-2	SC-3	SC-4		
2011	0,88	0,88	0,87	0,87		
2012	0,88	0,88	0,86	0,86		
2013	0,88	0,88	0,85	0,85		
2014	0,88	0,88	0,84	0,84		
2015	0,88	0,88	0,83	0,83		
2016	0,88	0,88	0,81	0,81		
2017	0,88	0,88	0,80	0,80		
2018	0,88	0,88	0,79	0,79		
2019	0,88	0,88	0,77	0,77		
2020	0,88	0,88	0,76	0,76		
2021	0,88	0,88	0,74	0,74		
2022	0,88	0,88	0,72	0,72		
2023	0,88	0,88	0,71	0,71		
2024	0,88	0,88	0,69	0,69		
2025	0,88	0,88	0,66	0,66		

Appendix C Model Outcomes (2011-2025)

Year	CO2 in Agriculture, Fishing and Mining Sector					
	BS	SC-2	SC-3	SC-4		
2011	318,20	321,50	318,20	318,20		
2012	312,56	318,30	310,03	310,35		
2013	306,93	315,06	301,83	302,47		
2014	301,30	311,72	293,39	294,39		
2015	295,67	308,26	284,73	286,10		
2016	290,05	304,68	275,83	277,59		
2017	284,46	300,98	266,67	268,86		
2018	278,89	297,15	257,26	259,88		
2019	273,35	293,17	247,58	250,66		
2020	267,86	289,05	237,64	241,19		
2021	262,40	284,78	227,44	231,47		
2022	256,99	280,36	216,98	221,49		
2023	251,63	275,78	206,27	211,26		
2024	246,33	271,02	195,33	200,78		
2025	241,08	266,10	184,17	190,07		

7.3 Appendix C

Appendix C Model Outcomes (2011-2025)

Year	CO2 in Industrial Sector (kTons)					
	BS	SC-2	SC-3	SC-4		
2011	7275,23	7583,27	7505,36	7391,86		
2012	7563,30	8200,15	7987,11	7755,35		
2013	7861,33	8869,90	8497,19	8134,83		
2014	8169,06	9594,82	9030,72	8525,55		
2015	8486,86	10379,51	9587,19	8926,64		
2016	8815,09	11228,88	10165,33	9336,64		
2017	9154,12	12148,06	10763,33	9753,73		
2018	9504,31	13142,91	11378,65	10175,67		
2019	9866,04	14219,42	12008,20	10599,78		
2020	10239,72	15384,19	12647,93	11022,65		
2021	10625,78	16644,26	13292,67	11440,60		
2022	11024,47	18007,37	13936,45	11849,01		
2023	11436,52	19481,82	14571,80	12242,44		
2024	11862,05	21076,42	15189,73	12614,67		
2025	12301,68	22800,74	15779,97	12958,47		

Appendix C Model Outcomes (2011-2025)

Year	CO2 in Construction Sector (kTons)					
	BS	SC-2	SC-3	SC-4		
2011	325,98	336,66	333,20	333,20		
2012	314,65	334,89	326,19	326,53		
2013	303,66	333,24	319,24	319,92		
2014	292,98	331,61	312,12	313,17		
2015	282,61	330,01	304,82	306,28		
2016	272,54	328,43	297,32	299,22		
2017	262,78	326,86	289,60	291,98		
2018	253,32	325,31	281,64	284,52		
2019	244,16	323,78	273,43	276,83		
2020	235,28	322,25	264,93	268,89		
2021	226,69	320,73	256,15	260,68		
2022	218,37	319,21	247,05	252,19		
2023	210,33	317,70	237,63	243,38		
2024	202,56	316,18	227,87	234,24		
2025	195,04	314,66	217,77	224,75		

Appendix C Model Outcomes (2011-2025)

Year	CO2 in Trade and Public services Sector (kTons)					
	BS	SC-2	SC-3	SC-4		
2011	7396,62	7778,20	7698,28	7635,80		
2012	7568,04	8351,52	8134,55	8011,28		
2013	7742,01	8969,84	8592,93	8403,28		
2014	7918,00	9634,38	9067,96	8806,90		
2015	8096,10	10348,70	9558,73	9221,24		
2016	8276,40	11116,45	10063,56	9644,77		
2017	8458,95	11941,51	10580,29	10075,62		
2018	8643,83	12828,22	11106,21	10511,52		
2019	8831,09	13780,91	11637,90	10949,57		
2020	9020,80	14804,38	12171,22	11386,48		
2021	9213,01	15903,89	12701,36	11818,22		
2022	9407,79	17084,80	13222,48	12240,08		
2023	9605,18	18353,18	13727,56	12646,43		
2024	9805,25	19715,14	14208,74	13030,95		
2025	10008,05	21177,49	14656,49	13386,21		

Appendix C Model Outcomes (2011-2025)

Year	CO2 in Transportation Sector (kTons)					
	BS	SC-2	SC-3	SC-4		
2011	17831,44	18415,35	18219,15	17890,24		
2012	18626,94	19825,21	19294,93	18623,73		
2013	19454,23	21349,38	20427,19	19382,05		
2014	20313,11	22991,69	21603,38	20153,22		
2015	21204,80	24761,42	22821,06	20934,48		
2016	22130,60	26668,48	24076,37	21721,74		
2017	23092,04	28723,14	25363,96	22510,32		
2018	24090,23	30936,62	26676,97	23294,65		
2019	25126,78	33321,03	28007,16	24067,94		
2020	26203,21	35889,28	29343,98	24822,51		
2021	27320,94	38655,21	30674,97	25549,67		
2022	28481,48	41633,66	31985,16	26238,96		
2023	29686,64	44840,68	33256,71	26878,77		
2024	30938,06	48293,12	34468,86	27455,73		
2025	32237,44	52009,47	35597,12	27954,56		

Appendix C Model Outcomes (2011-2025)

Year	CO2int (kt/kToe)					
	BS	SC-2	SC-3	SC-4		
2011	2,68	2,68	2,65	2,65		
2012	2,68	2,68	2,62	2,62		
2013	2,68	2,68	2,59	2,59		
2014	2,68	2,68	2,56	2,56		
2015	2,69	2,69	2,53	2,53		
2016	2,69	2,69	2,50	2,50		
2017	2,69	2,69	2,46	2,46		
2018	2,69	2,69	2,42	2,42		
2019	2,69	2,69	2,38	2,38		
2020	2,69	2,69	2,33	2,33		
2021	2,69	2,69	2,28	2,28		
2022	2,69	2,68	2,23	2,23		
2023	2,68	2,68	2,17	2,17		
2024	2,68	2,68	2,11	2,11		
2025	2,68	2,68	2,05	2,05		

Appendix C Model Outcomes (2011-2025)

Year	CO2pc-(kgCO2)					
	BS	SC-2	SC-3	SC-4		
2011	2261,64	2349,48	2324,87	2290,42		
2012	2316,00	2494,13	2428,31	2359,23		
2013	2371,57	2648,78	2535,81	2429,71		
2014	2428,17	2813,44	2645,63	2500,29		
2015	2485,89	2988,82	2757,41	2570,69		
2016	2544,72	3175,53	2870,53	2640,36		
2017	2604,74	3374,33	2984,32	2708,81		
2018	2665,95	3585,93	3097,91	2775,38		
2019	2728,40	3811,17	3210,37	2839,36		
2020	2792,11	4050,83	3320,50	2899,92		
2021	2857,14	4305,84	3427,01	2956,19		
2022	2923,49	4577,12	3528,38	3007,10		
2023	2991,21	4865,67	3622,85	3051,51		
2024	3060,35	5172,58	3708,50	3088,16		
2025	3130,92	5498,90	3783,04	3115,59		

7. APPENDIX

Appendix C Model Outcomes (2011-2025)

