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Valoración exergética de las industrias extractivas en el Ecuador: una contribución al análisis de la sustentabilidad de la economía ecuatoriana

Karla Michell Arias Marín

Asesor: Pedro Alarcón Cevallos

Lectores
Pablo Cabrera Barona
Fander Falconí
Pere Ariza Montobbio
Sara La Torre
Wilson Pérez

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Dedication

Para mi mamita Rebe, porque gracias a ti conozco el amor más puro. Porque ahora entiendo que los momentos son valiosos y efímeros. La fragilidad de la vida y el paso del tiempo. A ti te he dedicado cada uno de mis logros, cada paso que he dado ha sido gracias a ti y prometo dedicarte cada uno de mis suspiros y pensamientos cada día de mi vida. Prometo no bajar los brazos ni detener mis pasos porque yo soy y seré siempre tu legado. Te amo, gracias por creer siempre en mí, amor de mi vida.

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List of abbreviations and acronyms

DEA: Data Envelopment Analysis

EC: Efficiency Change

ERC: Exergy Replacement Cost

FDH: Free Disposal Hull

GDP: Gross Domestic Product

HHV: Higher Heating Value

PMI: Productivity Malmquist Index

SMB: Slacks-Based Measure

TC: Technological Change

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Quito, febrero de 2024.

Karla Arias

Karla Michell Arias Marín

Abstract

This study contributes to the literature on oil extraction efficiency and sustainability in developing countries. It comprises three chapters addressing distinct facets of this topic. The first chapter investigates the challenges of natural resource depletion and sustainability, incorporating the concept of quality degradation and utilizing metrics such as Exergy Replacement Cost (ERC) and Energy Return on Investment (EROI). These indicators are computed based on data from private oil companies operating in Ecuador from 1972 to 2020. Our findings reveal a concerning trend: as EROI decreases, oil prices rise, signifying an escalating extraction cost and a growing energy input requirement. Most notably, our analysis indicates that post-2034, continued oil extraction in Ecuador may no longer be financially viable due to diminishing field quality, leading to energy costs exceeding energy gains. In the second chapter, we examine the efficiency and productivity drivers in 18 private oil companies in Ecuador from 2011 to 2020, taking an industrial perspective. Employing a Malmquist pollutant-adjusted productivity index and panel regression, our research reveals that efficiency and productivity losses are closely linked to energy consumption levels and a lack of technical innovation within these companies during the study period. The third chapter employs a slacks-based-measure data-envelopment-analysis (SBM-DEA) model to optimize oil well benefits while minimizing undesirable outputs, such as carbon emissions and energy degradation. Furthermore, we apply a Malmquist Productivity Index (MPI) to assess and compare dynamic energy productivity efficiency among Latin American and African countries. Our analysis of 14 countries in these regions from 2006 to 2020 demonstrates that Equatorial Guinea, Gabon, Peru, and Bolivia exhibit higher energy efficiency than counterparts like Angola, Algeria, Mexico, Ecuador, and Colombia. Notably, our findings suggest that countries with higher extraction rates tend to be less efficient, resulting in greater environmental impact relative to economic benefits from extraction. In conclusion, this study underscores the importance of energy efficiency policies, which can significantly mitigate Greenhouse Gas (GHG) emissions and resource depletion at the national level while enhancing industry sustainability. We recommend that governments implement policies aimed at reducing energy consumption within the oil sector, including the reduction of electricity subsidies. Adopting realistic energy extraction costs is crucial in facilitating the transition towards renewable energy sources.

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Introduction

The study of energy-related issues took relevance for development economists since both global oil shocks (1973-1974 and 1979-1980). However, the study of the importance of energy in economics has its roots in history. Podolinsky (1980) is one of the first precursors of energy economics and was the first to explicitly examine the economic process, including aspects linked to thermodynamics. Nicolas Georgescu-Rogen (1971) stated the importance of energy in determining economic value, and Ayres (1998) concluded that energy and matter constitute the basis of the production process. Odum (1973) argued that the only criterion of economic efficiency is energy; the more significant the net energy obtained by a process, the more efficient that process will be. How the relationship between energy and economics has been approached has also evolved. Energy has been studied for its role as one of the main inputs to produce goods and services (Cook 1976), from its impact on economic growth (Stern 2011), and has even been considered as a fourth factor of production (Pokrovski 2003).

Thermodynamics analyzes the behavior of specific energy processes for their subsequent optimization, for example, by maximizing the useful work obtained from the combustion of fossil fuels. An essential contribution of thermodynamics to economic analysis is incorporating the idea of irreversibility. According to Machrafi (2019), an irreversible process is defined as a process that cannot return both the system and the surroundings to their original conditions. Any economic activity involves the use of resources; these resources entail an irreversible loss of part of this resource, which must be quantified and included in economic analyses (Valero and Torres 2006). This idea is fundamental because it shows the "purpose" (efficiency) at the heart of thermodynamics. Efficiency hence measures the quality of a process, and it requires comparing the product obtained with the resources needed to obtain it (Marmolejo-Correa and Gundersen 2012).

One of the central issues that energy economics has studied is energy efficiency. The idea of energy efficiency is intrinsically linked to that of energy service (Fell 2017), or useful energy. According to Oikonomou et al. (2009), energy efficiency concerns the ratio between the volume of energy consumed and the total energy services available (for example, heating, lighting, cooling, mobility, cooking, etc.). Hence, energy efficiency is related to nearly all human activities at both the microeconomic level of households and businesses and the macroeconomic considerations of resource management and environmental externalities.

Considering the significance of energy for the socio-economic system, it is essential to highlight the persistence of fossil fuels in the energy-economy relationship as the most important primary energy source in the last century. Oil represents 31% of global energy consumption sources, followed by coal 27%, and natural gas 24% (British Petroleum 2022). Oil extraction has increased from 3,158 Mt in 1990 to 4,221 Mt in 2021, which represents a rise of 42% approximately (IEA 2020a 2022). Meanwhile, oil consumption increased from 2,890 Mt in 1990 to 2,180 Mt to 4,399 in 2021; this represents a growth of 34%. The World Energy Outlook 2021 claims that energy generated from fossil fuels will remain the primary source and is still expected to meet about 75% of energy demand in 2030 (IEA 2021). However, it is known that the worldwide petroleum supply will eventually reach its productive limit and begin a long-term decline.

In the context of growing energy demand triggered by the recovery from the pandemic and an oil sector that requires transformation, one topic that has begun to gain momentum in the academic literature are oil depletion and the role that energy efficiency could play in promoting sustainable development. In addition, oil-exporting countries are facing some global challenges that require the transformation of this sector. First, climate change is one of the most pressing issues of our time. The Paris Agreement, aimed at keeping global warming below 1.5 °C compared to pre-industrial levels, although not explicitly, recognizes the role of fossil fuels use in altering the world's climate and therefore promotes the transition towards renewable energy sources. Second, access to affordable and quality energy carriers (such as electricity) is one of the primary objectives to ensure the welfare of the developed countries and reduce energy poverty in developing countries. Third, energy security and energy sovereignty have been brought back to the top of the international political agenda because of the war in Ukraine and the growing tensions between the West and Russia (Alarcón 2023).

The depletion of oil reserves is a problem that has been studied extensively and from various angles, especially as an environmental problem. However, those analyses have focused on the loss of quantity rather than quality. This research project is rather inspired by the role of energy efficiency to improve economic and environmental performance, hence, addresses the oil depletion problem as an efficiency problem. As it recognizes the importance of the idea of energy efficiency in thermodynamics, this research aims at contributing to a broader understanding of the implications of the irreversible loss of quality of energy resources, in this case, oil, for countries, industry, and society.

Considering this, the research issue prompting this study stems from the consequences of inadequate natural resource utilization, particularly non-renewable resources employed as primary energy sources. This mismanagement can result in inefficiencies both economically and energetically. These inefficiencies, in turn, exert profound repercussions on companies, societies, and the economies of developing nations that heavily rely on these resources.

The research problem addressed in this study holds significant contemporary relevance due to its contributions. Firstly, it engages in a critical discourse surrounding the deliberation of whether the preservation of oil reserves in their natural state might be more efficient than their continued extraction. This consideration gains further weight by incorporating meticulous assessments of energy costs and the irrevocable losses incurred with each barrel of oil extracted. Moreover, the study serves as a foundational underpinning for advocating the necessity of energy efficiency policies at the industrial level. Such policies are designed to bolster efficiency and productivity, thereby adding substantial depth to the discourse on corporate sustainability—an area that has remained relatively underexplored. Lastly, this research crucially bridges an evident void in the academic landscape by focusing on the relative efficiency dynamics within developing nations reliant on oil exports. Notably, while existing studies predominantly concentrate on developed contexts, this study's emphasis on developing economies presents a novel and indispensable contribution to the field.

To tackle this issue effectively, the pivotal research inquiry becomes: Are energy resources, specifically oil, being utilized efficiently in Ecuador and analogous developing nations? To address this inquiry, the thesis will be structured across three distinct chapters. The initial chapter focuses on assessing energy costs and efficiency. The subsequent chapter delves into the examination of drivers and barriers affecting energy efficiency within the oil sector. The final chapter investigates the ramifications of extractive activities on energy efficiency in developing countries. A more detailed breakdown of the chapter contents is provided below.

The first chapter intends to contribute to the academic literature by identifying the energy costs of oil depletion in a low-income exporting country and to what extent it would be efficient to continue extracting oil. For this purpose, this chapter analyze the case of Ecuador. In this sense, the question will be: Until what year is it efficient to continue oil extraction in Ecuador? This study will explain why it is essential to consider other variables different from oil prices when designing public policy.

The second chapter seeks to enhance the existing knowledge base on industrial-level energy efficiency analysis in the context of a developing nation. The objective of this chapter is to investigate the operational dynamics of drivers and barriers influencing energy efficiency within the industrial sector in Ecuador. Through empirical investigation, this chapter will shed light on the utilization of resources by private oil companies in this south American country, with a specific emphasis on energy resources. The primary objective is to furnish valuable insights into optimizing resource utilization within oil companies, enabling them to maximize profits while mitigating their emission footprint.

Chapter three critically assesses energy efficiency and productivity enhancements within developing oil-exporting countries. The goal of this chapter is to make a significant contribution to academic discourse by unveiling the intricate interplay between extractive activities, energy efficiency, and energy productivity improvements within developing countries. The assessment unfolds in two phases: firstly, by evaluating energy efficiency through the application of the DEA-SMB approach, and secondly, by employing the Malmquist Productivity Index approach to estimate energy productivity improvement. What sets this study apart is its innovative incorporation of energy depletion as an undesirable output within the DEA and Malmquist frameworks. While studies on efficiency in the oil sector have predominantly focused on developed countries, the research gap remains pronounced in the context of developing nations.

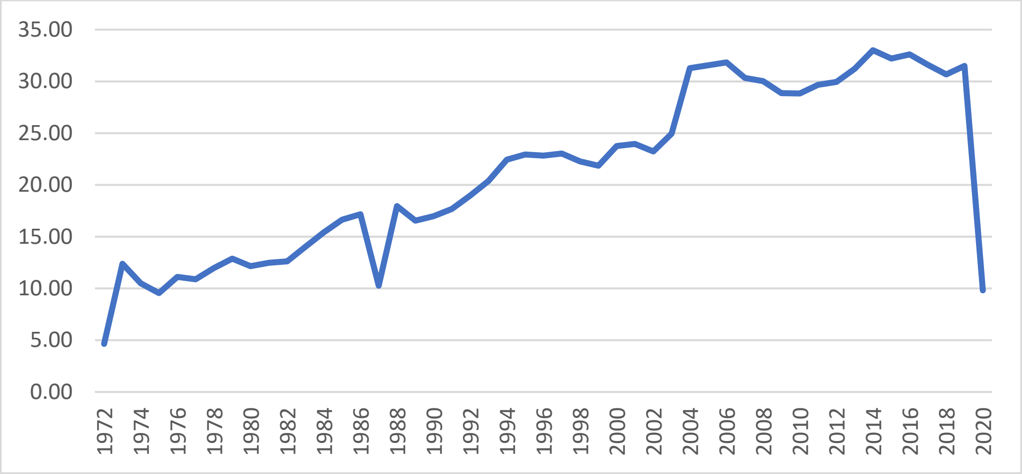
Chapter 1. The “real” cost of oil extraction in Ecuador

Energy and materials are critical for the socioeconomic system; they support food production, transportation, expansion of material stocks (infrastructure), and in general, the well-being of society (Valero and Valero 2014). The extraction of fossil fuels and mineral resources has grown exponentially since the industrial revolution, and far from decelerating, it is expected to increase in the coming decades (IEA 2021). The extraction of natural resources significantly impacts the quality of oil fields in a country. For the purpose of this chapter *quality of oil fields* is understood as the free natural energy bonus provided by nature for having oil concentrated in fields instead of dispersed throughout the atmosphere (Matharan 2014). In theory, oil extraction should offer governments a chance to boost economic growth and reduce inequality. It often leads to economic stagnation, social conflict, environmental degradation, and energy depletion (Ross 2004).

Talking about the efficiency and economic impacts of energy depletion, it is essential to understand the dynamics of this issue. This is a complex issue because it involves several dimensions. The total amount of fuel and non-fuel mineral resources on Earth is unaccountable. Generally, the mineral involved may be abundant enough on any reasonable time scale. There will be undiscovered deposits elsewhere or technological developments that allow access to new deposits and materials (Hannesson 2001). However, the impact will differ from a mineral resource export country’s perspective. Facing dwindling mineral deposits within its territory, or at any rate dwindling deposits of good quality, might affect its revenues significantly and increment energy costs.

Assessing energy depletion is a complex task. The implications of oil depletion for developed and underdeveloped economies are different. According to the IEA (2021), Ecuador has 8.3 billion barrels of proven crude oil reserves. Meanwhile, in terms of exergy Ecuador’s exergy of oil-proven reserves is 937.3 (Mtoe). Exergy is the maximum amount of useful work that can be obtained when some form of Energy is transformed (Alarcón 2023). Exergy can be understood as a measure of value because exergy is a measure of energy quality; high-exergy sources produce more useful work (British Petroleum 2022). Moreover, they are more “valuable” than those that produce less useful work because one will need fewer resources (i.e., Energy) to produce the same output. Not all energy forms have the same quality because they do not produce the same maximum amount of useful work (Whiting, et al. 2017). The evolution of oil production in Ecuador in exergy terms is shown in Figure 1.1.

Figure 1.1 Historical Extraction (Mtoe) (1972-2020)



Source: EP *Petroecuador* (2020)

This research aims to determine the exergy cost of quality loss from oil extraction in Ecuador. To address the first issue, this study adapts exergy Replacement Cost (ERC), including EROI as an indicator of quality loss. The main objective of using this approach in the analysis is to assess the issue of natural resource depletion and sustainability and incorporate quality degradation into the analysis. Using non-renewable natural resources as an input of many economic processes implies a loss; in this case, this study quantifies this loss in terms of exergy. Exergy becomes a suitable indicator to analyze sustainability in terms of "strong sustainability" because there is no possible substitutability once entropy destroys exergy. Entropy represents the unavailability of a system's thermal energy for conversion into useful work (Pal and Pal 1991). Oil is an excellent example to understand this because, unlike non-fuel minerals, a significant part of oil burns and is transformed into CO2. Once it happens, it is impossible to recycle or recover. ERC and EROI analysis provide a useful approach for examining the costs of quality loss of fuels and offer the possibility to look into the future in ways that markets seem unable to do.