Year	CO2-Total					
	BS	SC-2	SC-3	SC-4		
2011	33147,48	34434,98	34074,18	33569,31		
2012	34385,49	37030,08	36052,81	35027,23		
2013	35668,15	39837,42	38138,37	36542,54		
2014	36994,44	42864,22	40307,57	38093,23		
2015	38366,03	46127,91	42556,53	39674,73		
2016	39784,68	49646,92	44878,40	41279,96		
2017	41252,35	53440,55	47263,85	42900,51		
2018	42770,58	57530,22	49700,73	44526,25		
2019	44341,42	61938,30	52174,27	46144,78		
2020	45966,86	66689,16	54665,71	47741,72		
2021	47648,81	71808,88	57152,58	49300,65		
2022	49389,10	77325,40	59608,12	50801,72		
2023	51190,31	83269,15	61999,96	52222,27		
2024	53054,24	89671,89	64290,53	53536,37		
2025	54983,30	96568,46	66435,51	54714,07		

Appendix C Outcomes of Economic Model (2011-2025)

Year	qt-bs	IT	TBT	CHT	EIMPT	RNT
2011	120,42	30,96	-1,01	74,84	-17380,48	1371,30
2012	124,76	32,14	-0,98	77,14	-17549,54	1377,58
2013	129,14	33,41	-1,00	79,49	-17791,30	1391,00
2014	133,76	34,78	-1,02	81,88	-17976,80	1406,31
2015	138,61	36,27	-1,04	84,34	-18172,25	1426,71
2016	143,72	37,87	-1,07	86,85	-18349,82	1450,47
2017	149,10	39,60	-1,08	89,41	-18526,96	1475,83
2018	154,75	41,47	-1,09	92,04	-18697,68	1503,57
2019	160,69	43,47	-1,09	94,72	-18865,76	1532,50
2020	166,91	45,61	-1,07	97,45	-19028,59	1563,21
2021	173,40	47,89	-1,06	100,23	-19185,72	1595,26
2022	180,01	50,31	-1,12	103,05	-19335,30	1628,48
2023	186,97	52,87	-1,14	105,92	-19475,94	1664,81
2024	194,19	55,56	-1,15	108,84	-19606,41	1703,33
2025	201,66	58,36	-1,15	111,81	-19727,30	1743,91

Appendix C Outcomes of Economic Model (2011-2025)

Year	qt-SC-2	IT	TBT	CHT	EIMPT	RNT
2011	121,05	31,28	-1,62	76,24	-17820,16	1457,03
2012	126,83	32,76	-1,55	79,85	-18662,95	1574,61
2013	132,87	34,30	-1,47	83,63	-19545,60	1701,69
2014	139,19	35,93	-1,40	87,58	-20469,99	1839,08
2015	145,81	37,63	-1,34	91,72	-21438,10	1987,64
2016	152,72	39,41	-1,27	96,06	-22452,00	2148,33
2017	159,96	41,27	-1,21	100,60	-23513,85	2322,17
2018	167,52	43,22	-1,16	105,36	-24625,91	2510,28
2019	175,44	45,27	-1,10	110,34	-25790,57	2713,87
2020	183,72	47,41	-1,05	115,56	-27010,32	2934,28
2021	192,38	49,65	-1,00	121,03	-28287,75	3172,95
2022	201,44	52,00	-0,95	126,75	-29625,59	3431,45
2023	210,93	54,46	-0,91	132,75	-31026,71	3711,48
2024	220,86	57,03	-0,86	139,03	-32494,09	4014,91
2025	231,25	59,73	-0,82	145,60	-34030,87	4343,77

Appendix C Outcomes of Economic Model (2011-2025)

Year	qt-SC-3	IT	TBT	CHT	EIMPT	RNT
2011	121,17	31,28	-1,62	76,24	-17820,16	1468,03
2012	127,08	32,76	-1,55	79,85	-18662,95	1593,72
2013	133,26	34,30	-1,47	83,63	-19545,60	1733,46
2014	139,73	35,93	-1,40	87,58	-20469,99	1885,50
2015	146,51	37,63	-1,34	91,72	-21438,10	2053,08
2016	153,60	39,41	-1,27	96,06	-22452,00	2237,38
2017	161,03	41,27	-1,21	100,60	-23513,85	2437,66
2018	168,81	43,22	-1,16	105,36	-24625,91	2658,04
2019	176,96	45,27	-1,10	110,34	-25790,57	2898,68
2020	185,50	47,41	-1,05	115,56	-27010,32	3162,69
2021	194,46	49,65	-1,00	121,03	-28287,75	3451,48
2022	203,84	52,00	-0,95	126,75	-29625,59	3767,57
2023	213,67	54,46	-0,91	132,75	-31026,71	4113,98
2024	223,99	57,03	-0,86	139,03	-32494,09	4493,14
2025	234,80	59,73	-0,82	145,60	-34030,87	4908,67

Appendix C Outcomes of Economic Model (2011-2025)

Year	qt-SC-4	IT	TBT	CHT	EIMPT	RNT
2011	121,16	31,28	-1,62	76,24	-17820,16	1457,03
2012	127,05	32,76	-1,55	79,85	-18662,95	1574,61
2013	133,22	34,30	-1,47	83,63	-19545,60	1701,69
2014	139,68	35,93	-1,40	87,58	-20469,99	1839,08
2015	146,43	37,63	-1,34	91,72	-21438,10	1987,64
2016	153,50	39,41	-1,27	96,06	-22452,00	2148,33
2017	160,90	41,27	-1,21	100,60	-23513,85	2322,17
2018	168,64	43,22	-1,16	105,36	-24625,91	2510,28
2019	176,75	45,27	-1,10	110,34	-25790,57	2713,87
2020	185,24	47,41	-1,05	115,56	-27010,32	2934,28
2021	194,13	49,65	-1,00	121,03	-28287,75	3172,95
2022	203,45	52,00	-0,95	126,75	-29625,59	3431,45
2023	213,21	54,46	-0,91	132,75	-31026,71	3711,48
2024	223,43	57,03	-0,86	139,03	-32494,09	4014,91
2025	234,15	59,73	-0,82	145,60	-34030,87	4343,77

7.4 **Appendix D**

Appendix D presents the outcomes of the LDMI analysis (Chapter 4) year by year for the four considered scenarios in the period 1980-2025.

Appendix D LMDI (Additive decomposition)

Time (year)	Cact			
	BS	SC-2	SC-3	SC-4
1980				
1981	287,03	287,03	287,03	287,03
1982	218,74	218,74	218,74	218,74
1983	233,95	233,95	233,95	233,95
1984	252,18	252,18	252,18	252,18
1985	274,16	274,16	274,16	274,16
1986	304,42	304,42	304,42	304,42
1987	327,24	327,24	327,24	327,24
1988	343,98	343,98	343,98	343,98
1989	355,24	355,24	355,24	355,24
1990	357,65	357,65	357,65	357,65
1991	354,00	354,00	354,00	354,00
1992	344,55	344,55	344,55	344,55
1993	337,45	337,45	337,45	337,45
1994	342,63	342,63	342,63	342,63
1995	360,00	360,00	360,00	360,00
1996	388,55	388,55	388,55	388,55
1997	483,74	483,74	483,74	483,74
1998	416,74	416,74	416,74	416,74
1999	558,91	558,91	558,91	558,91
2000	651,84	651,84	651,84	651,84
2001	767,89	767,89	767,89	767,89
2002	879,43	879,43	879,43	879,43
2003	979,28	979,28	979,28	979,28
2004	1067,85	1067,85	1067,85	1067,85
2005	1130,62	1130,62	1130,62	1130,62
2006	1169,41	1169,41	1169,41	1169,41
2007	1183,17	1183,17	1183,17	1183,17
2008	1179,34	1179,34	1179,34	1179,34
2009	1174,93	1174,93	1174,93	1174,93
2010	1164,27	1164,27	1164,27	1164,27
2011	1081,51	2170,74	2159,21	2143,00
2012	1079,23	2217,49	1997,48	1989,30
2013	1118,67	2403,44	2131,72	2096,08
2014	1157,50	2594,22	2248,76	2186,58
2015	1197,25	2800,80	2369,83	2279,26
2016	1238,59	3023,57	2492,21	2372,24
2017	1282,14	3263,28	2615,84	2464,75
2018	1326,67	3521,67	2738,73	2556,78
2019	1373,14	3800,22	2860,63	2646,59
2020	1421,26	4100,41	2979,62	2734,21
2021	1471,37	4423,47	3094,31	2817,74
2022	1522,84	4771,65	3202,30	2896,51
2023	1576,98	5145,94	3302,25	2969,14
2024	1632,20	5549,76	3391,78	3033,94
2025	1690,13	5983,78	3468,41	3089,15

Appendix D LMDI (Multiplicative decomposition)

Time (year)	Dact			
	BS	SC-2	SC-3	SC-4
1980				
1981	1,02306775	1,02306775	1,02306775	1,02306775
1982	1,01729471	1,01729471	1,01729471	1,01729471
1983	1,01831468	1,01831468	1,01831468	1,01831468
1984	1,0195464	1,0195464	1,0195464	1,0195464
1985	1,02103268	1,02103268	1,02103268	1,02103268
1986	1,0230925	1,0230925	1,0230925	1,0230925
1987	1,02449141	1,02449141	1,02449141	1,02449141
1988	1,02534176	1,02534176	1,02534176	1,02534176
1989	1,02569218	1,02569218	1,02569218	1,02569218
1990	1,02530825	1,02530825	1,02530825	1,02530825
1991	1,02442633	1,02442633	1,02442633	1,02442633
1992	1,02309533	1,02309533	1,02309533	1,02309533
1993	1,02188192	1,02188192	1,02188192	1,02188192
1994	1,02140375	1,02140375	1,02140375	1,02140375
1995	1,02157854	1,02157854	1,02157854	1,02157854
1996	1,02227516	1,02227516	1,02227516	1,02227516
1997	1,02647545	1,02647545	1,02647545	1,02647545
1998	1,02169123	1,02169123	1,02169123	1,02169123
1999	1,02782945	1,02782945	1,02782945	1,02782945
2000	1,03093492	1,03093492	1,03093492	1,03093492
2001	1,03473132	1,03473132	1,03473132	1,03473132
2002	1,03788529	1,03788529	1,03788529	1,03788529
2003	1,040216	1,040216	1,040216	1,040216
2004	1,04191305	1,04191305	1,04191305	1,04191305
2005	1,04255594	1,04255594	1,04255594	1,04255594
2006	1,04238399	1,04238399	1,04238399	1,04238399
2007	1,04146234	1,04146234	1,04146234	1,04146234
2008	1,04010946	1,04010946	1,04010946	1,04010946
2009	1,03889761	1,03889761	1,03889761	1,03889761
2010	1,0375984	1,0375984	1,0375984	1,0375984
2011	1,03380978	1,067658	1,06765799	1,06765819
2012	1,03248146	1,06405305	1,05863745	1,05972431
2013	1,03245676	1,06456094	1,05916476	1,06033309
2014	1,03237614	1,06477639	1,05902367	1,06035297
2015	1,03228788	1,06499812	1,05888038	1,06037764
2016	1,03220873	1,0652053	1,05867765	1,06036608
2017	1,03215286	1,0653884	1,05843451	1,06031492
2018	1,03208618	1,06555845	1,05812789	1,06024123
2019	1,03203165	1,06571684	1,05777807	1,06012207
2020	1,03197996	1,06586366	1,05737286	1,05998058
2021	1,03193708	1,06599303	1,05691516	1,05979708
2022	1,03188773	1,06611431	1,0563932	1,05958277
2023	1,03185821	1,06621545	1,05581889	1,05933712
2024	1,03181365	1,06631657	1,05518889	1,05905586
2025	1,03178589	1,06639954	1,054502	1,0587366

Appendix D LMDI (Additive decomposition)

Time (year)	Cint			
	BS	SC-2	SC-3	SC-4
1980				
1981	62,22	62,22	62,22	62,22
1982	59,04	59,04	59,04	59,04
1983	47,28	47,28	47,28	47,28
1984	31,20	31,20	31,20	31,20
1985	11,38	11,38	11,38	11,38
1986	-7,59	-7,59	-7,59	-7,59
1987	-23,41	-23,41	-23,41	-23,41
1988	-36,87	-36,87	-36,87	-36,87
1989	-44,03	-44,03	-44,03	-44,03
1990	-45,60	-45,60	-45,60	-45,60
1991	-38,22	-38,22	-38,22	-38,22
1992	-20,30	-20,30	-20,30	-20,30
1993	7,78	7,78	7,78	7,78
1994	43,79	43,79	43,79	43,79
1995	85,11	85,11	85,11	85,11
1996	119,85	119,85	119,85	119,85
1997	145,13	145,13	145,13	145,13
1998	165,94	165,94	165,94	165,94
1999	180,58	180,58	180,58	180,58
2000	175,06	175,06	175,06	175,06
2001	171,92	171,92	171,92	171,92
2002	167,53	167,53	167,53	167,53
2003	131,34	131,34	131,34	131,34
2004	79,85	79,85	79,85	79,85
2005	23,83	23,83	23,83	23,83
2006	-31,50	-31,50	-31,50	-31,50
2007	-80,46	-80,46	-80,46	-80,46
2008	-114,22	-114,22	-114,22	-114,22
2009	-125,83	-125,83	-125,83	-125,83
2010	-134,78	-134,78	-134,78	-134,78
2011	112,97	114,91	114,30	-267,80
2012	119,45	125,48	123,14	-279,39
2013	126,15	136,71	131,95	-290,28
2014	133,09	148,79	141,13	-301,51
2015	140,32	161,85	150,69	-312,97
2016	147,75	175,84	160,50	-324,61
2017	155,56	191,03	170,71	-336,31
2018	163,61	207,30	181,10	-348,07
2019	171,94	224,81	191,66	-359,82
2020	180,63	243,74	202,39	-371,35
2021	189,62	264,07	213,12	-382,60
2022	198,95	285,97	223,80	-393,46
2023	208,69	309,62	234,35	-403,71
2024	218,69	334,94	244,47	-413,23
2025	229,19	362,36	254,21	-421,78

Appendix D LMDI (Additive decomposition)

Time (year)	Cmix			
	BS	SC-2	SC-3	SC-4
1980				
1981	-67,92	-67,92	-67,92	-67,92
1982	-69,79	-69,79	-69,79	-69,79
1983	-67,76	-67,76	-67,76	-67,76
1984	-60,42	-60,42	-60,42	-60,42
1985	-47,07	-47,07	-47,07	-47,07
1986	-29,79	-29,79	-29,79	-29,79
1987	-7,48	-7,48	-7,48	-7,48
1988	17,09	17,09	17,09	17,09
1989	44,32	44,32	44,32	44,32
1990	70,60	70,60	70,60	70,60
1991	91,62	91,62	91,62	91,62
1992	109,16	109,16	109,16	109,16
1993	124,18	124,18	124,18	124,18
1994	139,51	139,51	139,51	139,51
1995	153,13	153,13	153,13	153,13
1996	158,21	158,21	158,21	158,21
1997	160,51	160,51	160,51	160,51
1998	161,17	161,17	161,17	161,17
1999	160,17	160,17	160,17	160,17
2000	165,74	165,74	165,74	165,74
2001	170,23	170,23	170,23	170,23
2002	168,94	168,94	168,94	168,94
2003	159,60	159,60	159,60	159,60
2004	143,02	143,02	143,02	143,02
2005	118,49	118,49	118,49	118,49
2006	89,52	89,52	89,52	89,52
2007	67,98	67,98	67,98	67,98
2008	56,95	56,95	56,95	56,95
2009	54,60	54,60	54,60	54,60
2010	54,48	54,48	54,48	54,48
2011	39,19	42,80	-302,02	-300,55
2012	34,66	39,44	-348,29	-341,40
2013	30,09	35,99	-398,89	-385,48
2014	25,38	32,06	-456,95	-435,38
2015	20,45	27,54	-523,44	-491,82
2016	15,41	22,50	-599,54	-555,60
2017	10,13	16,74	-686,57	-627,64
2018	4,64	10,24	-785,97	-708,94
2019	-1,06	2,92	-899,65	-800,84
2020	-7,02	-5,33	-1029,33	-904,48
2021	-13,21	-14,57	-1177,22	-1021,40
2022	-19,68	-24,95	-1345,80	-1153,29
2023	-26,43	-36,55	-1537,76	-1301,94
2024	-33,53	-49,60	-1756,02	-1469,33
2025	-40,92	-64,10	-2004,23	-1658,00