The application of this approach to account for efficiency and sustainability of oil extraction in Ecuador is accurate due to three factors: 1) Ecuador has been an important oil exporter in Latin America that will become a net importer in a decade according to Espinoza et al. (2019), this will generate costs that future generations will have to face, not only economic but also in environmental terms 2) to understand the value of a resources from a different perspective, in this case from its capacity to produce useful work, this information will be useful in terms of natural resource management and efficiency 3) Ecuadorian government is promoting the development of mining as a new important industry to replace oil income, the energy cost will give us additional information about how much might will lose in terms of mineral wealth, learn from oil experience might provide inputs to develop mining in a more efficient way or even provide another argument to the debate about leaving minerals underground.

Among the findings of this investigation is that oil prices have been increasing as EROI decreases (they have a negative and significant relationship); this shows an increase in the cost of extraction, which means that more energy must be invested to obtain energy. On the other hand, it was found that from the year 2034, it will no longer be profitable to continue extracting oil since the quality of the fields will have decreased, with an EROI of 9:1, so it will cost much energy to extract a barrel of oil.

This chapter is divided as follows: The second section presents a literature review in which the concepts of Exergy, Exergy Replacement Cost, and EROI are explored, and a review of empirical works is also carried out, detailing the methods used and their results. In Section three, I explain the methodological framework, where the data and indicators used to measure energy efficiency are specified. In section four, I present the top results and findings of this investigation and its analysis. Finally, in section five, I conclude and give some policy recommendations.

1.1. Literature review

Exergy can be understood as a measure of value because exergy is a measure of energy quality; high-exergy sources produce more useful work. And therefore, they are more “valuable” than the ones that produce less useful work because one will need fewer resources (i.e., Energy) to produce the same output (Oikonomou, et al. 2009).

1.1.1. Exergy-based economic methods

Analytical Methods integrating exergy and economics have been developed over the last several decades, most of them following the steps of Georgescu- Rogen who is considered the pioneer in the field of thermodynamics of economics (Rosen 2008). Most exergy-based economic methods have common characteristics such as those (Tsatsaronis and Valero, 1989): 1) They associate exergy and economic analysis with achieving thermodynamic and economic objectives, such as optimization; 2) They recognize that exergy represents the “value” in a system. Therefore, they assign costs and/or prices to exergy-related variables; 3) They assess economic feasibility and profitability; 4) They allow to determining actual costs of outputs and accurate prices; 5) They determine appropriate allocations of economic resources; 6) Optimization is a particularly important application of exergy-based economic techniques.

Rosen (2008) has determined four main categories of exergy-based economic methodologies considering the following forms as the basis: 1) exergy-economic cost accounting, 2) exergy-economic calculus analysis, 3) exergy-economic similarity number, and 4) product/cost efficiency.

All the methods presented in Table 1.1 aim to give additional information and provided a better understanding of the relationship between exergy and economics. However, in the framework of the study of natural capital and sustainability, thermo-economics and exergy economics present the theoretical and methodological tools to address issues such as depletion of natural resources, economic performance, and environmental impacts of extractive industries. Therefore, for this research, I will focus on this methodological framework with emphasis in the applications of exergy to account for cost allocation.

Table 1.1. Exergy-based economic methods

Methods	Description	Advantage	Relevant Studies
Exergy-based pricing and cost allocation	The selection of energy sources is primarily based on prices, so it is important to determine prices appropriately. There is evidence (Bandura and Brodiansky 2001) that supports that the physical value of a commodity based on exergy is more accurate than the one based on energy. Therefore, prices of physical resources can thus be more rationally set based on exergy.	Exergy-based prices can promote resource savings and efficient technology. Exergy-based production expenses are shown to lead to natural price determination and corresponding general macroeconomic dynamics.	The use of exergy in economic valuations and the correlation of exergy with price determination has been analyzed by Bandura and Brodiansky (2001) in "Thermodynamics extends economics potentials"
EXCEM analysis	EXCEM (exergy, cost, energy, and mass) analysis focuses on the four keys and can help assess and improve systems and processes. EXCEM analysis presumes an understanding of the system or process performance requires examination of all flows of exergy, cost, energy, and mass through a system. Balances can be written for each EXCEM quantity. Mass and energy are conserved. Exergy and cost are not conserved, as exergy cannot increase while cost cannot decrease.	EXCEM analysis is intended as a unified aid for thermodynamic, economic, and environmental decisions and design.	EXCEM analysis is presented in Rosen and Dincer (2003) paper entitled Exergy-cost-energy, mass analysis of thermal systems and processes.
Loss-cost ratio analysis	Loss-cost ratio analysis focuses on the ratio of thermodynamic loss rate to capital cost. Loss-cost ratio analysis identifies correlations	The insights provided with this exergy-based economic method can assist in analysis and design.	Loss-cost ratio analysis has been applied by Rosen and Dincer (2003) as an application to a coal-fired

	between capital costs and specific second law-based thermodynamic losses. Correlations are observed between capital costs and exergy-based thermodynamic losses for systems and their components, suggesting that designers incorporate exergy-based economic recommendations into designs. The ratio of loss rate to cost based on total and internal exergy loss rates is normally the most useful.		electrical generating station.
Thermoeconomics and exergo-economics	Exergoeconomics and thermoeconomics are exergy-based economic methods (Sciubba 2001). Exergy and microeconomics form the basis of Thermo economic (Yantovski 1994) The utility is a central concept in microeconomics and is closely related to exergy (Ayres 1998). With thermoeconomics, exergy efficiencies are determined, while non-energy expenditures such as financial and labor costs are related to the technical parameters of the device under consideration (Valero 1998). The method measures the number of exergy resources to produce a good. Costs must be properly formed to understand and evaluate exergy costs and resource degradation, as well as cost and irreversibility relations (Valero, et al. 1986).	Exergy accounting utilizes exergy costs and is useful for diagnosing energy systems and accounting for natural exergy resources (Valero 1998). The exergy tax is an example of how exergy can be introduced into economics to fix externalities (Santarelli 2004). Exergo-economics provides a thermodynamic foundation for rational resource use (Sciubba 2005).	There are several scientific papers showing the theoretical foundations and applications of exergy cost accounting and thermoeconomics such as the work developed by (Yantovski 1994; Sciubba 2001; Valero, et al. 2006).

Exergy and ecological economics (Exergy Economics)	If the Earth is treated as a closed system, the concepts of exergy and entropy yield different economic implications, suggesting that constraints are imposed on economic growth because economic processes utilize high-exergy (or low-entropy) raw materials such as fuels and high-grade minerals, and discard low-exergy (or high-entropy) wastes. Economics and the second law have been linked via eco-thermodynamics, which assumes the economic significance of the second law is that exergy is not conserved and is a useful measure of resource quality and quantity (Ayres 1998). Exergy is treated as a factor of production like labor and capital, with strong implications for economic growth theory (Ayres and Warr 2005).	The approach allows direct quantitative comparisons of factors like labor, environmental impact, and externalities (Ayres, Brockway and Aramendia 2019). Thermodynamics and economics are integrated to obtain exergy-based indicators of sustainable development (Ferrari, Genoud and Lesourd 2001) The method allows firmsand governments to set environmental goals and programs (Rosen 2008).	There are several significant types of research in this area such as the one developed by Ayres (1998) "Eco-thermodynamics: economics and the second law", (Ayres, Brockway and Aramendia 2019). "The key role of energy in economic growth", (Ferrari, Genoud and Lesourd 2001). "Thermodynamics and economics: towardsexergy-based indicators of sustainable development"; Sciubba and Zullo (2011) "Is sustainability a thermodynamic concept?", and others.

Source: Based on Rosen (2008).

1.1.2. Exergy and cost accounting

The idea of combining exergy and cost streams was first introduced by Benedict in 1948, he determined the total cost attributable to the irreversibility's and used this cost for "optimal design" (Valero and Torres 2006). In 1952, Rant introduced the name "exergy", defined as external useful work in opposition to the energy (internal work)[1]. Tribus and Evans Fin the early 1960's developed the idea of exergy costing and its applications to engineering economics, they called it "Thermoeconomics"[2]. El-Sayed, worked with Evans and Tribus in combining second law of thermodynamics with economic considerations, for optimization of energy systems and published in 1970 a key paper, called "Thermoeconomics and the Design of Heat Systems". In parallel, Gaggioli directed the Ph.D. Theses of Reistad (1970) and Wepfer (1979) on "Second Law Costing" methods that include the definition of rules to provide a rational distribution of the cost.

In 1985, Gaggioli encouraged the discussion of thermoeconomics in the American Society of Mechanical Engineers (ASME), promoting annual international meetings that included the discussion of the breakthroughs in this field (Valero and Torres 2006). The interest and works regarding to thermoeconomic analysis highly increased since then: Tsatsaronis (1985), introduces the key concept of Fuel and Product. Kotas (1985) published the book "The Exergy Method of Thermal Plant Analysis", that is one of the basic references in in exergy analysis and thermoeconomics. Frangopoulos (1983)and Von Spakovsky (1986), applied and formalized the method of Evans and El-Sayed. In 1986 Valero and co-workers published another key paper "A General Theory of Energy Saving" where the Theory of Exergy Cost was introduced (Valero and Torres 2006).

In the 1990s important work starts to achieve a greater standardization and formalism. The potentialities of thermoeconomics methods to analyze environmental and economic issues has helped to increase the interest in this field around 1993 (Valero 1998). From an engineering perspective the interest for applying these kinds of methods was motivated by the question about the limits of perfection in devices like heat exchangers. Engineers' efforts towards reversible processes are affected by economic conditions, considering that investment is a restriction (Tsatsaronis 1985). For economist, the interest is motivated by the idea that there are ecological, more specifically, thermodynamic limits for economic activities and economic

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[1] Other outstanding authors are Beyer, Baehr, Brodiansky, Szargut, and Knoche among others.

[2] The essence of the Evans-Tribus procedure was to trace the flow of money, fuel cost and operation and amortized capital cost through a plant, associating the utility of each stream with its exergy.

growth (Ayres 1998), and that the role of energy as a factor of production has been underestimated by mainstream economics (Ayres and Warr 2005).

Thermoeconomic methods are generally divided in two categories, those based on cost accounting[3] and those based on optimization techniques[4]. Cost accounting methods help to determine the actual cost of products and provide a rational basis for pricing, while optimization methods are used to find optimum design or operation conditions (Valero and Torres 2006). This research will use cost accounting methods more specific in ERC to analyze depletion of mineral resources, efficiency, and sustainability.

1.1.3. ERC as a measurement of energy efficiency and natural resources depletion

Exergy Replacement Cost (ERC) quantifies the exergy needed to reconcentrate extracted mineral (fuel and no-fuel) from the reference environment (RE) to the condition of concentration found in the mine via the best available technology (Valero and Valero 2014). The RE is a condition with stable equilibrium, with all parts at rest relative to one another. No chemical reactions can occur between the environmental components. The reference environment acts as an infinite system and is a sink and source of heat and materials (Alzahrani and Dincer 2018). Valero and Valero (2014) proposed "Thanatia[5]" as a boundary limit and as a reference environment for calculating the exergy costs of mineral resources, it represents an exergy baseline of a theoretical future planet where all viable non-renewable resources have been consumed and dispersed. As mineral deposits become exhausted, the exergy difference between a mine and the baseline reduces.

ERC considers the scarcity degree of the commodities in the crust and the energy required to extract them. When a mineral (fuel and non-fuel) is scarcer and its extraction processes are more difficult, its ERC value becomes higher (Valero and Valero 2014). It also considers the use of the best available technology because as mentioned by Valero et al. (2014), considering that efficiency is the heart of thermodynamics, any improvement to efficiency will immediately decrease the cost of production. Hence the importance of optimizing the use of those inputs with the greatest exergy replacement costs, as they are the most important in terms of conservation.

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[3] Exergy Cost Theory, Average Cost Approach, Last-In-First-Out Approach, and those based on optimization techniques.

[4] Thermoeconomic Functional Analysis, Engineering Functional Analysis

[5] Thanatia is a conceptual model of a twilight Earth depleted in resources and a reference base that allows, by comparison, the calculation of the exergy of the planet's abiotic resources (Valero & Valero, 2014).

The ERC is based on the idea that when a resource is extracted over time, the quantity and quality of deposits still available tends to decrease and the exergy investment to obtain the same unit will rise, assuming that the best technology is used and that the easiest deposits to extract are first to become depleted (Whiting, et al. 2017). To estimate the exergy replacement cost defining a reference environment is important. Exergy is evaluated with respect to a reference environment.

Within the framework of exergy accounting, exergy in minerals has two components, chemical, and concentration exergies. The total exergy (b^*) is the minimum amount of exergy required to get the mineral from a reference environment (Thanatia) (Domínguez, Valero and Valero 2013). Total exergy is the sum of the chemical composition and concentration exergy:

$$b_i^* = b_{ch} + b_c \qquad (1)$$

ERC considers the cost of the creation of natural compounds or chemical composition and the cost of concentration of those compounds into viable deposits or exergy concentration (Carmona and Whiting 2014) as shown in equation (2).

$$= b_i^* = k_{chi} \times b_{chi} + k_{ci} \times b_{ci} \qquad (2)$$

Where:

$b_i^* =$ ERC of compound i

$b_{chi} =$ chemichal exergy of i

$b_{ci} =$ concentration of exergy of i

k_{chi} ; $k_{ci} =$ are dimensionless parameters, are the chemical (formation) and concentration exergy costs when the best available technology (BAT) is used to respectively form and concentrate i. According to Valero and Valero (2014):

k_{chi} is the physical and dimensionless unit exergy replacement cost of refining, calculated as the ratio between the real energy invested in the process and the minimum chemical exergy

(b_{ch}). And k_{ci} is the unit exergy replacement cost of concentration, calculated as the ratio between the real energy invested in the process and the minimum concentration exergy (b_c). These parameters must be determined for each type of mineral with the assumption that the same technology is applied in all concentration ranges, including those found in Thanatia and in mineral deposits.

There is a significant difference between applying ERC for fuels and for non-fuels minerals. mentioned that, the value of a given fossil fuel relies on its inherent chemical exergy, which once burnt disappears, this means that once fossil fuels are burned, they cannot be replaced or re- concentrate (Valero and Valero 2014). Meanwhile, the chemical exergy of metals and other non-fuel minerals does not disappear, it is the concentrated state of minerals in deposits that is eventually lost. To develop a comparative analysis, it is important to consider that fossil fuels can be thermodynamically compared to the ERC of non-fuel mineral resources. In fact, the exergy of fossil fuels is in the same order of magnitude as the ERC of minerals.