Appendix D LMDI (Additive decomposition)

Time (year)	Cemf			
	BS	SC-2	SC-3	SC-4
1980				
1981	0,00	0,00	0,00	0,00
1982	0,00	0,00	0,00	0,00
1983	0,00	0,00	0,00	0,00
1984	0,00	0,00	0,00	0,00
1985	0,00	0,00	0,00	0,00
1986	0,00	0,00	0,00	0,00
1987	0,00	0,00	0,00	0,00
1988	0,00	0,00	0,00	0,00
1989	0,00	0,00	0,00	0,00
1990	0,00	0,00	0,00	0,00
1991	0,00	0,00	0,00	0,00
1992	0,00	0,00	0,00	0,00
1993	0,00	0,00	0,00	0,00
1994	0,00	0,00	0,00	0,00
1995	0,00	0,00	0,00	0,00
1996	0,00	0,00	0,00	0,00
1997	0,00	0,00	0,00	0,00
1998	0,00	0,00	0,00	0,00
1999	0,00	0,00	0,00	0,00
2000	0,00	0,00	0,00	0,00
2001	0,00	0,00	0,00	0,00
2002	0,00	0,00	0,00	0,00
2003	0,00	0,00	0,00	0,00
2004	0,00	0,00	0,00	0,00
2005	0,00	0,00	0,00	0,00
2006	0,00	0,00	0,00	0,00
2007	0,00	0,00	0,00	0,00
2008	0,00	0,00	0,00	0,00
2009	0,00	0,00	0,00	0,00
2010	0,00	0,00	0,00	0,00
2011	0,00	0,00	0,00	0,00
2012	0,00	0,00	0,00	0,00
2013	0,00	0,00	0,00	0,00
2014	0,00	0,00	0,00	0,00
2015	0,00	0,00	0,00	0,00
2016	0,00	0,00	0,00	0,00
2017	0,00	0,00	0,00	0,00
2018	0,00	0,00	0,00	0,00
2019	0,00	0,00	0,00	0,00
2020	0,00	0,00	0,00	0,00
2021	0,00	0,00	0,00	0,00
2022	0,00	0,00	0,00	0,00
2023	0,00	0,00	0,00	0,00
2024	0,00	0,00	0,00	0,00
2025	0,00	0,00	0,00	0,00

Appendix D LMDI (Additive decomposition)

Time (year)	Ctot			
	BS	SC-2	SC-3	SC-4
1980				
1981	279,64	279,64	279,64	279,64
1982	206,67	206,67	206,67	206,67
1983	212,07	212,07	212,07	212,07
1984	221,99	221,99	221,99	221,99
1985	238,01	238,01	238,01	238,01
1986	268,21	268,21	268,21	268,21
1987	298,98	298,98	298,98	298,98
1988	330,22	330,22	330,22	330,22
1989	365,87	365,87	365,87	365,87
1990	398,66	398,66	398,66	398,66
1991	430,62	430,62	430,62	430,62
1992	464,39	464,39	464,39	464,39
1993	509,53	509,53	509,53	509,53
1994	576,70	576,70	576,70	576,70
1995	659,06	659,06	659,06	659,06
1996	729,62	729,62	729,62	729,62
1997	848,92	848,92	848,92	848,92
1998	793,35	793,35	793,35	793,35
1999	933,02	933,02	933,02	933,02
2000	1004,48	1004,48	1004,48	1004,48
2001	1093,98	1093,98	1093,98	1093,98
2002	1173,53	1173,53	1173,53	1173,53
2003	1202,90	1202,90	1202,90	1202,90
2004	1200,22	1200,22	1200,22	1200,22
2005	1163,55	1163,55	1163,55	1163,55
2006	1098,95	1098,95	1098,95	1098,95
2007	1023,90	1023,90	1023,90	1023,90
2008	960,22	960,22	960,22	960,22
2009	928,74	928,74	928,74	928,74
2010	900,73	900,73	900,73	900,73
2011	1222,11	2441,63	2084,06	1686,51
2012	1222,43	2504,73	1892,39	1486,36
2013	1264,55	2707,82	1991,90	1543,69
2014	1306,16	2916,89	2067,52	1578,82
2015	1349,26	3143,37	2139,78	1609,88
2016	1393,67	3386,80	2203,80	1633,41
2017	1440,53	3648,58	2258,79	1648,29
2018	1488,70	3930,61	2301,23	1653,60
2019	1538,91	4234,33	2328,78	1646,18
2020	1591,02	4561,22	2337,63	1624,96
2021	1644,96	4912,33	2323,73	1586,39
2022	1700,43	5290,25	2282,28	1528,30
2023	1759,35	5697,00	2209,72	1448,21
2024	1818,77	6134,23	2099,14	1341,50
2025	1881,51	6604,27	1945,13	1204,64

Appendix D LMDI (Additive decomposition)

Time (year)	Cstr			
	BS	SC-2	SC-3	SC-4
1980				
1981	-1,69	-1,69	-1,69	-1,69
1982	-1,32	-1,32	-1,32	-1,32
1983	-1,40	-1,40	-1,40	-1,40
1984	-0,96	-0,96	-0,96	-0,96
1985	-0,45	-0,45	-0,45	-0,45
1986	1,16	1,16	1,16	1,16
1987	2,63	2,63	2,63	2,63
1988	6,01	6,01	6,01	6,01
1989	10,34	10,34	10,34	10,34
1990	16,00	16,00	16,00	16,00
1991	23,21	23,21	23,21	23,21
1992	30,99	30,99	30,99	30,99
1993	40,13	40,13	40,13	40,13
1994	50,78	50,78	50,78	50,78
1995	60,82	60,82	60,82	60,82
1996	63,01	63,01	63,01	63,01
1997	59,55	59,55	59,55	59,55
1998	49,49	49,49	49,49	49,49
1999	33,36	33,36	33,36	33,36
2000	11,84	11,84	11,84	11,84
2001	-16,07	-16,07	-16,07	-16,07
2002	-42,37	-42,37	-42,37	-42,37
2003	-67,32	-67,32	-67,32	-67,32
2004	-90,51	-90,51	-90,51	-90,51
2005	-109,39	-109,39	-109,39	-109,39
2006	-128,47	-128,47	-128,47	-128,47
2007	-146,79	-146,79	-146,79	-146,79
2008	-161,85	-161,85	-161,85	-161,85
2009	-174,96	-174,96	-174,96	-174,96
2010	-183,24	-183,24	-183,24	-183,24
2011	-11,56	113,18	112,58	111,86
2012	-10,91	122,31	120,05	117,85
2013	-10,37	131,68	127,13	123,37
2014	-9,80	141,82	134,57	129,13
2015	-8,76	153,18	142,70	135,41
2016	-8,07	164,90	150,62	141,38
2017	-7,30	177,54	158,81	147,48
2018	-6,22	191,39	167,38	153,83
2019	-5,11	206,37	176,15	160,25
2020	-3,86	222,40	184,94	166,59
2021	-2,82	239,36	193,52	172,65
2022	-1,68	257,58	201,99	178,55
2023	0,12	277,98	210,88	184,72
2024	1,41	299,13	218,91	190,11
2025	3,11	322,23	226,74	195,28

7.5 Appendix E

Appendix E presents values of CO_2-income elasticity for Ecuador (2011-2025). Figure 5.5 in Chapter 5 is based on this data.

Appendix E Evolution of CO2-income elasticity for Ecuador (2011-2025)

Year	BS	SC-2	SC-3	SC-4
2011	1,1127	1,42	1,388	1,395
2012	1,107	1,376	1,3	1,31
2013	1,091	1,407	1,288	1,312
2014	1,096	1,415	1,314	1,373
2015	1,102	1,416	1,292	1,347
2016	1,106	1,406	1,248	1,282
2017	1,11	1,383	1,189	1,184
2018	1,112	1,35	1,126	1,071
2019	1,115	1,313	1,069	0,964
2020	1,116	1,278	1,023	0,873
2021	1,118	1,248	0,986	0,801
2022	1,12	1,225	0,958	0,745
2023	1,121	1,208	0,935	0,703
2024	1,122	1,194	0,916	0,669
2025	1,123	1,185	0,898	0,641

7.6 Appendix F

Appendix F presents the programming of the model in Vensim platform. Note that the programming is based on the equation system of Section 3.7 in Chapter 3.

7. APPENDIX

```
(001)   c= INTEG (
                "c %",
                        2.83148e+010)
(002)   "c %"=
                IF THEN ELSE(Time<2010,c*c r/100,c*"esc-c"/100)
(003)   c r = WITH LOOKUP (
                Time,
                        ([(1980,2)-(2025,4)],(1980,3.33),(1981,3.22),(1982,3.13),(1983,3.1),(1984
        ,3.09),(1985,3.07),(1986,2.99),(1987,2.86),(1988,2.71),(1989,2.55),(1990,2.41
        ),(1991,2.27),(1992,2.15),(1993,2.07),(1994,2.03),(1995,2.05),(1996,2.14),
        (1997,2.29),(1998,2.5),(1999,2.83),(2000,3.18),(2001,3.44),(2002,3.61),(2003
        ,3.71),(2004,3.75),(2005,3.77),(2006,3.77),(2007,3.76),(2008,3.73),(2009,3.63
        ),(2010,2.96),(2025,2.96) ))
(004)   c11=
                e11*uT1
(005)   c12=
                e12*uT2
(006)   c13=
                e13*uT3
(007)   c21=
                e21*uT1
(008)   c22=
                e22*uT2
(009)   c23=
                e23*uT3
(010)   c31=
                e31*uT1
(011)   c32=
                e32*uT2
(012)   c33=
                e33*uT3
(013)   c41=
                e41*uT1
(014)   c42=
                e42*uT2
(015)   c43=
                e43*uT3
(016)   c51=
                e51*uT1
(017)   c52=
                e52*uT2
(018)   c53=
                e53*uT3
(019)   CO2=
                c11+c12+c13+c21+c22+c23+c31+c32+c33+c41+c42+c43+c51+c52+c53
(020)   "CO2-s"=
                E*"co2int-s"
(021)   "co2int-c"=
                CO2/E
(022)   "co2int-s"=
```

```
                0.0303*es1
(023)   E=
                (e1+e2+e3+e4+e5)
(024)   e1=
                q1*i1/(10^11)
(025)   e11=
                e1*m11
(026)   e12=
                e1*m12
(027)   e13=
                e1*m13
(028)   e2=
                q2*i2/(10^11)
(029)   e21=
                e2*m21
(030)   e22=
                e2*m22
(031)   e23=
                e2*m23
(032)   e3=
                q3*i3/(10^11)
(033)   e31=
                e3*m31
(034)   e32=
                e3*m32
(035)   e33=
                e3*m33
(036)   e4=
                q4*i4/(10^11)
(037)   e41=
                e4*m41
(038)   e42=
                e4*m42
(039)   e43=
                e4*m43
(040)   e5=
                q5*i5/(10^11)
(041)   e51=
                e5*m51
(042)   e52=
                e5*m52
(043)   e53=
                e5*m53
(044)   ef51 r = WITH LOOKUP (
                Time,
                        ([(1980,10)-(2010,100)],(1980,0),(2010,0)))
(045)   eimp= INTEG (
                "eimp %",
                        -6490.22
                        )
```

```
(046)   "eimp %"=
            IF THEN ELSE(Time<2010,eimp*eimp r/100,eimp*"esc-eimp"/100)
(047)   eimp r = WITH LOOKUP (
            Time,
                ([(1980,0)-(2025,10)],(1980,6.96),(1981,6.54),(1982,6.18),(1983,5.73),(1984
        ,5.26),(1985,4.89),(1986,4.77),(1987,5),(1988,5.03),(1989,4.98),(1990,4.82
        ),(1991,4.52),(1992,4.06),(1993,3.45),(1994,2.79),(1995,2.24),(1996,1.89),
        (1997,1.74),(1998,1.77),(1999,1.9),(2000,2.09),(2001,2.29),(2002,2.47),(2003
        ,2.45),(2004,2.13),(2005,1.68),(2006,1.23),(2007,0.89),(2008,0.69),(2009,0.63
        ),(2010,2.74),(2025,2.74) ))
(048)   "es-m42 r" = WITH LOOKUP (
            Time,
                ([(1980,10)-(2010,100)],(1980,0),(2010,0)))
(049)   es1=
            (100-(es2+es3))
(050)   es11= INTEG (
            es1/100*"es11%"/100,
                es1/100*0.8/100)
(051)   es11 r = WITH LOOKUP (
            Time,
                ([(1980,-100)-(2010,100)],(1980,40.31),(1981,12.39),(1982,14.68),(1983,-
        10.7),(1984,8.22),(1985,36.45),(1986,-51.42),(1987,80.57),(1988,61.06),(1989
        ,73.87),(1990,18.52),(1991,-45.22),(1992,5.28),(1993,74.98),(1994,-46.2),(
        1995,0.97),(1996,22.66),(1997,-17.88),(1998,-2.2),(1999,13.26),(2000,-10.47
        ),(2001,6.87),(2001,-5.32),(2002,78.43),(2003,12.08),(2004,-22.66),(2005,59.89
        ),(2006,-0.63),(2007,-27.28),(2008,6.87),(2009,5.84),(2010,6.84) ))
(052)   "es11%"=
            IF THEN ELSE(Time<2010, es11*es11 r/100, es11*"esc-es11"/100)
(053)   es12= INTEG (
            es1/100*"es12%"/100,
                es1/100*0/100)
(054)   es12 r = WITH LOOKUP (
            Time,
                ([(1980,0)-(2010,0.2)],(1980,0),(2010,0) ))
(055)   "es12%"=
            IF THEN ELSE(Time<2010, es12*es12 r/100, es12*"esc-es12"/100)
(056)   es13=
            es1/100-(es11+es12)
(057)   es2= INTEG (
            "es2%",
                1.22049
                )
(058)   es2 r = WITH LOOKUP (
            Time,
                ([(1980,-2)-(2020,60)],(1980,59.61),(1981,37.48),(1982,27.11),(1983,20.85
        ),(1984,16.23),(1985,12.76),(1986,9.96),(1987,7.69),(1988,5.84),(1989,4.33
        ),(1990,3.1),(1991,2.11),(1992,1.25),(1993,0.43),(1994,-0.26),(1995,-0.66)
        ,(1996,-0.92),(1997,-1.13),(1998,-1.32),(1999,-1.56),(2000,-1.74),(2001,-1.71
        ),(2002,-1.46),(2003,-0.96),(2004,-0.29),(2005,0.44),(2006,1.04),(2007,1.33
        ),(2008,1.32),(2009,1.31),(2010,1.31),(2011,2.04),(2020,2.04) ))
```

```
(059)   "es2%"=
                IF THEN ELSE(Time<2010, es2*es2 r/100, es2*"esc-e2"/100)
(060)   es3= INTEG (
                "es3%",
                        19.7351
                        )
(061)   es3 r = WITH LOOKUP (
                Time,
                        ([(1980,-8)-(2020,-0)],(1980,-1.26),(1981,-1.29),(1982,-1.41),(1983,-1.65
        ),(1984,-1.98),(1985,-2.37),(1986,-2.82),(1987,-3.37),(1988,-3.96),(1989,-
        4.54),(1990,-4.95),(1991,-5.28),(1992,-5.57),(1993,-5.86),(1994,-6.05),(1995
        ,-6.12),(1996,-6.12),(1997,-6.08),(1998,-5.97),(1999,-6.1),(2000,-6.21),(2001
        ,-6.27),(2002,-6.21),(2003,-5.95),(2004,-5.5),(2005,-5),(2006,-4.63),(2007
        ,-4.52),(2008,-4.59),(2009,-4.76),(2010,-5.14),(2020,-5.14) ))
(062)   "es3%"=
                IF THEN ELSE(Time<2010, es3*es3 r/100, es3*"esc-e3"/100)
(063)   "esc-c"=
                2.96
(064)   "esc-e2"=
                2.04
(065)   "esc-e3"=
                -5.14
(066)   "esc-eef31"=
                0
(067)   "esc-eimp"=
                2.74
(068)   "esc-es11"=
                5.86
(069)   "esc-es12"=
                0
(070)   "esc-i"=
                4.15
(071)   "esc-i1"=
                -5.39
(072)   "esc-i2"=
                0.52
(073)   "esc-i3"=
                -7.29
(074)   "esc-i4"=
                -0.19
(075)   "esc-i5"=
                0.82
(076)   "esc-m11"=
                0
(077)   "esc-m12 r" = WITH LOOKUP (
                Time,
                        ([(1980,10)-(2010,100)],(1980,0),(2010,0) ))
```

```
(078)   "esc-m12"=
                0
(079)   "esc-m21"=
                0
(080)   "esc-m22"=
                20
(081)   "esc-m32"=
                0
(082)   "esc-m41"=
                0
(083)   "esc-m42"=
                80
(084)   "esc-m51"=
                0
(085)   "esc-m52"=
                0
(086)   "esc-pob"=
                1.3