To account ERC of fossil fuels only the chemical exergy of the resource is considered, and it can be approximated to their high heating values. Valero and Valero (2014) calculated chemical exergy for fuel-oil 1, 2, and 4 since they are the most used, as shown in Table 1.2

Table 1.2. Higher Heating Value (HHV[6]) of different fossil fuels (kJ/kg) and ERC (GJ/ton)

Fuel	HHV	ERC (GJ/ton)
Fuel-oil 1	46,365	46.3
Fuel-oil 2	45,509	45.5
Fuel-oil 4	43,920	43.9

Source: Valero and Valero (2014)

The conversion factor to transform energy units into mass units is 1 GJ = 2.39 × 10−8 Mtoe. This allows working in energy units as well as mass units to develop any energy and mineral balance. Whiting, et al. (2017) highlighted that while the concept of ERC can serve as a

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[6] Higher Heating Value: A measure of heat content based on the gross energy content of a combustible fuel.

measure of mineral depletion, its definition necessitates further clarification. In relation to Thanatia or the RE, the authors expounded that the process of restoring a mineral to the mine does not require the consumption of exergy. Instead, it entails the expenditure of exergy to generate a deposit capable of satisfying people's needs.

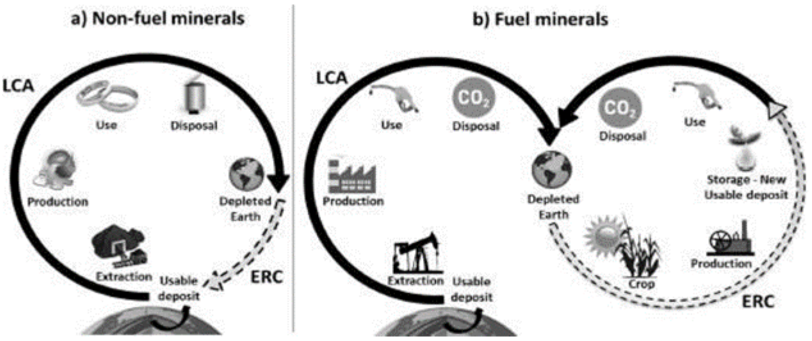
These first observations have two important implications: According to (Whiting, et al. 2017), this new definition of ERC will support the circular economy philosophy that stands that if we transform outputs back into inputs, the economy will be able to expand using less natural capital. The second implication is that “ERC can be used to evaluate the sustainability of any defined process or product, given that it measures the amount of exergy society would have to consume in order to re-capture and re concentrating a mineral to the point that it can be exploited by future generations to meet their needs” (Whiting, et al. 2017).

The second suggestion the “Lisboa school” make to clarify the definition of ERC is to focus on fossil fuel, and it imply considering “Nature´s ability through photosynthesis to provide a usable deposit that fulfills the function of fossil fuels, in the form of biomass” (Whiting, et al. 2017, 17). there on they mention Valero and Valero (2014, 552):

> Focus on society’s current inability to accelerate geological processes to provide fossil fuels, rather than Nature’s ability […]. Photosynthesis is important to the ERC concept because, although there is some research into synthetic fossil fuels, currently it is the only way that the carbon cycle can be closed, given that no established technology exists which can capture, concentrate, and re-convert atmospheric carbon dioxide back into fossil fuel. […] This allows for a quantitative comparison between […] non-fuel and fuel mineral calculations that existed previously. Such inconsistencies led to a considerable sub-estimation of the physical and economic cost of providing future generations with the resources needed to fulfill functions currently supported by fossil fuels.

The authors suggested that combining photosynthesis and the technological advancements achieved in bio-product accounting of resource depletion can be standardized and contribute to closing the carbon cycle, as shown in Figure 1.2.

Figure 1.2 ERC scope of non-fuel minerals and fossil fuel minerals



Source: Whiting et al. (2017)

In this respect, Whiling et al. (2017, 206) mentioned that:

> Chemical exergy is not the same as the exergy required to re-capture and re-concentrate carbon dioxide, using currently available technology, into a hydrocarbon used to be re-used. […] The difference between the ERC and chemical exergy is that the former represents the cumulative exergy required to obtain a resource using current (or best) available technology, while the latter is the "minimum replacement cost." Furthermore, the problem with Valero's (2014) statement is that there is an inherent assumption that the only way to create new fuel deposits is through geological processes that transform organic material into fossil fuels. And while it is true that fossil fuels cannot be reproduced within an individual's lifetime with the current best available technology, such as carbon capture and storage, the carbon cycle can be closed through photosynthesis. Consequently, the best available technology, as it stands, is the planting and processing of fuel crops, or the diversion of organic wastes, to produce alternative fuels that fulfill the function of fossil fuels […]

Considering this, the authors of "Lisboa school" had proposed an alternative pathway of analysis called "sun-to-fuel" and "crop-to-fuel" that include photosynthesis and bio-products that might substitute in some level fossil fuels and close the carbon cycle into the analysis. They calculated the ERC of each one, as is shown in Table 1.3.

Table 1.3. ERC of fossil fuels, including ERC of photosynthesis and bio-production

Mineral	k or ERC Photosynthesis (Mj/Mj)	k or ERC Bioproduction (Mj/Mj)	k or Total ERC (Mj/Mj)	Total ERC (Gj/Tonne)
Coal	61.12	3.64	62.35	1414.7

Oil	43.06	6.15	47.52	2170.0
Natural Gas	13.73	3.00	16.19	575.3

Source: Whiting et al. (2017)

The ERC method has been mainly applied to no-fuel minerals until recently because the methodological approach proposed by Valero and Valero (2014) focuses on society´s current inability to accelerate geological processes to provide fossil fuels rather than Nature's ability to provide a usable deposit that fulfills the function of fossil fuels. Current academic work includes the accounting of non-fuel mineral depletion at global (Valero and Valero 2014), regional (Palacios, et al. 2018b; Palacios, et al. 2018a) national (Carmona, et al. 2017; Valero and Torres 2006; Calvo, et al. 2021), and product scale (Valero, et al. 2006). That is why the contribution of Whiting, et al. (2017) presents the opportunity to develop an analysis of fuel minerals depletion as well.

The approach used by Whiting et al. (2017) complements this idea because they talk about the importance of considering nature´s ability (through photosynthesis) to provide a usable deposit of fuels that can substitute the function of fossil fuels. The authors suggest that with the help of technology and bio-products, we can reduce the depletion of mineral capital and close the carbon cycle. This, of course, is an alternative. However, still, we will have some level of inevitable loss as energy demand rises, and there will be a trade-off between energy security and food security.

It is important to remember that ERC is based on a resource extracted over time, the quantity and quality of deposits still available tend to decrease, and the exergy investment to obtain the same unit will rise, assuming that the best technology is used and that the easiest deposits to extract are first to become depleted (Whiting, et al. 2017). Second, there is a lack of information about properties such as resource quality and relative concentration (Valero and Torres 2006).

Considering the application of ERC for fuel minerals, (Valero and Valero 2014, 280) mentioned that fuels have the particularity that their quality (grade) remains near-constant with extraction. Therefore, the value of fuels is closely related to their chemical exergy content. Carmona, Whiting, Carrasco, and Sousa (2017) complement this approach by making an adjustment to the reference environment (ER) the authors mention that “a society does not need to consume exergy to place a mineral back into the mine but instead needs to consume the exergy necessary to provide a usable manmade deposit.” From this perspective, ERC can be used to evaluate the sustainability of any defined process or product, given that it measures the amount of exergy society would have to consume to re-capture and re-concentrate a mineral to the point that it can be exploited by future generations to meet their needs.

This paper aims to contribute to this methodological approach by proposing an adaptation of ERC using EROI to account for quality loss. Also, I will apply the ERC approach considering the suggestion made by “Lisboa School” about using the ER considering the exergy necessary to provide a usable manmade deposit and not Thanatia.

In this sense, the "EROI" is a proposed physical indicator that is used as a proxy of the quality of energy resources as energy return on (energy) invested (from which its acronym EROI comes), which, like its financial counterpart return on investment (ROI) is a ratio of outputs to inputs (Cleveland, Costanza, et al. 1984). We define EROI as the ratio that measures the energy produced in relation to the energy used to create it (Fizaine and Court 2016, Murphy and Hall, Energy return on investment, peak oil, and the end of economic growth 2011). The basic economic theory leads to the expectation that a declining EROI may be associated with an increasing marginal cost of production and, ultimately, an increasing price at which the commodity (energy) is traded (Heun and Wit 2012).

1.1.4. EROI as a measurement of energy investment and quality

There are significant contributions that examine how EROI relates to the price of oil and economic growth. For instance, Murphy and Hall (2011) examined the relationship between EROI, oil price, and economic growth. They found that high oil prices led to an increase in energy expenditures as a share of GDP, which has historically led to recessions. They found that oil prices and EROI are inversely related, implying that increasing the oil supply by exploiting unconventional and lower EROI sources would require high oil prices. This created what Murphy and Hall (2011) called the ‘economic growth paradox: increasing the oil supply to support economic growth will require high oil prices that will undermine that economic growth. King and Hall (2011) analyze the relations between EROI, energy price, and the profitability of the energy business. They study individual fossil and renewable energy businesses and the electricity sector, finding similar results proving that as EROI decreases for depleting fossil fuel production, the corresponding energy prices increase dramatically. Also, Heun and Wit (2012) investigated whether a declining EROI is associated with an increasing oil price and speculated on the implications of these results on oil policy.

A study by Espinoza et al. (2019) calculates the peak oil for Ecuador using the Hubbert curve; the authors conclude that the peak oil extraction obtained ranges between 196 and 215 MMbbl and would be reached in the years 2014-2025. Research had projected the future oil extraction in Ecuador based on Hubbert models; they obtained the peak oil extraction in a range between 196 and 215 MMbbl and would be reached in the years 2014-2025 (Espinoza, et al. 2019); this means that Ecuador could become a net oil importer between 2024 and 2035, depending on the model and demand scenario.

1.2. Methodological Framework

This section introduces the methodological framework employed in this study. Building on the preceding sections, it's evident that the challenges surrounding appropriate energy resource utilization and sustainability are both critical and multifaceted, given the pivotal role of energy in upholding the economic system. Consequently, the core objective of this research is to enrich the discourse on oil extraction efficiency and sustainability, employing the private oil sector in Ecuador as a case study. In pursuit of this goal, the study addresses the pivotal question: "Up to which year does the continued extraction of oil in Ecuador remain both efficient and sustainable?" As previously mentioned, oil extraction in Ecuador is economically and energetically important, so it is necessary to incorporate an indicator that allows the loss of well quality caused by the extractive process to be added to the efficiency analysis. To do this, I use the exergy replacement cost (ERC) through the EROI as a degradation factor to determine energy cost.

In this sense, this section develops four stages: 1) data gathering of fuel minerals (oil) for the period 2000-2020; 2) conversion into chemical exergy terms; 3) calculation of the EROI as a degradation indicator for the same period; 4) calculation of the energy cost of oil extraction in Ecuador.

1.2.1. Data gathering

The first stage consisted of the collection of extraction data of fuel minerals. For this study, only oil is considered due to its importance for the Ecuadorian economy and the Ecuadorian energy matrix. Data regarding fossil fuel extraction, reserves, and consumption were provided by National Energy Balance 2020, issued by the Ministry of Energy and Non-Renewable Natural Resources.

To analyze oil in terms of its energy generation capacity, I will express its chemical exergy. According to Valero and Valero (2014), the chemical exergy of the resource can be approximated to their high heating values. They calculated chemical exergy for fuel-oil 1, 2 and 4 since they are the most used as shown in Table 1.3. For this study I will use the HHV of fuel-2 calculated by Valero & Valero (2014), showed in Table 1.3.

1.2.2. Chemical exergy

To convert extraction from barrels to tons I used the conversion factor of the *Manual Estadística Energética* (2017) provided by Latin American Organization of Energy (OLADE). Once we have the value of oil in exergy terms, I will calculate the degradation factor EROI. To include the factor of "degradation" we will use the Energy Return on Investment (EROI) of oil in Ecuador for the period 2006-2020. To determine EROI of oil extraction in Ecuador I will use the methodology proposed by Amores et al. (2020).

To determine the point in which it is not profitable from an energy perspective to keep extracting resources. I will project the historical EROI until 2040 considering the Energy Forecasting Study of Ecuador (2012-2040) made by the Ministry of Electricity and Renewable Energy of Ecuador (currently known as Ministry of Energy and Non-Renewable Natural Resources). I will consider two theorical points of comparison. The first one is the EROI in 1:1 (energy efficient) this means that if I invert one barrel of oil, I will obtain 1 barrel of oil; the assumption here is that this is the limit because an investment of 1 barrel of oil to obtain less than one barrel will be consider inefficient. The second is the minimum EROI that will be required for a sustainable society. To determine this point, I will consider the results calculated by several authors such as Hall et al. (2009), Sloman (2014) and Fizaine and Court (2016).

1.2.3. EROI as a degradation indicator

To include the factor of "degradation" we will use the Energy Return on Investment (EROI) of oil in Ecuador for the period 2000-2020. EROI can be expressed as:

$$EROI = \frac{Energy\ returned}{Energy\ invested} \qquad (3)$$

EROI is a ratio for describing a measure of energy produced in relation to the energy used to extract it (Fizaine and Court 2016, Murphy and Hall, Energy return on investment, peak oil, and the end of economic growth 2011). Several methods for calculating the EROI have been proposed with methodological differences. The disagreements relate to the way energy flows (Murphy 2014), system boundaries, and residual energy embedded in co-products are identified and quantified (Castro, González and Capellan 2019). To determine EROI of oil extraction in Ecuador, the methodology proposed by Amores et al. (2020) is used.

These authors perform a preliminary calculation of the EROI of Ecuadorian oil, at a country level and by blocks, obtaining preliminary results EROI for oil production blocks 7, 10, 15, 16, 21, 46, 47, 56, 57, 60, 61, 62 and 67. Therefore, based on Amores et al. (2020) and Muphy (2014) EROI can be expressed by the following equation $EROI_{1d}$:

$$EROI = \frac{E_o}{E_i} \tag{4}$$

Where:

E_o = consumption of fuels for electricity generation.

E_i = the volume of scaled production, in energy terms as tons of oil equivalent (TEP), which is measured prior to entering the Trans Ecuadorian Oil Pipeline System (SOTE) and the Heavy Crude Oil Pipeline (OCP) through Lease Automatic Custody Transfer (LACT) and Automatic Custody Transfer (ACT) units.