(087)   "esc-s2"=
                0.07
(088)   "esc-s3"=
                0.74
(089)   "esc-s4"=
                -0.81
(090)   "esc-s5"=
                0.25
(091)   "esc-tb"=
                -4.12
(092)   FINAL TIME  = 2030
        Units: year
        The final time for the simulation.
(093)   i= INTEG (
                "i %",
                        8.92732e+009)
(094)   "i %"=
                IF THEN ELSE(Time<2010,i*i r/100,i*"esc-i"/100)
(095)   i r = WITH LOOKUP (
                Time,
                        ([(1980,0)-(2025,10)],(1980,0.94),(1981,1.06),(1982,1.37),(1983,1.95),(1984
        ,2.53),(1985,3.2),(1986,3.47),(1987,3.41),(1988,3.15),(1989,2.83),(1990,2.66
        ),(1991,2.64),(1992,2.72),(1993,2.8),(1994,2.88),(1995,3.02),(1996,3.28),(
        1997,3.59),(1998,4.01),(1999,4.71),(2000,5.3),(2001,5.64),(2002,5.81),(2003
        ,5.97),(2004,5.99),(2005,5.89),(2006,5.7),(2007,5.4),(2008,5.12),(2009,4.89
        ),(2010,4.15),(2025,4.15) ))
        Units: 1/year
(096)   i1= INTEG (
                "i1%",
                        15.7858
                        )
```

```
(097)   i1 r = WITH LOOKUP (
                Time,
                        ([(1980,-20)-(2030,20)],(1980,2.42),(1981,2.1),(1982,1.29),(1983,0.02),(
        1984,-1.74),(1985,-3.82),(1986,-6.09),(1987,-8.46
        ),(1988,-10.66),(1989,-12.16),(1990,-12.98),(1991,-13.15),(1992,-12.71),(1993
        ,-11.69),(1994,-10.11),(1995,-8.18),(1996,-
        6.19),(1997,-4.38),(1998,-2.96),(1999,-1.98),(2000,-1.43),(2001,-1.32),(2002
        ,-1.54),(2003,-1.88),(2004,-2.13),(2005,-2.34
        ),(2006,-2.54),(2007,-2.79),(2008,-2.97),(2009,-3.1),(2010,-3.1),(2020,-5)
         ))
(098)   "i1%"=
                IF THEN ELSE(Time<2010, i1*i1 r/100, i1*"esc-i1"/100 )
(099)   i2= INTEG (
                "i2%",
                        144.164
                        )
(100)   i2 r = WITH LOOKUP (
                Time,
                        ([(1980,-8)-(2050,6)],(1980,1.45),(1981,1.36),(1982,1.17),(1983,0.95),(1984
        ,0.73),(1985,0.58),(1986,0.55),(1987,0.64),(1988,0.89),(1989,1.27),(1990,1.76
        ),(1991,2.31),(1992,2.86),(1993,3.3),(1994,3.44),(1995,3.33),(1996,3.09),(
        1997,2.82),(1998,2.5),(1999,2.09),(2000,1.54),(2001,0.85),(2002,0.007),(2003
        ,-0.82),(2004,-1.76),(2005,-2.47),(2006,-3.02),(2007,-3.48),(2008,-3.78),(
        2009,-3.97),(2010,-3.97),(2011,-1),(2020,-1),(2050,0) ))
(101)   "i2%"=
                IF THEN ELSE(Time<2010, i2*i2 r/100, i2*"esc-i2"/100 )
(102)   i3= INTEG (
                "i3%",
                        147.112
                        )
(103)   i3 r = WITH LOOKUP (
                Time,
                        ([(1981,-20)-(2030,6)],(1980,-6.99),(1981,-7.52),(1982,-8.16),(1983,-8.89
        ),(1984,-9.79),(1985,-10.96),(1986,-12.46),(1987
        ,-14.28),(1988,-16.19),(1989,-17.5),(1990,-19.09),(1991,-17.87),(1992,-14.43
        ),(1994,-11.18),(1995,-7.47),(1996,-4.11),(1997
        ,-1.54),(1998,-0.11),(1999,-0.03),(2000,-0.45),(2001,-1.11),(2002,-1.85),(
        2003,-2.65),(2004,-3.29),(2005,-3.83),(2006,-4.22
        ),(2007,-4.53),(2008,-4.77),(2009,-4.94),(2010,-4.77),(2020,-6.77) ))
(104)   "i3%"=
                IF THEN ELSE(Time<2010, i3*i3 r/100, i3*"esc-i3"/100 )
(105)   i4= INTEG (
                "i4%",
                        94.462
                        )
(106)   i4 r = WITH LOOKUP (
                Time,
                        ([(1981,-4)-(2050,2)],(1980,-1.73),(1981,-1.77),(1982,-1.86),(1983,-1.95
        ),(1984,-2.03),(1985,-2.11),(1986,-2.16),(1987,-2.18),(1988,-2.11),(1989,-
        1.9),(1990,-1.52),(1991,-1),(1992,-0.39),(1993,0.27),(1994,0.85),(1995,1.18
```

```
        ),(1996,1.31),(1997,1.32),(1998,1.21),(1999,0.67),(2000,0.35),(2001,0.35),
        (2002,0.06),(2003,-0.19),(2004,-0.31),(2005,-0.32),(2006,-0.28),(2007,-0.22
        ),(2008,-0.15),(2009,-0.14),(2010,-0.14),(2011,-1),(2020,-1),(2050,0) ))
(107)   "i4%"=
                IF THEN ELSE(Time<2010, i4*i4 r/100, i4*"esc-i4"/100)
(108)   i5= INTEG (
                "i5%",
                        446.103
                        )
(109)   i5 r = WITH LOOKUP (
                Time,
                        ([(1981,-4)-(2050,2)],(1980,2.54),(1981,2.43),(1982,2.25),(1983,2.05),(1984
        ,1.84),(1985,1.69),(1986,1.59),(1987,1.5),(1988,1.41),(1989,1.24),(1990,1.05
        ),(1991,0.9),(1992,0.82),(1993,0.8),(1994,0.87),(1995,0.97),(1996,1.05),(1997
        ,1.14),(1998,1.23),(1999,1.34),(2000,1.38),(2001,1.27),(2002,1.06),(2003,0.75
        ),(2004,0.39),(2005,0.02),(2006,-0.3),(2007,-0.51),(2008,-0.58),(2009,-0.61
        ),(2010,-0.61),(2011,-1),(2020,-1),(2050,0) ))
(110)   "i5%"=
                IF THEN ELSE(Time<2010, i5*i5 r/100 , i5*"esc-i5"/100)
(111)   INITIAL TIME  = 1980
        Units: year
        The initial time for the simulation.
(112)   m11= INTEG (
                ("m11%"/100)*es11,
                        5/100)
(113)   m11 r = WITH LOOKUP (
                Time,
                        ([(1980,10)-(2010,100)],(1980,0),(2010,0) ))
(114)   "m11%"=
                IF THEN ELSE(Time<2010, m11*m11 r/100, m11*"esc-m11"/100)
(115)   m12= INTEG (
                "m12%"/100*es12,
                        0/100)
(116)   "m12%"=
                IF THEN ELSE(Time<2010, m12*"esc-m12 r"/100, m12*"esc-m12"/100)
(117)   m13=
                (1-(m11+m12))*es13
(118)   m21= INTEG (
                ("m21%"/100)*es11,
                        5/100)
(119)   m21 r = WITH LOOKUP (
                Time,
                        ([(1980,10)-(2010,100)],(1980,0),(2010,0) ))
(120)   "m21%"=
                IF THEN ELSE(Time<2010, m21*m21 r/100, m21*"esc-m21"/100)
(121)   m22= INTEG (
                "m22%"/100*es12,
                        0/100)
(122)   m22 r = WITH LOOKUP (
                Time,
```

```
                    ([(1980,10)-(2010,100)],(1980,20),(2010,20) ))
(123)   "m22%"=
                IF THEN ELSE(Time<2010, m22*m22 r/100, m22*"esc-m22"/100)
(124)   m23=
                (1-(m21+m22))*es13
(125)   m31= INTEG (
                ("m31%"/100)*es11,
                    5/100)
(126)   m31 r = WITH LOOKUP (
                Time,
                    ([(1980,10)-(2010,100)],(1980,0),(2010,0) ))
(127)   "m31%"=
                IF THEN ELSE(Time<2010, m31*m31 r/100, m31*"esc-eef31"/100)
(128)   m32= INTEG (
                "m32%"/100*es12,
                    0/100)
(129)   m32 r = WITH LOOKUP (
                Time,
                    ([(1980,10)-(2010,100)],(1980,0),(2010,0) ))
(130)   "m32%"=
                IF THEN ELSE(Time<2010, m32*m32 r/100, m32*"esc-m32"/100)
(131)   m33=
                (1-(m31+m32))*es13
(132)   m41= INTEG (
                ("m41%"/100)*es11,
                    5/100)
(133)   m41 r = WITH LOOKUP (
                Time,
                    ([(1980,10)-(2010,100)],(1980,0),(2010,0) ))
(134)   "m41%"=
                IF THEN ELSE(Time<2010, m41*m41 r/100, m41*"esc-m41"/100)
(135)   m42= INTEG (
                "m42%"/100*es12,
                    0/100)
(136)   "m42%"=
                IF THEN ELSE(Time<2010, m42*"es-m42 r"/100, m42*"esc-m42"/100)
(137)   m43=
                (1-(m41+m42))*es13
(138)   m51= INTEG (
                ("m51%"/100)*es11,
                    1/100)
(139)   "m51%"=
                IF THEN ELSE(Time<2010, m51*ef51 r/100, m51*"esc-m51"/100)
(140)   m52= INTEG (
                "m52%"/100*es12,
                    0/100)
(141)   m52 r = WITH LOOKUP (
                Time,
                    ([(1980,10)-(2010,100)],(1980,0),(2010,0)))
```

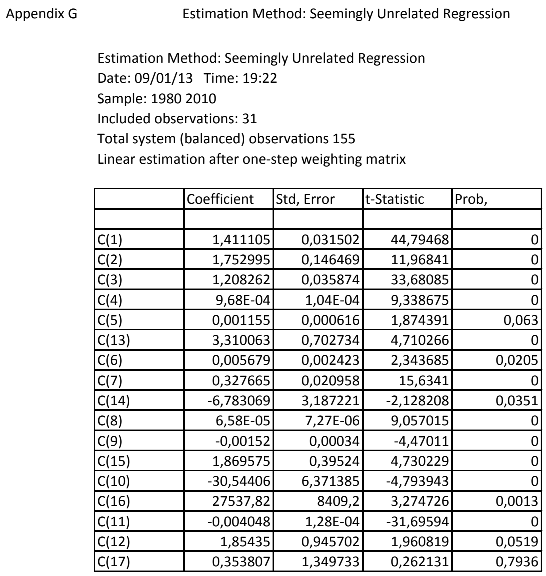
```
(142)   "m52%"=
                IF THEN ELSE(Time<2010, m52*m52 r/100, m52*"esc-m52"/100)
(143)   m53=
                (1-(m51+m52))*es13
(144)   pob= INTEG (
                "pob %",
                        7.94689e+006)
(145)   "pob %"=
                IF THEN ELSE(Time<2010,pob*pob r/100,pob*"esc-pob"/100)
(146)   pob r = WITH LOOKUP (
                Time,
                        ([(1980,0)-(2025,4)],(1980,2.91),(1981,2.83),(1982,2.75),(1983,2.68),(1984
        ,2.61),(1985,2.55),(1986,2.48),(1987,2.41),(1988,2.35),(1989,2.27),(1990,2.2
        ),(1991,2.12),(1992,2.05),(1993,1.97),(1994,1.9),(1995,1.84),(1996,1.78),(
        1997,1.74),(1998,1.7),(1999,1.68),(2000,1.66),(2001,1.64),(2002,1.63),(2003
        ,1.61),(2004,1.59),(2005,1.57),(2006,1.54),(2007,1.52),(2008,1.5),(2009,1.47
        ),(2010,1.44),(2025,1.3) ))
(147)   Q=
                1.20772*c + 1.15776*i + 0.997272*tb + 504457*eimp - 4.98877e+006*RN +
9.63411e+009
        EXP(0.162483*LN(i)-0.005391*LN(tb)+0.961963*LN(c)-0.122869*LN(eim
                        p)-0.166514*LN(RN))
(148)   q1=
                Q*s1
(149)   q2=
                Q*s2
(150)   q3=
                Q*s3
(151)   q4=
                Q*s4
(152)   q5=
                Q*s5
(153)   Qpc=
                Q/pob
(154)   RN= INTEG (
                (es2+es3)*E/100 - RN,
                        1087.42)
(155)   s1=
                100-(s2+s3+s4+s5)
(156)   s2= INTEG (
                "s2%",
                        14.1344)
(157)   s2 r = WITH LOOKUP (
                Time,
                        ([(1981,-1)-(2025,6)],(1980,0.04),(1981,0.04),(1982,0.04),(1983,0.03),(1984
        ,0.03),(1985,0.02),(1986,0.01),(1987,-0.02),(1988,-0.06),(1989,-0.1),(1990
        ,-0.16),(1991,-0.23),(1992,-0.32),(1993,-0.44),(1994,-0.53),(1995,-0.58),(
        1996,-0.65),(1997,-0.74),(1998,-0.82),(1999,-0.87),(2000,-0.77),(2001,-0.56
        ),(2002,-0.24),(2003,0.15),(2004,0.61),(2005,1.03),(2006,1.4),(2007,1.67),
        (2008,1.8),(2009,1.81),(2010,1.81),(2011,1),(2030,1),(2050,0) ))
```

```
(158)   "s2%"=
                IF THEN ELSE(Time<2010, s2*s2 r/100, s2*"esc-s2"/100 )
(159)   s3= INTEG (
                "s3%",
                        8.34912)
(160)   s3 r = WITH LOOKUP (
                Time,
                        ([(1981,-2)-(2030,6)],(1980,0.03),(1981,0.03),(1982,0.03),(1983,0.02),(1984
        ,-0.01),(1985,-0.04),(1986,-0.09),(1987,-0.15),(1988,-0.23),(1989,-0.34),(
        1990,-0.48),(1991,-0.6),(1992,-0.73),(1993,-0.85),(1994,-0.99),(1995,-1.03
        ),(1996,-0.83),(1997,-0.52),(1998,-0.05),(1999,0.71),(2000,1.4),(2001,1.9)
        ,(2002,2.21),(2003,2.44),(2004,2.58),(2005,2.68),(2006,2.67),(2007,2.56),(
        2008,2.45),(2009,2.31),(2010,2.31),(2020,0.85) ))
(161)   "s3%"=
                IF THEN ELSE(Time<2010,s3*s3 r/100,s3*"esc-s3"/100)
(162)   s4= INTEG (
                "s4%",
                        39.4618
                        )
(163)   s4 r = WITH LOOKUP (
                Time,
                        ([(1981,-4)-(2050,6)],(1980,0.02),(1981,0.02),(1982,0.02),(1983,0.02),(1984
        ,0.02),(1985,0.02),(1986,0.01),(1987,0),(1988,-0.01),(1989,-0.03),(1990,-0.06
        ),(1991,-0.09),(1992,-0.14),(1993,-0.21),(1994,-0.26),(1995,-0.3),(1996,-0.35
        ),(1997,-0.43),(1998,-0.53),(1999,-0.64),(2000,-0.75),(2001,-0.91),(2002,-
        1.11),(2003,-1.32),(2004,-1.52),(2005,-1.74),(2006,-1.96),(2007,-2.15),(2007
        ,-2.15),(2008,-2.3),(2009,-2.38),(2010,-2.38),(2011,1),(2030,1),(2050,5) )
        )
(164)   "s4%"=
                IF THEN ELSE(Time<2010,s4*s4 r/100,s4*"esc-s4"/100)
(165)   s5= INTEG (
                "s5%",
                        9.38983)
(166)   s5 r = WITH LOOKUP (
                Time,
                        ([(1981,-0.2)-(2030,6)],(1980,-0.05),(1981,-0.04),(1982,-0.04),(1983,-0.03
        ),(1984,-0.02),(1985,0.01),(1986,0.04),(1987,0.1),(1988,0.17),(1989,0.26),
        (1990,0.37),(1991,0.48),(1992,0.61),(1993,0.76),(1994,0.88),(1995,0.89),(1995
        ,0.89),(1996,0.84),(1997,0.74),(1998,0.6),(1999,0.43),(2000,0.22),(2001,0.07
        ),(2002,-0.03),(2003,-0.1),(2004,-0.13),(2005,-0.15),(2006,-0.16),(2007,-0.16
        ),(2008,-0.16),(2009,-0.16),(2010,-0.16),(2020,0.23) ))
(167)   "s5%"=
                IF THEN ELSE(Time<2010,s5*s5 r/100,s5*"esc-s5"/100)
(168)   SAVEPER  =
            TIME STEP
        Units: year [0,?]
        The frequency with which output is stored.
(169)   tb= INTEG (
                "tb %",
                        -8.6961e+008
```

```
                              )
(170)   "tb %"=
                IF THEN ELSE(Time<2010,tb*tb r/100,tb*"esc-tb"/100)
(171)   tb r = WITH LOOKUP (
                Time,
                              ([(1980,-100)-(2025,2000)],(1980,-2.41),(1981,-2.35),(1982,-2.11),(1983,
        0.42),(1984,4.08),(1985,6.16),(1986,2.96),(1987,-4.64),(1988,-12.71),(1989
        ,-20.99),(1990,-26.61),(1991,-27.87),(1992,-22.77),(1993,-16.32),(1994,-9.21
        ),(1995,-0.28),(1996,-88.44),(1997,1147.95),(1998,26.33),(1999,36.89),(2000
        ,36.92),(2001,25.98),(2002,16.27),(2003,12.15),(2004,11.77),(2005,14.05),(
        2006,17.61),(2007,19.98),(2008,20.09),(2009,18.13),(2010,-4.12),(2025,-4.12
        ) ))
(172)   TIME STEP  = 1
        Units: year [0,?]
        The time step for the simulation.
(173)   uT1=
                15.3*(44/12)*(0.041868)
(174)   uT2=
                25.8*(44/12)*(0.041868)
(175)   uT3=
                20*(44/12)*(0.041868)
```