Pearson correlation

1.2.4. Evolution of energy cost

To account for the energy cost I used the following steps:

First, I use the EROI to calculate the percentage of additional energy required each year using the following equation:

$$\left(\frac{\frac{1}{EROI}t_1 - \frac{1}{EROI}t_0}{\frac{1}{EROI}t_0} \right) \times 100 \tag{5}$$

Second, to determine the energy cost I multiply the % additional energy (Equation 5) by the historical extraction rate (Ext):

$$Energy\ cost = \Delta(Eq.5) \times Ext. \tag{6}$$

Finally, I multiply the historical extraction (Ext) in chemical exergy terms (Mtoe) by (1+ additional energy fraction) to determine the site "degradation" (Mtoe):

$$Site\ degradation = \Delta(Ext.) \times \left(1 + (Eq.5)\right) \tag{7}$$

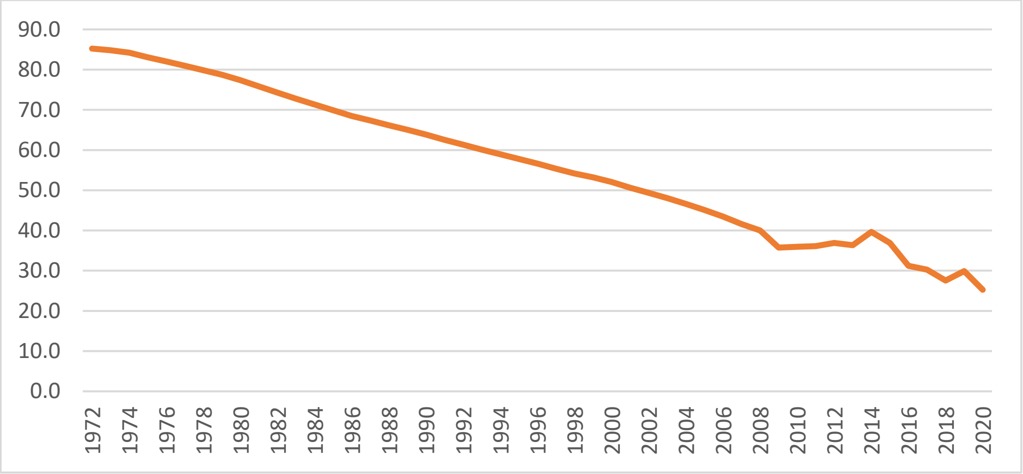
Having clear the procedure to be followed in the next section the results are presented.

1.3. Results

The first thing to consider is that in the case of oil, only the chemical exergy is considered to account for the ERC, since its exergy concentration is equal to zero due to the exergy lost in the combustion process is burned and transformed into CO2 and therefore cannot be reconcentrated. In terms of exergy replacement cost (ERC), Valero and Valero (2014) determined the ERC for fuel minerals (Table 1.3). Acording to Palacios et al. (2018b) higher values of ERC indicate a higher quality of minerals and imply a higher loss of mineral wealth when they are extracted. It can be seen in Table 3.3 that ERC values for minerals that are abundant and easily extracted, like coal, are lower than those which are scarcer, because their extraction implies higher energy consumption.

Also, the EROI for the period 1972-2020 shows a decreasing trend, which is in line with what is stated in the literature for other case studies. The EROI was used as a degradation factor to determine the energy cost of oil extraction in the country. A decreasing EROI implies that more energy is required to obtain the same outcome energy. In other words, while EROI is decreasing, the degradation of the field in energy terms is increasing. This implies that as a barrel of oil is extracted, the oil field loses not only quantity but also the quality of energy production. It is necessary to invest more energy to extract the next barrel (see Figure 1.3.).

Figure 1.3. EROI and additional energy cost in Ecuador 1972-2020



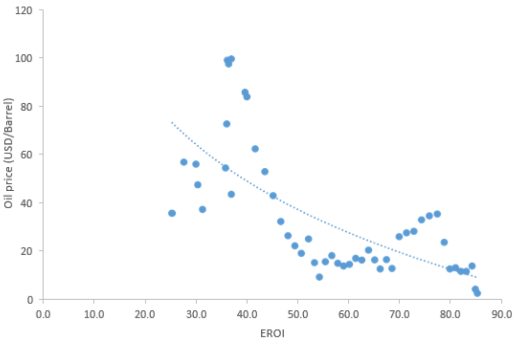
Elaborated by the autor

In the case of Ecuador, in 1972, when the oil boom began, the EROI was 85.2; it should be noted that this data has certain limitations since, until 2006, all companies did not need to report data on operations, so this data has some information gaps. Since 2006, it has been mandatory for all companies to report information on operations and costs so that more information is available and the EROI calculation is more rigorous. With these clarifications, it can be seen that in 2006 the EROI was 43.5 and decreased to 25.25 in 2020. These calculations would follow the decreasing trend shown in other studies on EROI around the world. For example, in the United Kingdom (Brand-Correa, et al. 2017; Hall 2017), United States (Cleveland 2005; Heun and Wit 2012), China (Xu, et al. 2020; Feng, et al. 2018) and developing countries (Bangladesh, India, Thailand, Brasil, Nepal, Uruguay, China, Pakistan, Zambia, Ethiopia, Sierra Leone and Zimbabwe) (Lambert, et al. 2014).

On the other hand, when analyzing the relationship between the EROI and the price of oil in Ecuador, there is a significant and negative relationship. This implies that as the EROI declines, oil prices tend to increase over time due to the increase in extraction costs (see Figure 1.4). In other words, more energy is required to extract energy from crude oil, and this has a direct impact on prices. The price of international oil is determined by biophysical, economic, financial, and geopolitical factors. Regarding biophysical factors, authors such as Murphy (2014) and Kreps (2020) have identified that as the cost of oil extraction increases, the price increases for countries such as the United States, Canada, Mexico, and Brazil. Likewise, the extraction cost (in energy terms) is a variable that negatively influences the EROI calculation since it is a proxy for the energy required to extract a barrel of oil. In fact, Kreps states, "in biophysical economics terms, "low EROI" is another way of saying high cost." Therefore, the continuous increase in oil extraction costs at the international level, because of the depletion of this resource and the greater energy invested for its extraction, explain the negative relationship between the EROI and the price of oil. This relationship is validated for the Ecuadorian case, and the fact that it is a price taker country does not affect the sign of the relationship, since Ecuadorian oil prices move in the same direction as international prices. In addition, according to Hall (2014), the trend of high prices has led to oil producers to relay in poor quality fields located in difficult places together with the enhanced recovery of oil from existing field which increase energy intensive, therefore the level of EROI drops (Figure 1.4).

The EROI allows us to show from a biophysical perspective the reduction in avoided costs as actual costs increase. These ‘real’ costs must be borne by the actors who benefit directly from the extraction of the resource, i.e., the oil companies. The moment the government subsidizes electricity, it is the citizens who assume this real cost, thus reducing the welfare of society. The distortion generated by subsidies on welfare will not be an issue that will be analyzed in this paper, but it is considered an important topic that should be addressed in future research.

Figure 1.4. EROI and additional energy cost in Ecuador 1972-2020



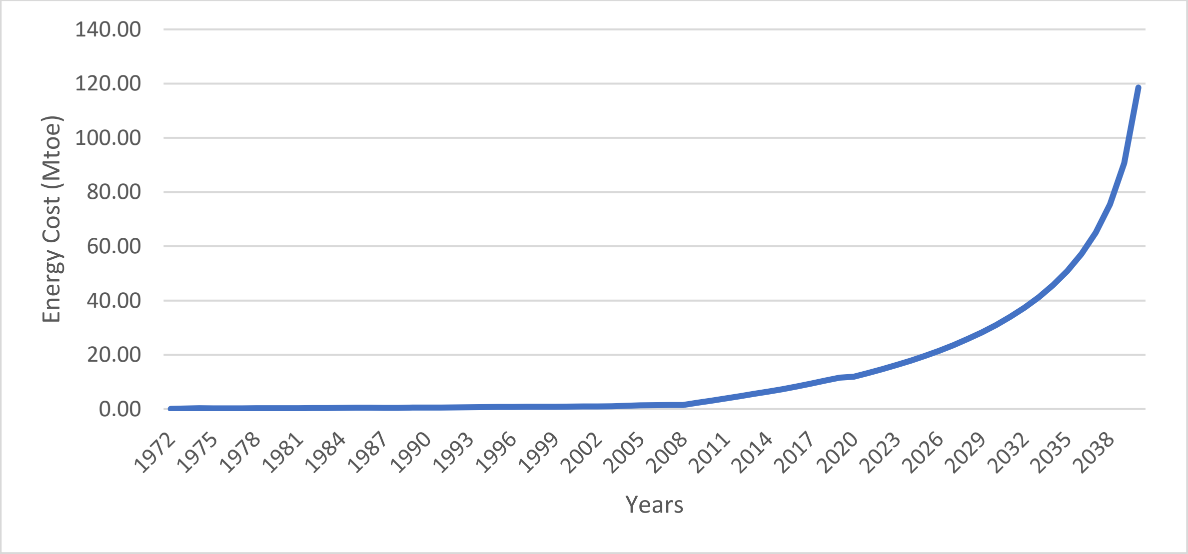
Source: Elaborated by the author

Note: A linear projection was used to calculate oil prices. The R^2 coefficient showing the fit of the data to the regression is 0.5. The curve fit is quadratic.

1.3.1. Energy cost calculation using EROI

As mentioned in the previous sections, an adaptation of the ERC using EROI will be used to measure the energy cost of oil extraction in Ecuador. As can be seen in Figure 1.5., the energy cost follows an exponential path, this follows the results obtained for non-fuel minerals presented in Valero and Valero (2014).

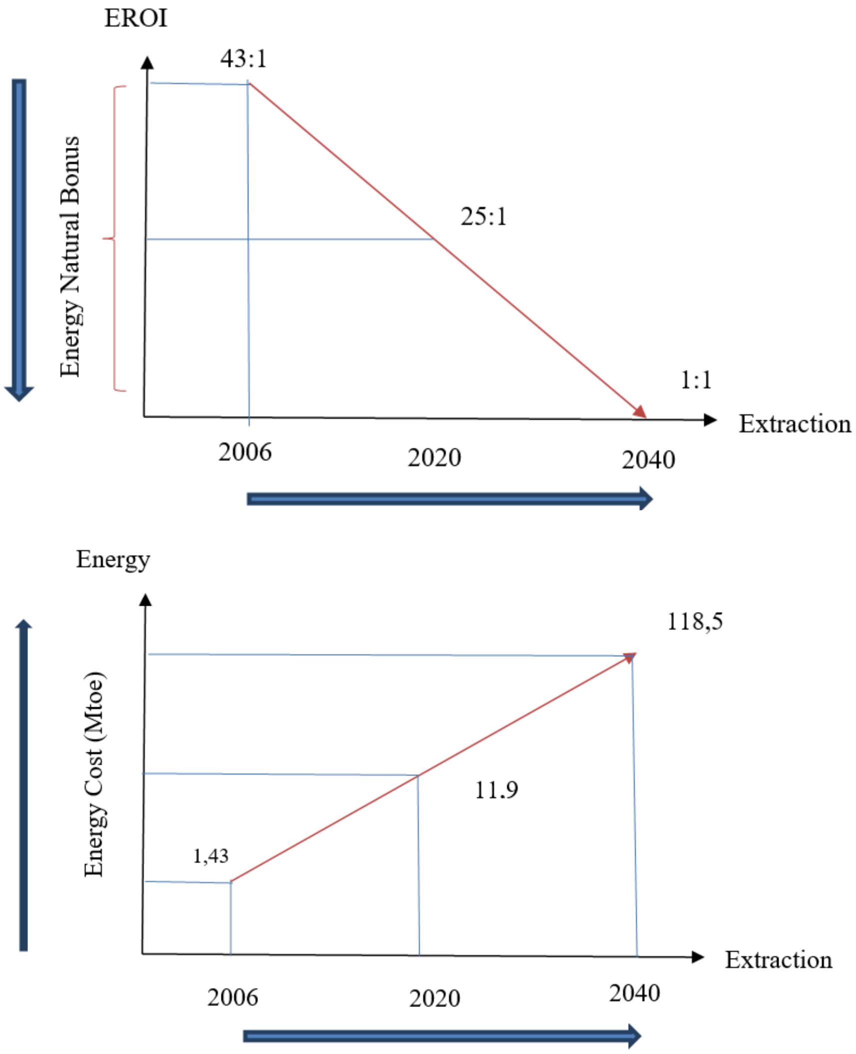
Figure 1.5. Energy cost of oil in Ecuador (1972-2040)



Source: Elaborated by the autor

According to Valero and Valero (2014) nature provides a natural energy bonus that is reduced every time we extract an additional barrel of oil. This implies that as we reduce this natural energy bonus, the energy cost of extraction increases. This fact has significant impacts for society since it implies that the companies that started their activities at time (t_0) benefited from this bonus and had to invest less energy. Companies that take on the project years later must assume higher energy costs. In terms of intertemporal justice, States should consider this cost of quality degradation for the calculation of royalties, since although the depletion of reserves in terms of quantity is currently considered in the calculation, their depletion in terms of quality is not considered Figure 1.6. shows a representation of the reduction in energy bonus linked to an increase in extraction and therefore in energy cost.

Figure 1.6. Declining on energy natural bonus vs increment of energy cost (2006-2040)



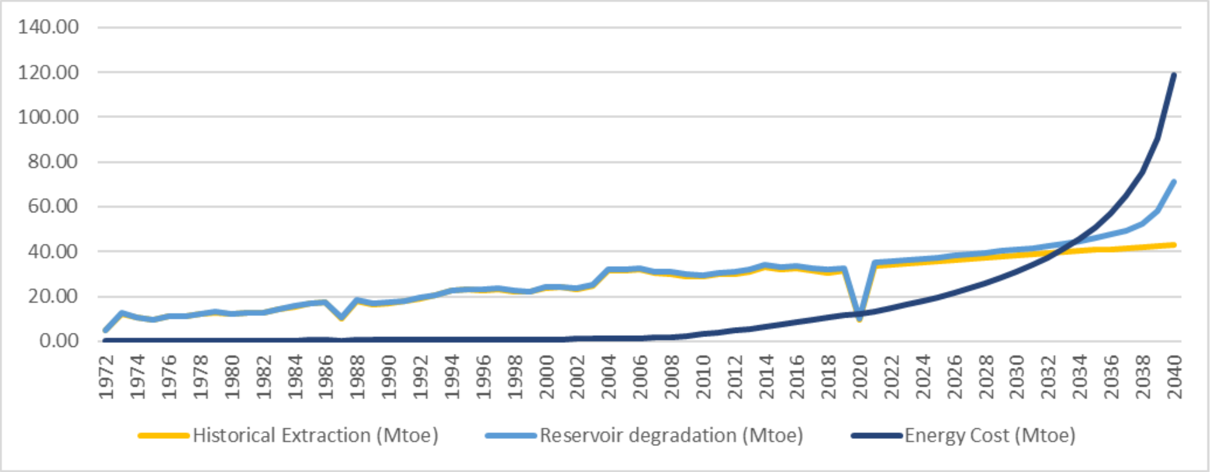
Source: *Elaborated by the autor*

It is also important to note that the increase in energy costs has important implications for the States. In Ecuador, for example, electricity is subsidized, and the increase in energy costs implies an increase in the number of subsidies. This implies that the State will allocate more funds to energy subsidies and less funds to areas such as health and education. Finally, the increase in energy costs affects future generations who will have to invest more energy to maintain a lifestyle similar to the current one. The analysis of energy costs contributes to the discussion on sustainability, since the energy bonus lost with extraction is irreparable and affects the quality of life of future generations. In this sense, several authors have spoken of the minimum EROI required to maintain a sustainable society.

1.3.2. Minimum EROI required for a sustainable society

There is plenty debate about the minimum EROI for a "sustainable society", Hall et al. (2006) developed a study for US for oil and bioethanol and they conclude that the minimum EROI required was 3:1. Meanwhile Sloman (2014) an EROI of 2 could be made to work in a society structured to devoting half its energy (in the strictly thermodynamic sense) to building replacement energy generation equipment. In the case of Ecuador oil industry in 2034, the quality of the fields will decrease in a point that is not profitable to keep extracting the resource (see figure). The EROI in this year will be 9:1, this value is close to the minimum EROI found by Fizaine & Court (2016) that conclude that US growth was only possible if its primary energy system has at least a minimum EROI of approximately 11:1.

Figure 1.7. Evolution of extraction vs. variation of the energy cost 1972-2040



Source: Elaborated by the autor

In addition, it is important to mention that this finding agree with the study of Espinoza et al. (2019) that developed Hubbert based models to project future oil extraction in Ecuador and they concluded that Ecuador could become a net oil importer between 2024 and 2035, depending on the model and demand scenario.

1.3.3. Efficiency and sustainability: EROI 1:1

An EROI of 1:1 implies that for every barrel of oil invested we get 1 barrel of oil, so after that point it is no longer efficient to continue extracting in energy terms since I would have to invest more energy than I get. Currently in many countries this phenomenon is occurring since the oil industry is still profitable and more energy is invested using biofuels to compensate for the degradation of the oilfields (Castro, González and Capellan 2019). For the purposes of this thesis an EROI of 1:1 will be considered as the efficiency limit. That is, after this point it will not be considered efficient to continue extracting oil in energy terms.

1.4. Conclusions and Discussion

In summary, this study underscores the critical role of energy in all facets of economic production and exchange, emphasizing the historical reliance on abundant fossil energy. However, as we confront the reality of declining Energy Return on Investment (EROI) for traditional fossil fuels and the relatively lower EROI of renewable and non-conventional energy sources, it becomes evident that our energy landscape is shifting. This shift has far-reaching implications for our society and economy.

At the societal level, the decline in EROI necessitates an increasing diversion of energy output and economic resources towards sustaining the energy needed to drive our economy. This phenomenon raises concerns about the sustainability of our current economic model.

In the context of Ecuador, our analysis spanning the years 1972-2020 mirrors the global trend of decreasing EROI. This trend serves as a key factor in determining the energy cost of oil extraction in the country, illustrating that not only does the quantity of energy production decline as oil is extracted, but the quality diminishes as well. This means that each subsequent barrel of oil extraction requires more energy investment.

Furthermore, our investigation reveals a significant and negative correlation between EROI and oil prices in Ecuador. As EROI declines, oil prices tend to rise due to increased extraction costs, highlighting the direct impact of energy investment on market prices. These findings are consistent with existing literature, further reinforcing the global implications of declining EROI.

Moreover, our analysis projects a critical juncture in 2034 when the quality of oil fields reaches a point where extraction is no longer economically viable. The projected EROI for that year is 9:1, which aligns closely with the minimum EROI threshold identified by Fizaine and Court (2016) for sustaining economic growth in the United States. This projection also corresponds with the conclusions drawn by Espinoza et al. (2019), who employed Hubbert-based models to forecast Ecuador's future oil extraction. Their findings suggest that Ecuador may transition from a net oil exporter to an importer between 2024 and 2035, contingent on various models and demand scenarios.

In conclusion, our study underscores the urgency of addressing declining EROI and its far-reaching consequences for the global economy. It serves as a critical call to action, emphasizing the need for sustainable energy solutions and careful economic planning to mitigate the impending challenges associated with diminishing energy returns in the coming decades.

This analysis sheds light on the urgent need to transition to more efficient and sustainable energy sources, which will not only benefit Ecuador but can also serve as a valuable example for other nations facing similar challenges. By addressing these critical issues proactively, we can work towards a more efficient, sustainable, and economically prosperous future for generations to come.

Chapter 2. Energy efficiency and environmental productivity: Analysis of oil companies in Ecuador

2.1. Introduction[7]

According to the International Energy Agency, the oil industry contributes to approximately a third of the world's total carbon emissions (IEA 2021).Thus, oil companies must be more efficient and balance pollution mitigation and economic performance. Some studies show the importance of energy efficiency in improving the economic performance of oil companies by reducing costs (Midor, et al. 2021, Yáñez, et al. 2018, Longwell 2002). However, when assessing the energy efficiency of oil companies, most studies have frequently ignored environmental aspects (Hou, et al. 2019; Jung, Kim and Rhee 2001). Therefore, fewer studies are focusing on the environmental performance of oil companies. According to the literature in production economics, environmental productivity refers to the efficient utilization of pollution abatement and how this might influence the costs of alternative production and pollution abatement technologies (Kaneko and Managi 2004). Studies in this field are scarce, and most have been developed in developed countries and Asia.; see, e.g., Tavana et al. (2019), Wegener and Amin (2019), Sueyoshi and Wang (2014, 2018), Da Silveira et al. (2017), Azedeh et al. (2015), Song et al. (2015), Sueyoshi and Goto (2015), among others. To the author's knowledge, no studies have been developed in which energy efficiency and environmental productivity change in the oil sector is evaluated in Latin America, nor has a specific case study been made in the oil sector in one country in the region. This chapter aims to contribute to the literature on analyzing energy efficiency and environmental productivity at the industrial level by providing empirical evidence for private oil companies in Ecuador. The objective is to provide relevant information on how to use resources in oil sector companies to maximize their profits and minimize the emissions they produce.

For this chapter, it was considered a sample of 18 Ecuadorian private oil companies associated with extraction and refining activities of crude Oil in Ecuador. Ecuador is the fifth oil producer in South America. In 2019 oil extraction was 193.8 million barrels, of which 40.96 million barrels (21%) were extracted by private companies. Among all industry sectors, the petroleum industry is of particular interest to Ecuador because of its economic and environmental significance. Public and private companies own the oil industry in Ecuador. The public sector plays a more significant role due to more production and higher investment

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[7] A section of this chapter is devoted to the paper titled "Environmental Productivity Assessment: An Illustration with the Ecuadorian Oil Industry," which has been successfully accepted and published in the prestigious journal "Managerial and Decision Economics.

(World Bank 2018). Although, between 2000 and 2006, the sector was led by private investment. A shift in contract agreements in 2011 resulted in a decrease in the investment made by private operators. Oil is also essential for the Ecuadorian energy sector; in 2018, Oil represented 86.9 percent of the national energy supply. According to the Third National Communication on Climate Change and First Biennial Update Report (UNFCCC 2017), in Ecuador, the energy sector produced 37 594 Gg of carbon dioxide equivalent (CO2e), representing 47 percent of total GHG emissions in 2012. The energy industry is a significant contributor to GHG emissions in the country, especially for the burning of fossil fuels. In 2012 this activity accounted for 36 822.54 Gg (CO2e), representing 97.95 percent of energy sector emissions.

Based on production value added during 2011-2020, the following sectors had the most significant share in GDP: Manufacture (14.10%), National trade (10.50%), Agriculture and fishing (9.18%), and Oil and quarrying (8.53%). Also, in the period analyzed, oil exports accounted for 54.83% of total exports, and oil revenues for 30% of overall fiscal income (Central Bank of Ecuador 2021).

To assess environmental efficiency and environmental productivity in Ecuador's oil companies, a non-parametric production model (Tulkens 1993) is applied as a practical approach to evaluating the pollution-adjusted productivity change of Ecuadorian petroleum companies. This method is widely applied in the literature for production analysis (Sueyoshi, Yuan and Goto 2017, Zhou, Ang and Poh 2008). As the difference of parametric models, this type of modeling does not need to specify a mathematical form for the production function explicitly. Moreover, it allows for assessing the environmental efficiency of multi-inputs and multi outputs production units by relaxing the convexity property of the pollution-generating technologies. To the best of the author‘s knowledge, no research has been performed in the oil industry field that analyses environmental productivity change considering a pollution-generating production model. Knowing the prominent drivers of energy efficiency and environmental productivity change is a significant concern in the applied economics literature (Miao, et al. 2019; Shen, Boussemart and Leleu 2017; Valadkhani, Roshdi and Smyth 2016) This chapter displays the main components of the pollution-adjusted productivity variation considering Ecuadorian oil companies. Identifying the primary sources of pollution-adjusted productivity change allows for displaying internal (technological processes, management skills, Etc.) or external (environmental policies, economic context, etc.) constraints that influence productivity variation. The main results of this chapter suggest that losses in efficiency and productivity are subject to the level of energy consumption and lack of technical change in companies for the period analyzed.

The remainder of this chapter is structured as follows. Section 2 displays the studies that approach the driver of energy efficiency and the non-parametric models to estimate energy efficiency. The parametric and non-parametric approach is presented in Section 3. The empirical illustration is provided in Section 4. Finally, Section 5 focuses on the discussion and conclusions of this research.

2.2. Literature Review

2.2.1. Environmental Productivity

In a context where natural resources are increasingly constrained, it is important to consider that a company's environmental productivity (EP) is an essential piece of information that companies needs to contemplate when they want to improve their performance. It is helpful to review what is meant by the term "productivity." Productivity expresses a relationship between the quantity of goods and services produced by a business, or an economy and the quantity of labor, capital, energy, and other resources needed to produce those goods and services (Finman and Laitner 2001). Meanwhile, EP involves the analysis of a company's relative efficiency in its use of and impact on natural resources (Wang and Shen 2016). According to the literature in production economics, environmental productivity refers to efficient utilization of pollution abatement and how this might influence the costs of alternative production and pollution abatement technologies (Kaneko and Managi 2004). Studies related to environmental productivity are scarce, and most have focused on developed countries (Beltrán-Esteve, Giménez and Picazo-Tadeo 2019) and Asia (Kaneko and Managi 2004).Most studies reviewed focus on implementing environmental regulation to improve environmental productivity in companies and countries (Wang and Shen 2016, Dewar 1984). Also, some of these issues are widely covered over industrial energy efficiency; studies in this field have found that improving energy efficiency and incorporating energy efficiency technologies have significant benefits on environmental productivity and allows to meet sustainable development goals (Cagno, et al. 2013).

2.2.2. Energy Efficiency and environmental productivity

Some studies review the relationship between energy efficiency improvement measures and productivity in the industry. Finman & Laitner (2001) reviewed more than 77 industrial case studies; the authors suggest that energy efficiency investments yield significant non-energy benefits, which are often not calculated. The description of energy-efficient technologies as opportunities for larger productivity improvements has significant implications for re-thinking how we quantify the savings associated with capital investment and the leverage points for promoting energy efficiency but may even challenge methods to use for conventional economic assessments. Blumstein et al. (1980) identifies six kinds of barriers that firms face to achieving industrial energy efficiency: 1) misplaced incentives, meaning the economic gains of obtaining energy efficiency are not always perceived by the decision makers; 2) lack of information; 3) regulation; referring to existing legal framework that conflicts with cost-effective measures; 4) market structure; as for example, the energy efficiency solution is not offered on the market; 5) financing, such as technologies that requires high initial investment; 6) firm's customs, as company practices that generate low energy efficiency performance. However, when assessing energy efficiency and industry productivity, most studies have frequently ignored environmental aspects to improve productivity (Jung, Kim and Rhee 2001). In addition, few studies focus on the environmental performance of oil companies (Hou, et al. 2019).

In the case of developing countries, the adoption of energy efficiency technologies and better practices with clear sustainable goals by firms are rarely explored in the literature. One of the reasons may be the lack of management support, prioritizing growth over environmental protection (Grover and Karplus 2020). The findings of Karplus, Shen, and Zhang (2020) suggest that companies in China do not usually consider energy efficiency interventions with return periods longer than one year. Energy efficiency efforts are essential in improving processes, minimizing the Impacts of oil quality depletion, and achieving sustainable development (Keskin, Dincer and Dincer 2020). Affordable clean energy and climate action are among the seventeen sustainable development goals. Energy security and environmental protection have become one of the most important issues on today's international agenda. In recent years, while the use of renewable energy is increasingly growing, fossil fuels still account for about 80% of global energy consumption due to their affordability in comparison with other sources of energy (IEA 2020b). However, these resources are scarce and highly pollutant. Policymakers, analysts, and business leaders increasingly pay more attention to energy efficiency to balance the relationship between energy economic growth and environmental pollution.

2.2.3. Energy efficiency and environmental productivity estimation methods

Knowing the primary sources of efficiency and productivity variation is of particular interest in the economic literature. Non-parametric programming modelings for production analysis are broadly applied to assess these issues. Some studies employed a DEA methodology using linear programming techniques (Boussofiane, Dyson and Thanassoulis 1991) to deal with undesirable outputs, such as GHG emissions, which ultimately affect companies' efficiencies. Many approaches have been put forward to account for this issue, such as parametric output and input distance functions (Färe, Grosskopf and Knox, et al. 1993, Coggins and Swinton 1996, Hailu and Veeman 2001, Ho, Dey and Higson 2006) and DEA methods (Skevas, Lansink and Stefanou 2012, 2014; Serra, Chambers and Lansink 2014; Kabata 2011; Yang, Wei and Chengzhi 2009; Ramli, Munisamy and Arabi 2013).

Song, Zhang, and Wang (2015) applied the Network DEA model to divide efficiency scores into two subcategories, thus feeding back more accurate results. In China, production and environmental efficiency changes were evaluated in twenty local oil companies. Sueyoshi and Goto (2015) incorporated Malmquist's index in the environmental assessment of oil companies' studies. Azedeh et al. (2015) demonstrated the usability of DEA in studies related to health, safety, and the environment in an oil refinery, improving ergonomic features in the business. Tavana et al. (2019) defined a fun multi-objective multi-period network DEA model customized to evaluate the dynamic performance of oil refineries in the presence of undesirable outputs. Wegener and Amin (2019) developed an inverse DEA model for optimizing GHG emissions applied to the oil and gas industry. The inverse DEA model minimizes the overall GHG emissions generated by a set of decision-making units (DMUs) for producing a certain level of outputs, given that the DMUs maintain at least their current performance status. Furthermore, Managi (2011) made an empirical contribution in this field based on data on the petroleum industry. The authors applied two alternative flexible production technologies to measure total factor productivity growth and test the significance of the convexity axiom using a nonparametric test of closeness between unknown distributions. The empirical results revealed significant differences, indicating that this production technology is likely non-convex.

Considering the above, this empirical study proposed a non-convex DEA modelling and a parametric model to analyze oil industry energy efficiency and productivity with undesirable outputs in private companies in Ecuador.

2.3. Methodological Framework

To analyze the issue of energy efficiency and environmental productivity in private oil companies in Ecuador this research employs a DEA model. DEA is an efficiency evaluation method based on the concept of relative efficiency. There are different types of DEA model such as SMB—DEA model, that is non-radial and non-input or non-output oriented, directly utilizes inputs and outputs to determine the efficiency measurement of DMUs. In line with this study's purpose, the SMB—DEA model with undesirable output is applied to estimate the energy efficiency and environmental productivity of 18 private oil companies in Ecuador. The selection criteria were given by comparing the companies size, and reported earnings between companies, with the aim of finding comparable units. This study only incorporates variables whose values can be changed in a reasonable period by decision-making units (Çelen 2013), and that allows for maximizing the benefits of oil extraction and minimizing undesirable outputs. To analyze and compare the dynamic efficiency of energy productivity among oil companies the Malmquist Productivity Index (MPI) is adopted. The MPI approach assesses the multi-faceted and multi-output environmental impact of time frame changes. This approach is used to account for the change in industry policy efficiency, with the advantage of estimating the functional association among inputs and outputs. The Malmquist and DEA approach are among the most used tools to estimate energy efficiency in industry (Zhou, Ang and Poh 2008; Zheng 2021). These methods are presented in more detail in the following sections.