7.7 Appendix G

Appendix G presents the outcomes of the Seemingly Unrelated Regression (SUR) method that was used to solve the equation system in Section 3.7 in Chapter 3.



Appendix G Estimation Method: Seemingly Unrelated Regression

Estimation Method: Seemingly Unrelated Regression
Date: 09/01/13 Time: 19:22
Sample: 1980 2010
Included observations: 31
Total system (balanced) observations 155
Linear estimation after one-step weighting matrix

	Coefficient	Std, Error	t-Statistic	Prob,
C(1)	1,411105	0,031502	44,79468	0
C(2)	1,752995	0,146469	11,96841	0
C(3)	1,208262	0,035874	33,68085	0
C(4)	9,68E-04	1,04E-04	9,338675	0
C(5)	0,001155	0,000616	1,874391	0,063
C(13)	3,310063	0,702734	4,710266	0
C(6)	0,005679	0,002423	2,343685	0,0205
C(7)	0,327665	0,020958	15,6341	0
C(14)	-6,783069	3,187221	-2,128208	0,0351
C(8)	6,58E-05	7,27E-06	9,057015	0
C(9)	-0,00152	0,00034	-4,47011	0
C(15)	1,869575	0,39524	4,730229	0
C(10)	-30,54406	6,371385	-4,793943	0
C(16)	27537,82	8409,2	3,274726	0,0013
C(11)	-0,004048	1,28E-04	-31,69594	0
C(12)	1,85435	0,945702	1,960819	0,0519
C(17)	0,353807	1,349733	0,262131	0,7936

```
Appendix G              Estimation Method: Seemingly Unrelated Regression

              Determinant residual covari:   3,90E+02


              Equation: QT=C(1)*IT+C(2)*TBT+C(3)*CHT+C(4)*EIMPXENT+C(5)
                    *RNXENT+C(13)
              Observations: 31
              R-squared         0,999984    Mean dependent var           75,38
              Adjusted R-sq     0,999981    S,D, dependent var        19,47725
              S,E, of regress   0,085893    Sum squared resid         0,184442
              Durbin-Watso      0,351924

              Equation: IT=C(6)*RNXENT+C(7)*CHT+C(14)
              Observations: 31
              R-squared         0,861443    Mean dependent var         17,0929
              Adjusted R-sq     0,851546    S,D, dependent var        5,026978
              S,E, of regress   1,936881    Sum squared resid         105,0422
              Durbin-Watso      0,068576

              Equation: TBT=C(8)*EIMPXENT+C(9)*RNXENT+C(15)
              Observations: 31
              R-squared         0,895226    Mean dependent var       -0,970968
              Adjusted R-sq     0,887742    S,D, dependent var        0,326687
              S,E, of regress   0,109456    Sum squared resid         0,335459
              Durbin-Watso      0,374838

              Equation: EIMPXENT=C(10)*RNXENT+C(16)
              Observations: 31
              R-squared         0,423466    Mean dependent var       -12715,41
              Adjusted R-sq     0,403586    S,D, dependent var        3418,343
              S,E, of regress   2639,913    Sum squared resid         2,02E+08
              Durbin-Watso      0,050567

              Equation: CHT=C(11)*EIMPXENT+C(12)*TBT+C(17)
              Observations: 31
              R-squared         0,972547    Mean dependent var        50,02516
              Adjusted R-sq     0,970586    S,D, dependent var        13,53326
              S,E, of regress   2,321005    Sum squared resid         150,8378
              Durbin-Watso      0,091579
```

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