2.3.1. Non-parametric model: DEA model and environmental productivity adjusted Malmquist Index.

This section displays the efficiency evaluation and productivity indices. The DEA method takes an economic system or a production process as an activity, where an entity (a unit) produces a certain number of “productions” by investing a certain number of elements within a limited range (Li, Li and Wu 2013). These entities (units) are called decision-making units (DMUs). Many DMUs constitute to be respective evaluation groups. The efficient production frontier is built on evaluating, with each input or output indicator’s weight as the variable under the analysis of input and output ratios. In the end, an efficient DMU or an inefficient

DMU can be determined according to the distance between this DMU and the efficient production frontier (Debreu 1951, Farrell 1957, Shephard 1953). These distance functions fully multiple inputs-outputs production processes. The following definition presents the multiplicative distance function (Abad 2018).

Definition 1

$$\begin{gathered} For\ any\ (x_t,\ y_t) \in\ R_+^{n+m}, where\ y_{\ t} = \left(y_t^d, y_t^u\right) \\ \in\ R_+^m\ , the\ multplication\ adjusted\ distance\ function, D^{\emptyset} \\ :\ R_+^m\ \rightarrow R\ \cup \infty\ is\ defined\ below: \\ D^{\emptyset}(\ x, y)\ = \begin{cases} inf_{\beta}\left\{\beta \in [0,1]: \left(\beta^{\alpha} x_t\ , \beta^{\gamma^d} {y_t}^d, \beta^{\gamma^u} {y_t}^u\ \right) \epsilon T\ \right\} \\ if\ \left(\beta^{\alpha} x_t\ , \beta^{\gamma^d} {y_t}^d, \beta^{\gamma^u} {y_t}^u\ \right) \epsilon T, \beta > 0 \\ else \\ \infty \end{cases} \\ where\ \emptyset = (\alpha, \gamma^d, \gamma^u) \epsilon \{0,1\}^{m^d} x \{0,1\}^{m^u} \end{gathered} \tag{8}$$

The multiplicative pollution adjusted function is employed to compute the Malmquist index. According to Nishimizu and Page **Fuente especificada no válida.**, this index can be discomposed into technical change (TEC) and technical efficiency change (EC) when examining productivity change. TEC was defined as change in the best practice production frontier, while EC was defined to include all other productivity change, including ‘learning by doing, diffusion of new technological knowledge, improved managerial practice, scale efficiency and so on’.

The next equations display the productivity index for the model:

$$\begin{aligned} & PM_t^{\emptyset}\ \left(x_{t,t+1}, y_{t,t+1}\right) = TEC * EC \\ & = \frac{D_t^{1,-1,0}\left(x_{t+1}, y_{t+1}^d, y_{t+1}^u\right)}{D_t^{1,-1,0}(x_t,\ y_t)}\ x\ \frac{D_t^{1,0,1}\left(x_{t+1}, y_t^d, y_{t+1}^u\right)}{D_t^{1,0,1}(x_t,\ y_t)} \end{aligned} \tag{9}$$

If the efficiency changes in $EC^{\emptyset}{}_{t,t+1}$ is greater than 1 then, efficiency progress arises over the periods (t) and (t + 1). Moreover, technological improvement occurs between the periods (t) and (t + 1) when $TC^{\emptyset}{}_{t,t+1}$.

Where:

$(x^t, y^t), (x^{t+1}, y^{t+1})$ are outputs and inputs vectors in t and $t + 1$

$D_{t,}, D_{t,t+1}$ are the distance functions between t and $t + 1$

2.3.2. Parametric model: Panel regression

I investigated the relationship between productivity index and economic variables using a Tobit panel regression model to specify individual DMU effects and cross-section data commonalities (Liu and Liu 2016). The standard linear model is not appropriate for such analysis, because the predicted values of efficiency scores may lie outside the unit interval. As the accumulation of scores at unity is a natural consequence of the DEA approach, the Tobit model was employed (Riaño and Larres 2021).

The relationship between energy practices and oil companies and the efficiency score is described using the model below:

$$MI_{it} = \beta_0 + \beta_1 Energy_{it} + \beta_2\, Capital_{it} + \beta_3 Employment_{it} + \beta_4 Emmisions_{it} + \beta_5 Oilproduction_{it} + \varepsilon_{it} \quad (11)$$

Where *MI* is the dependent variable, representing the scores obtained from the efficiency evaluation. Emissions represents CO_2 emissions per capita, introduced in logarithms and *Capital* in level, measured by the capital to labor ratio; Employment and is the labor, measured in person, and Energy is energy consumption measure in kwts/hour.

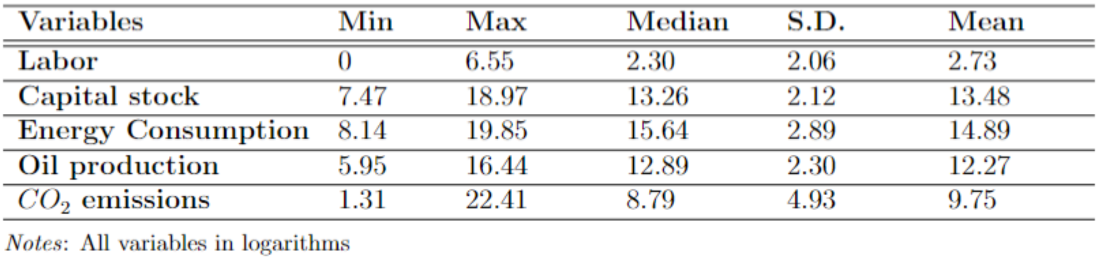
2.4. Data in brief

A sample of 18 private oil companies in Ecuador is considered over the period 2011–2020. The data set used in this research is built with the population of registered oil Ecuadorian formal firms, constructed from the balance sheets and financial statements registered on the official website of the *Superintendencia de Compañías, Valores y Seguros* (SCVS). This information is reported annually directly by firms to the SCVS.

The inputs and outputs selected are used in other DEA studies before for efficiency analysis of energy related industries to assess and monitor technical efficiency performance across a sample of companies, these inputs and outputs are directed related to the production process and have a greater relevance on the enterprises management level (Perreto et al. 2022).. Three inputs are selected: (i) number of formal employees of each company and (ii) net tangible assets (capital stock). Information about the number of legally registered employees (i) is declared by each company. The capital stock (ii) is set as the sum of the real dollar value of buildings, machinery and vehicles by assuming a depreciation of 5, 10, and 20 percent. Precisely, the methodology of Camino and Bermudez (2021) is employed. Hence, the capital stock is valued considering the gross investment in equipment in year *(t),* net fixed assets in real value (physical capital in year *(t – 1)),* a depreciation rate and the price index for equipment at the industry level obtained from the Ecuadorian National Institute of Statistics. And, the energy consumption of firms, measure in kilowatts/hour, that considers the energy consumption of fossil fuels registered by firms in the official statements provided by SCVS. These in-puts permit to produce different outputs. Thus, we consider one desirable output, (iii) number of oil barrels and one undesirable output represented by (iv) CO2 emissions.

The number of extracted barrels of oil (iii) is defined based on the variable "sales" (American dollars) reported in the balance sheets and financial statements registered on the official website of the SCVS. Obviously, we divide it by the price (American dollars/barrel) to obtain the variable "number of extracted barrels of oil". The reference price (WTI) is considered allowing comparisons with another international research in the same field. The CO2 emissions (tons of CO2 equivalents) (iv) is measured by using the methodology of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Table 2.1. Descriptive Statics of Input and Output variables



Variables	Min	Max	Median	S.D.	Mean
Labor	0	6.55	2.30	2.06	2.73
Capital stock	7.47	18.97	13.26	2.12	13.48
Energy Consumption	8.14	19.85	15.64	2.89	14.89
Oil production	5.95	16.44	12.89	2.30	12.27
CO_2 emissions	1.31	22.41	8.79	4.93	9.75

Notes: All variables in logarithms

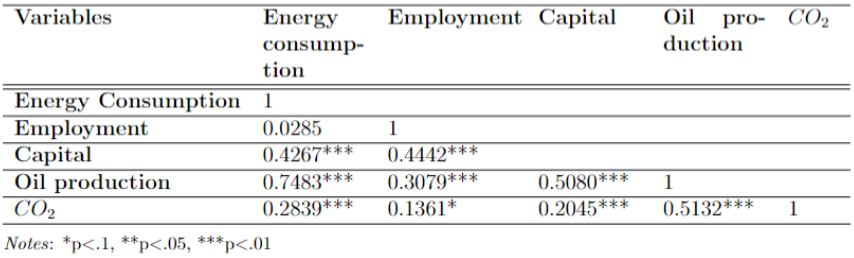
Elaborated by the author

Table 2.1. presents the descriptive statistics of the variables used in this study. The statistical description of the data set displays variation in the database. The standard deviation (S.D.) values indicate unbalanced growth of private oil companies in Ecuador over the period 2012-2020.

2.4.1. Correlation matrix

This table represents the correlation matrix for the input and output variables in the sample. The variables selected as inputs are highly correlated with the outputs conferring validity to our empirical strategy. The high correlation found also confirms the association between the selected inputs and outputs as statistically significant at 90%.

Table 2.2. Correlation Matrix



Variables	Energy consumption	Employment	Capital	Oil production	CO_2
Energy Consumption	1				
Employment	0.0285	1			
Capital	0.4267***	0.4442***			
Oil production	0.7483***	0.3079***	0.5080***	1	
CO_2	0.2839***	0.1361*	0.2045***	0.5132***	1

Notes: *p<.1, **p<.05, ***p<.01

Elaborated by the author

2.5. Results

2.5.1. Malmquist Index pollution-adjusted productivity

The results outlined in the table reveal the PM productivity indices scores and their decompositions over the period 2012-2020. The first column displays the Malmquist index scores (MC), and the other two columns show the main drivers of the environmental productivity change, namely the technological change (TC) and the efficiency variation components (EC), respectively.

Table 2.3. Malmquist Index scores for 2012-2020

2012			2013			2014			2015			2016			2017			2018			2019			2020		
MI	EC	TC	MI	EC	TC	MI	EC	TC	MI	EC	TC	MI	EC	TC	MI	EC	TC	MI	EC	TC	MI	EC	TC	MI	EC	TC
0.99	1.03	0.96	0.90	0.94	0.96	0.98	1.00	0.98	1.04	1.00	1.04	0.94	1.00	0.94	1.16	1.00	1.16	1.10	1.00	1.10	1.45	1.04	1.40	1.34	0.98	1.37
0.47	1.00	0.47	0.47	1.08	0.44	0.37	1.01	0.37	0.42	1.00	0.42	0.41	1.00	0.41	0.33	1.00	0.33	0.30	1.00	0.30	0.35	0.99	0.36	0.36	1.02	0.36
2.51	1.00	2.51	2.05	1.00	2.05	2.04	1.00	2.03	1.85	1.00	1.85	1.78	1.00	1.78	1.69	1.00	1.69	1.91	1.00	1.91	1.18	0.89	1.32	1.21	0.93	1.30
1.19	1.00	1.19	1.06	0.98	1.08	0.85	0.97	0.87	1.07	1.00	1.07	0.90	0.99	0.91	0.88	1.00	0.88	0.93	1.00	0.93	1.21	1.11	1.09	1.16	1.08	1.08
0.36	1.00	0.36	0.45	1.02	0.44	0.52	1.01	0.51	0.49	1.00	0.49	0.58	1.01	0.58	0.61	0.98	0.62	0.55	1.00	0.55	0.60	0.96	0.63	0.64	1.00	0.64
2.81	1.00	2.81	2.67	1.00	2.67	2.31	1.01	2.28	2.30	1.00	2.30	2.75	1.00	2.75	2.81	1.02	2.77	2.60	1.00	2.60	1.94	0.95	2.05	2.05	1.00	2.05
0.63	0.89	0.71	0.56	0.87	0.64	0.64	0.88	0.73	0.75	1.00	0.75	0.54	0.95	0.57	0.55	0.94	0.59	0.56	0.93	0.60	0.57	1.06	0.54	0.50	0.93	0.54
1.01	1.02	0.99	1.16	1.09	1.06	1.27	1.13	1.13	1.28	1.00	1.28	1.35	1.06	1.28	1.32	1.07	1.23	1.30	1.07	1.21	1.22	0.92	1.32	1.43	1.08	1.32
0.55	1.04	0.53	0.54	1.00	0.54	0.51	1.00	0.50	0.49	1.00	0.49	0.52	1.00	0.52	0.52	1.00	0.52	0.60	1.00	0.60	0.86	1.15	0.74	0.73	1.00	0.73

2.40	1.06	2.27	2.33	1.05	2.23	2.04	1.00	2.04	1.87	1.00	1.87	1.87	1.00	1.87	1.77	0.98	1.81	1.86	0.91	2.05	0.96	0.77	1.25	1.10	0.91	1.21
1.10	1.00	1.10	0.99	0.91	1.09	1.00	1.00	1.00	1.07	1.00	1.07	1.06	1.00	1.06	1.07	1.02	1.05	1.15	1.10	1.04	1.92	1.30	1.48	1.65	1.09	1.51
0.55	0.99	0.56	0.59	1.10	0.54	0.57	1.00	0.57	0.56	1.00	0.56	0.70	1.00	0.70	0.73	1.00	0.73	0.74	1.00	0.74	0.59	0.99	0.60	0.53	0.88	0.60
1.70	1.01	1.69	1.72	0.98	1.76	2.06	1.00	2.06	2.04	1.00	2.04	1.32	1.00	1.32	1.00	1.00	1.00	1.05	1.00	1.05	1.09	0.95	1.15	1.31	1.15	1.15
0.93	1.00	0.94	0.94	1.01	0.93	0.92	0.98	0.93	0.95	0.99	0.96	0.99	1.00	0.99	0.95	1.00	0.95	0.96	1.00	0.96	1.04	0.98	1.06	1.07	1.00	1.07
1.10	1.01	1.09	1.07	0.98	1.09	1.11	1.02	1.09	1.06	1.01	1.04	1.01	1.00	1.01	1.05	1.00	1.05	1.03	0.99	1.04	0.98	1.08	0.91	0.91	1.00	0.91
0.41	1.00	0.41	0.44	1.03	0.42	0.34	0.99	0.35	0.45	1.00	0.45	0.35	1.00	0.35	0.56	0.98	0.57	0.54	1.01	0.54	0.60	1.01	0.59	0.55	0.94	0.58
1.07	1.00	1.07	1.11	0.99	1.12	1.34	1.01	1.33	1.02	0.99	1.03	0.94	1.00	0.94	1.95	1.02	1.92	1.96	1.00	1.96	1.11	0.67	1.65	1.72	1.06	1.62
0.82	0.94	0.87	0.94	0.96	0.97	0.83	0.99	0.84	1.07	1.00	1.07	1.18	1.00	1.18	0.67	1.00	0.67	0.66	1.00	0.66	1.02	1.41	0.72	0.71	1.00	0.71

2.5.2. Analysis of overall efficiency (MI)

Table 2.3. reports the average annual PM productivity indices for the 18 oil companies in Ecuador over the analyzed period. In the DEA model, the companies whose efficiency is 1 or greater than 1 make up the production frontier, compared to those whose efficiency is less than 1 which are DEA inefficient. Therefore, the results in Table 2.3. and Table 2.4 for the overall energy efficiency (MI) score showed that more than half of the companies are inefficient during the time frame. The group of companies have an average of energy efficiency score of 1.80. From this group, only 3 companies have a greater Malmquist Index Score than the average. In order words, only three firms perform better than the average. The slowdown in productivity scores could be linked to firms with higher levels oil and gas production and CO2 emissions during the analyzed period, as most firms with low consumption of fossil fuels have a better ratio between output and pollution, and consequently, are more sustainable in terms of energy efficiency.

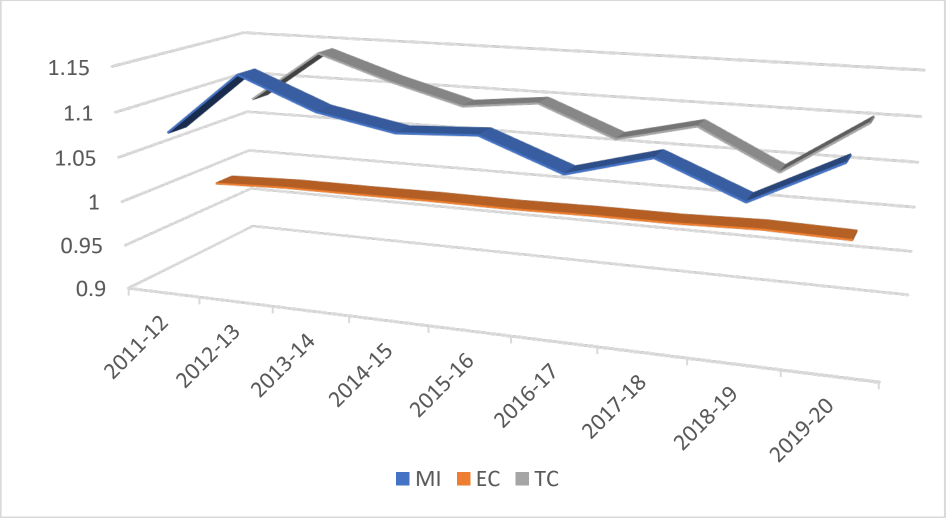
Table 2.4 Ranking of oil companies according to Malmquist Index

Companies above 1		Companies below 1	
AMLATMINAS S.A.	1,077	AMODAIMI-OIL COMPANY, S.L.	0,38
ENAP SIPETROL S.A.	2,53	COMPAÑIA SUDAMERICANA DE FOSFOROS DEL ECUADOR FOSFOROCOMP S.A.	0,53
ANDES PETROLEUM ECUADOR LTD.	1,81	EQUIPENINSULA S.A.	0,60
LOGISPETROL SERVICIOS PETROLEROS CIA. LTDA.	1,19	ERINCORP S.A.	0,57

PETROORIENTAL S.A.	1,04	OVERSEAS PETROLEUM AND INVESTMENT CORPORATION	0,62
REPSOL ECUADOR S.A.	1,29	PETROLEOS SUD AMERICANOS DEL ECUADOR PETROLAMEREC S.A.	0,96
HILONG OIL SERVICE & ENGINEERING ECUADOR CIA. LTDA.	1,83	PETRORIVA S.A.	0,45
EQUIPO PETROLERO S.A.	1,23	SAXON ENERGY SERVICES DEL ECUADOR S.A.	0,89
CARLOS PUIG & ASOCIADOS S.A.	1,00		
PDVSA ECUADOR S.A.	1.45		
AVERAGE	1,88		

On the other hand, the energy efficiency scores for most companies exhibit an important decrease between 2012-2019 as seen in Table 2.1., this period coincides with important reforms in Ecuador referring to private contribution in the oil sector, resulting in lower investment in capital projects and less resources designated for innovation in these companies (World Bank 2018).

Figure 2.1. Malmquist Index decomposition (2011-2020)



2.5.3. Analysis of technical and efficiency variation changes

The mean technical efficiency change (TC) for the 18 companies selected in the period analyzed was - 0,091%, meanwhile there was not a significant scale change (EC) over time (Figure 2.1). Globally, the results suggest that the energy efficiency performance of the Ecuadorian oil industry is dependent on the technical change in production, but it is important to note:

1. In relation to the overall energy efficiency scores for 2011-2012, 2012-2013 and 2014-2015, most companies presented a drop in the technical and efficiency component scores during the period analyzed. This means that the energy inefficiency of these firms was driven by less technological advances without any commensurate efficiency improvements in the internal management of the firms.

2. For 2018-2019 the PMI index show marginally reduce and a then a positive boost in 2019-2020, these results suggest that although in 2020 the industry suffered an important reduction in oil production due to the Covid-19 outbreak, the overall energy efficiency and productivity levels were positive affected, and that could be related to the decrease in CO_2 emissions during the period even if there weren't significant technical and energy efficiency change.

2.5.4. Tobit Panel Regression results

Having obtained the PMI analysis, we want to find the primary economic indicators that affect efficiency scores. The Hausman test[8] is employed to choose between the fixed-effect and random-effect model—suitable for the panel regression analysis. The results indicate the random effect model is more suitable for the panel regression evaluation.

Table 2.5. Tobit Panel regression results

Variables	
Energy consumption	-0,0193*
	(0,0103)
Employment	-0,138***
	(0,0210)
Capital	-0,0139
	(0,0175)
Oil production	0,0508**
	(0,0229)
CO2 emissions	-0,00334
	(0,00307)

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[8] The test proposed by Hausman (1978) is a chi-square test that determines whether differences are systematic and significant between two estimates. It is mainly used to determine whether an estimator is consistent or whether a variable is relevant or not.

Observations	180
Number of n	18

Note: Standard errors in parentheses *** p<0,01, ** p<0,05, * p<0,1

Elaborated by the author

Thus, in the next step, we employ the random effect model to measure the impact of the indicators on PMI (Table 2.5). Per the analysis, MI has a weak negative correlation with energy consumption at a 10% significance level. And a negative relationship with employment at a 1% significance level. These results suggest that for Ecuador, the energy and industrial efficiency of oil companies depends on their labor strategy and the consumption of fossil fuels in their extractive activities.

2.5.5. Linking the results to the Ecuadorian context

Between 2013 and 2014, Ecuador experienced an increase in oil production of 5.6% over the previous year (BCE 2014). This growth in production was driven especially by extraction from state-owned companies. However, the increase was widespread. Given the fall in international prices, Ecuadorian companies increased their production targets to compensate for the price shock on their revenues. Additionally, this strategy of increasing production led Petroamazonas to delegate the exploitation of oil fields and other activities to foreign capital companies: Schlumberger (France/USA) and Tecpetrol (Argentina); Sinopec International and Sinopec Services (China); Sertecpet (Ecuador), Montecz (Colombia) and Edinpetrol (Colombia); YPF (Argentina); and Halliburton (USA) (Ministry of Hydrocarbons 2014).

On the other hand, in 2016 there was another significant drop in the price of oil with a price of 26.5 USD, achieving a recovery period until December 2019 with a price of 66.48 USD per barrel (Morales et al. 2022). During these years, the Ecuadorian government changed the methodology for calculating oil reserves, changed the contract modality to fee-based services and signed new contracts for additional exploration and exploitation of marginal fields, operational alliances, strategic alliances, exploration of unified and shared fields with foreign privately owned companies.

In both sub-periods, as previously mentioned, the Ecuadorian government carried out public policy measures to attract more private investment in the oil industry and increase production. The increase in production, according to the results of the DEA model, was generated maintaining the same relationship between inputs and outputs, so that a slight increase in productivity during these years can be evidenced.

However, as Larrea (2020) points out, information on reserves suggests that most Ecuador's oil resources have been extracted, and that future exports will be declining and limited in duration, suggesting that these improvements in terms of productivity are temporary, and the declining trend in terms of production volume, crude oil quality, and lower energy efficiency will continue in the coming years.

2.6. Conclusions

This chapter analyzes the main drivers of efficiency and productivity in private oil companies in Ecuador. Moreover, the prominent sources of pollution-adjusted productivity variation are provided by considering polluting and no polluting parts of the productivity variation. A sample of 18 Ecuadorian oil companies from 2011-2020 is selected. A non-parametric model and Malmquist index were developed to evaluate the energy efficiency and productivity of private oil companies in Ecuador.

It is notable that more than half of the companies in our analysis were deemed inefficient according to the DEA model, with an average energy efficiency score of 1.80. Only three companies consistently outperformed this average, suggesting that the majority of firms struggled to achieve optimal energy efficiency. This trend appears to be associated with companies that had higher levels of oil and gas production and CO2 emissions during the analyzed period. Those companies with lower fossil fuel consumption displayed a more favorable output-to-pollution ratio, showcasing greater sustainability in terms of energy efficiency.

The observed decrease in energy efficiency scores for most companies from 2012 to 2019 (as seen in Table 2.1.) coincides with significant reforms in Ecuador's oil sector, resulting in reduced investment in capital projects and innovation within these firms, as reported by the World Bank (2018).

The Malmquist index scores (MC), along with their decomposition into technological change (TC) and efficiency variation components (EC), shed light on the industry's performance. Regarding technical efficiency change (TC) and scale change (EC), this analysis indicates a minimal overall change in scale over time (Table 2.1), emphasizing the dependency of energy efficiency performance on technical advancements in production.

Two crucial observations can be drawn from these findings:

The years 2011-2012, 2012-2013, and 2014-2015 witnessed a decline in both technical and efficiency component scores, indicating that energy inefficiency during this period was primarily driven by a lack of technological progress without corresponding efficiency improvements in internal management.

In 2018-2019, there was a marginal reduction in the PMI index followed by a positive boost in 2019-2020. This suggests that, despite a significant reduction in oil production due to the Covid-19 outbreak in 2020, energy efficiency and productivity levels were positively affected, possibly due to decreased CO2 emissions, even in the absence of significant technical and energy efficiency changes.

To further explore the factors influencing efficiency scores, we employed the random effect model for panel regression analysis. The results indicate that energy consumption has a weak negative correlation with MI at a 10% significance level, while employment shows a negative relationship with MI at a 1% significance level. This implies that energy and industrial efficiency in Ecuador's oil companies are closely linked to their labor strategies and fossil fuel consumption in extractive activities.

In summary, the analysis suggests that the energy efficiency of Ecuador's oil industry is influenced by a complex interplay of factors, including technological advancements, labor strategies, and fossil fuel consumption. The historical context of reforms, oil price fluctuations, and government policies has also had a significant impact on productivity levels. However, it is essential to note that while improvements in productivity may have occurred during certain periods, the long-term trend suggests that Ecuador's oil resources are becoming increasingly depleted, leading to future declines in production volume, crude oil quality, and energy efficiency. These challenges underscore the need for sustained efforts towards sustainability and efficiency within the industry.

Chapter 3. Energy efficiency and energy depletion in oil-exporting developing countries

3.1. Introduction[9]

This chapter addresses how oil-exporting developing countries maximize macroeconomic outputs while minimizing bad environmental outputs (GHG emissions and oil depletion). The energy sector is trying to reduce the participation of fossil fuels in electricity generation to meet climate change targets. According to Olivier, Schure and Peters (2017), about 70% of total global GHG emissions are in the form of CO2 due to the combustion of fossil fuels. To follow a steady path to the target of keeping global warming below 1.5°C compared to pre-industrial levels, the world will have to reduce fossil fuel extraction by about 6% per year between 2020 and 2030 (SEI, et al. 2021). This issue translates into a reduction of investment in developing new oil projects and, thus, a reduction of income in oil exports in developing countries (Solano-Rodriguez, et al. 2019). It is generally agreed that the strategic way to mitigate global warming is by adopting a carbon emissions reduction policy, efficient use of energy (Iqbal, et al. 2019), and the decarbonization of the economy towards the use of renewable sources (Papadis and Tsatsaronis 2020). In addition, this study aims to incorporate into the analysis the issue of oil depletion, more specifically, the reduction in the quality of the oil deposits for developing countries.

Despite the importance that climate change and oil depletion have on the economic and energy performance of oil-exporting developing countries, more needs to be studied. In fact, to the best of the author's knowledge, a study has yet to be developed that includes CO2 emissions, oil depletion, and economic growth from a performance/efficiency perspective in oil-exporting developing countries. Hence, it is essential to understand these topics better to achieve carbon emissions reduction improvements. In addition, most studies on efficiency in the oil sector have been developed in countries of the Global North. However, studies in developing countries still need to be made. In this regard, this study aims to expand the knowledge about the efficient use of energy resources in Latin America and African oil-developing exporting countries for tailored evidence for benchmarking and tracking GHG emissions reduction improvements in the Global South[10].

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[9] This chapter was accepted for publication in "The Handbook of Energy, Sustainability and Economic Growth" to be published by Edward Elgar Publishing Ltd in 2023.

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Some Latin American and African countries are excellent examples to study this issue. In this sense, Latin America extracts 9.5% of the world's oil extraction (British Petroleum 2022). Brazil, Mexico, and Venezuela dominate Latin American oil extraction. These countries are responsible for about 75% of the region's total output and are also giants on the international stage (Calvo, et al. 2021). Meanwhile, in 2019, approximately 10% of the world's oil demand was extracted in Africa, which gives an idea of how rich in natural resources the continent is. Besides, in Africa, five of the major oil-exporting countries worldwide are Angola, Nigeria, Algeria, Libya, and Egypt (IEA 2020a). These countries depend highly on oil rent and are vulnerable to price shocks.

To assess the issues of energy efficiency and energy productivity improvements in Latin America and Africa developing oil-exporting countries. This chapter applies the DEA-SMB approach to evaluate energy efficiency in this group of countries. It also implements the Malmquist Productivity Index approach to estimate energy productivity improvement. The novelty of this study is the introduction of energy depletion as undesirable output in DEA and Malmquist estimations. The results of the SBM-DEA model indicate that among a sample of 14 countries in Africa and Latin America from 2006-2020, countries such as Equatorial Guinea, Gabon, Peru, and Bolivia have higher energy efficiency than their counterparts in Angola, Algeria, Mexico, Ecuador, and Colombia. The principal conclusion of this chapter shows that countries with higher extraction rates are less efficient; this means that the environmental impacts are higher than the economic benefits they obtain from extraction.

This chapter is divided into four sections. The first section presents a literature review in which I introduce the main concepts and empirical work developed in this field. The second section describes the methodological framework used in this study. Here it is present the data used for the model and the specification of the SMB-DEA model applied in this study. The third section presents the principal findings of this investigation. Moreover, the final section concludes and offers policy recommendations.

3.2. Literature review

The literature review found that energy efficiency is an important goal among developing countries (Popkova and Sergi 2021). Furthermore, in the case of oil-exporting countries, energy efficiency is a crucial energy policy instrument as it is strongly linked to commercial and energy security. It can also deliver environmental benefits such as CO2 emissions reductions and reduce the depletion of energy resources (Li and Tao 2017). To measure and study energy efficiency dynamic change, most researchers have applied traditional DEA models and Malmquist productivity indexes (Zhou, Ang and Poh 2008). These methods have been used for the research of energy efficiency in OCDE countries (Fidanoski, Simeonovski and Cvetkoska 2021), Asia (Kim, et al. 2015), and the United States (Grösche 2009). Despite there being literature about energy efficiency evaluation in Latin American and African countries, many of these studies focus on a particular energy industry sector or country (Delfín, Guardado and Navarro 2021) or fail to consider the specific features that can contribute to or worsen the implementation of energy policies in this region (Popkova and Sergi 2021). Moreover, there is limited empirical evidence in developing countries considering other negative environmental factors besides CO2 emissions involved in energy production.

3.2.1. Energy Efficiency at a macroeconomic level

From an energy economics perspective, energy is considered an input into the production of desired energy services, rather than an end. At the individual product level, energy efficiency can be considered one of the products characteristics, alongside product cost and other attributes (Newell, Jaffe and Stavins 1999). Meanwhile, at a more aggregate level, the energy efficiency of a sector or the economy can be measured as the level of gross domestic product per unit of energy consumed in its production (Metcalf 2008; Wing 2008).

It is also important to distinguish between energy efficiency and economic efficiency. Maximizing economic efficiency, typically operationalized as maximizing net benefits to society, is generally not going to imply maximizing energy efficiency, which is a physical concept and comes at a cost (Giraudet and Missemer 2019). Private economic decisions about the level of energy efficiency chosen for products will depend on the economic efficiency of the market conditions the consumer faces (e.g., energy prices, information availability) as well as the economic behavior of the individual decision maker (e.g., cost-minimizing behavior) (Paul 1985). Market conditions may depart from efficiency if there are market failures, such as environmental externalities or imperfect information (Ruderman, Levine and McMahon 1987).

There is a debate about energy efficiency potentialities, particularly the case for the engineering perspective versus the economic view. While engineering-based studies regularly emphasize significant potentials for efficiency gains (Granade, et al. 2009), economists have long questioned these works by noting that if such potentials did exist, economic agents would spontaneously exploit them. These contrasting views translate into "technologist" vs. "economic" approaches (Huntington, Schipper and Sanstad 1994, Sorrell, O'Malley, et al. 2004a, 2004b). These points to more general controversies about the relationship between engineering and economics. Already examined in the context of technological change (Rosenberg 1975), these controversies are now an emerging area of research in the history of economic thought (Duarte and Giraud 2020).

From an economic perspective, energy efficiency choices consist of investment decisions of economic actors. There is a trade-off between higher initial capital costs and uncertain lower future energy operating costs (Gillingham, Newell and Palmer 2009). The initial cost is the difference between a relatively energy-efficient product's purchase and installation cost and an equivalent product that provides the same energy services but uses more energy (Gillingham, Newell and Palmer 2009). The decision of whether to make the energy efficient investment requires weighing this initial capital cost against the expected future savings. Assessing future savings requires forming expectations of future energy prices, changes in other operating costs related to energy use (e.g., pollution charges), the intensity of use of the product, and equipment lifetime. A privately optimal decision would consist of choosing the level of energy efficiency to minimize the present value of private costs. In contrast, economic efficiency at a societal level would entail minimizing social costs.

However, the relationship between the concepts of economics and energy efficiency is a point of continuing debate. Most analysts agree that policies should balance the benefits of energy efficiency against the associated costs to improve environmental and economic performance. The mainstream economy views competitive markets as sufficient to achieve an optimal level of energy efficiency (Sutherland 1991). However, empirical evidence suggests that the level of energy efficiency achieved in today's markets is lower than the level that would prevail, given the full implementation of cost-minimizing technologies (Carlsmith, et al. 1990). Other studies that address this issue focus on how energy efficiency can change energy demand and its impact on economic decisions.

One of the principal limitations of the study of the relationship between energy efficiency and the impact on economic variables (i.e., GDP) is the complexity of the inclusion in the analysis of the energy demand dimension. Energy demand is generated by a diverse set of activities at the level of households and firms; important information is lost when heterogeneous data are reduced to simple aggregates. Solow (1987) argues that this empirical paradox may reflect inadequacies in the underlying assumptions of the aggregate production function approach. In this same line, Schipper et al. (1992) stress the importance of grounding energy demand analysis on specific technologies and end-use activities. Analysts can only draw valid inferences regarding the ties between energy efficiency and the broader economy at this aggregation scale. Despite these methodological concerns, the importance of energy and, more specifically, energy efficiency in economic models and, more specifically, growth models remain an important topic in energy economics.

3.2.2. Energy Efficiency, Economic Growth, and sustainability

The relationship between energy efficiency and economic growth has been highlighted in the literature before. According to Çengel (2011), energy efficiency is necessary to reduce energy use to the minimum level without decreasing the standard of living, production quality, and profitability. Energy scarcity is an international issue because most energy sources used in production are non-renewable. Therefore, the costs of electricity account for a large part of the expenses of firms and countries, so looking for ways to reduce this cost is important for long-run sustainability (Saldanha, Gouvea and Pinheiro 2016).

In addition, energy efficiency efforts play an essential role in achieving sustainable development (Burak 2021). Affordable-clean energy and climate action are among the seventeen goals of sustainable development announced by the United Nations. Energy security and environmental protection have become one of the most important issues on today's international agenda. In recent years, while the use of renewable energy is increasingly growing, fossil fuels still account for 80% of global energy consumption due to their affordability in comparison with other sources of energy (IEA 2019). However, these resources are scarce and highly pollutant. Policymakers, analysts, and business leaders increasingly pay more attention to energy efficiency to balance the relationship between energy economic growth and environmental pollution. This has resulted in many studies on energy efficiency in recent years.

Likewise, energy efficiency is commonly seen as a key policy option for environmental sustainability purposes. It also has recently been promoted as an industrial policy to boost economic growth (Yan, et al. 2022). Despite many anecdotal accounts of the relationship between energy efficiency and economic growth, empirical evidence of a causal link is not entirely proven.

3.2.3. Energy efficiency estimation methods

The literature shows that there are several methods for estimating energy efficiency and economic growth. These methods can be parametric or non-parametric. The most prominent parametric method is Total Factor Productivity. Among the non-parametric methods, stands out Data Envelopment Analysis (Sarpong, et al. 2022). Although there are studies that use both Total Factor Productivity and Data Envelopment Analysis to study energy efficiency, most studies focus on high-income countries (Sueyoshi and Goto 2015; Damette and Seghir 2013; Paradi, Rouatt and Zhu 2011, Ramanathan 2006) and Asia (Zhang, Li and Ji 2020; Haider, Shadab and Sharma 2019; Zhao, et al. 2018; Guo, Zheng and Zheng 2016). There are few studies that applied DEA focused on developing countries, Africa (Adom 2019, Ouedraogo 2017); (Esso and Keho 2016); and Latin America (Castro, et al. 2018, Altomonte, Coviello and Lutz 2003). But no studies have been found that applied this method to analyze these two regions together.

There are few studies that analyze energy efficiency and economic growth, it can mention the study by Tachega et al. (2021), this study mentions that there is no U-shape relationship between energy efficiency and GDP in African countries, suggesting that energy efficiency does not eventually improve with economic growth. Their investigation assesses the energy efficiency, energy productivity improvement, and the determinants of energy efficiency of 14 oil-producing countries in Africa during 2010-2017, using the SMB-DEA approach. Secondly, they implemented the Malmquist Productivity Index approach to estimate energy productivity improvement.

Valadkhani, Roshdi and Smyth (2015) used a multicomponent DEA framework to examine the interplay between economic and energy efficiency for all 29 OECD countries and then classify each country in terms of their relative economic and energy efficiency. They found a high correlation between energy efficiency, CO2 emissions, and real GDP. In this sense, the authors suggest that higher economic growth and energy efficiency are not incompatible policy goals.

Also, Azadeh and Kokabi (2016) employed a DEA, principal component analysis, and numerical taxonomy approach to analyze energy efficiency in energy-intensive sectors, such as iron, steel, oil refining, and cement manufacturing sectors in some OECD countries. The study emphasis the importance of difference structural effects on each manufacturing industry and inputs-output variables according to their production processes. In this regard, Xu et al.

(2020) assert that energy efficiency depends on the structure of energy consumption of the firms or countries, still dominated by fossil energy, carbon emissions, wastewater, and waste gas generated by the input of traditional energy sources. Thus, most studies in this line of thought include CO2 emissions.

On the other hand, Zhang, Li and Ji (2020) found that relatively low environmental conditions in emerging economies are due to high energy intensity and low energy efficiency. They used a data envelopment analysis (DEA) model to measure energy efficiency, energy intensity, and environment to view the trajectory of the Kuznets Curve for the underline economies with a panel dataset from 1990–2013 of 15 developing countries. They suggest that renewable energy sources must be treated as essential for achieving sustainable economic goals without environmental degradation in emerging economies. This study emphasizes whether the reduction of undesirable outputs (CO2 emissions and natural resources depletion) will affect the overall country's economic growth. Thus, the question of this paper is whether there is a trade-off between achieving growth and environmental sustainability in energy-intensive economies.

Finally, Huang et al. (2020) studied how improving the energy efficiency of emerging economies to achieve efficient global development of BRICS countries in the past three decades. The authors applied the Latin America-based DEA to analyze this group of countries' energy structure and energy-saving potential. The results of empirical analysis show that Brazil and Russia ranked first and last with an average efficiency of 0.5941 and 0.0921, respectively. Second, the Latin America variable of each country is substantial. Third, the reasons for inefficiency vary from country to country. The research results help us understand the changing trend of energy efficiency and the reasons for low efficiency in BRICS. They can provide a reference for formulating scientific development strategies and policies to improve efficiency in these countries.

3.3. Methodological Framework

To analyze the issue of energy efficiency and energy depletion in oil-exporting developing countries this research employs the SBM-DEA model. The DEA method is an efficiency evaluation method based on the concept of relative efficiency. The SMB—DEA, a type of DEA model that is non-radial and non-input or non-output oriented, directly utilizes inputs and outputs to determine the efficiency measurement of DMUs. In line with this study's purpose, the SMB DEA model with undesirable output is applied to estimate the energy efficiency of 14 oil-producing economies in Latin America and Africa. This study only incorporates variables whose values can be changed in a reasonable period by decision-making units (Çelen 2013), and that allows for maximizing the benefits of oil extraction and minimizing undesirable outputs, which in this case are carbon emissions and energy depletion from the use of oil wells. To analyze and compare the dynamic efficiency of energy productivity among the Latin America and African countries the Malmquist Productivity Index (MPI) is adopted. The MPI approach assesses the multi-faceted environmental impact of time frame changes. This approach is used to account for variations in policy efficiency, with the advantage of not state a functional association among inputs and outputs. The Malmquist and DEA approach are among the most used tools to estimate energy efficiency (Zhou, Ang and Poh 2008; Zheng 2021).

This analysis is carried out for developing countries that are oil exporters, from Latin America and Africa, in the period from 2006 to 2020. The selection criteria were given by comparing the economic and oil export levels between countries of both regions, with the aim of finding comparable economies. Consequently, the countries analyzed in this study are Colombia, Argentina, Brazil, Ecuador, Mexico, Bolivia, Peru, Gabon, South Africa, Algeria, Angola, Egypt, and Equatorial Guinea.

3.3.1. Assessing energy efficiency with DEA

This method, proposed by Charnes, Cooper and Rhodes in 1978, attracted great attention and came to the fore in efficiency analysis research. DEA is used to determine the relative technical efficiency of a set of comparable decision-making units (DMUs) involving multiple inputs and multiple outputs (Nemoto and Goto 1999).The objective of DEA is to identify the most efficient DMU with a labeled efficiency highest score of 1. The efficiency score is the calculated ratio of weighted total output to the total weighted input done by mathematical programming to maximize each DMU's relative efficiency score by transforming different input and output measures into a single efficiency measure (Charnes, Cooper y Rhodes 1978).

The DEA has many essential advantages; for example, it can be used to address issues with multiple inputs and outputs, and different scales do not affect it. In addition, it does not require strict assumptions before analysis as in parametric methods. For these reasons, today, the DEA is widely used in many areas as well as in the field of energy efficiency (Feizabadi, Gligor y Alibakhshi 2019). Besides, the DEA method has substantial advantages in mitigating subjective factors, simplifying equations, etc. (Tone 2001). The main point of using this approach in research is that it allows this study to address the issue of how resources are being used. DEA becomes a suitable methodology for analyzing the efficiency of the oil sector in development countries because it allows for assessing the comparative efficiency of decision-making units (DMUs) in a scenario with multiple possible inputs and outputs (Nemoto and Goto 1999).

3.3.2. Treating undesirable and desirable outputs with DEA

A common issue in DEA is accounting for undesirable outputs in the production process. The current understanding is that researchers should praise DMUs for providing desirable or marketable outputs and penalize them for undesirable outputs (Yang and Pollitt 2010). If inefficiency exists in production, the undesirable pollutants should be reduced to improve the inefficiency and should be treated differently (Seiford and Zhu 2002).

The first lousy output production model proposed by Färe et al. (1993) was based on the concept of joint production using the Weak Disposability (W.D.). Kuosmanen (2005) proposed to enhance this model by introducing a non-uniform abatement factor to capture all feasible production plans. Rødseth (2016) examined this issue and found that positive prices may be appropriate in cases where bad are recuperated by good outputs. There have been some objections to the weak disability model, such as those raised by Hailu and Veeman (2001) that "the weakly disposable approach leaves the impact of undesirable outputs on efficiency undetermined," whereas Färe and Grosskopf (2003) responded that they disagree as the weakly disposable DEA model is consistent with physical laws and it allows the treatment of undesirable outputs showing the opportunity cost of reducing them.

On the other hand, indirect approaches refer to treating the undesirable output as a classical input, whereas the undesirable output is moved to the input side of the model after some transformation and treated as one of the inputs (Khan, Ramli and Baten 2015), as both inputs and undesirable outputs are the values that need to be minimized, and therefore it is acceptable to treat both in the same manner. However, Seiford and Zhu (2002) highlighted that treating undesirable outputs as inputs will distort the actual production process since the relationship between inputs and outputs in the production process will be lost.

Generally, the traditional methods used to treat undesirable outputs have been quite challenging for researchers working on DEA (Halkos and Petrou 2019). To conclude, the four most used methods in treating undesirable outputs include: 1) ignoring them from the production function, 2) treating them as regular inputs, 3) treating them as standard outputs, and 4) performing necessary transformations to take them into account (Yang and Pollitt 2010).

SMB DEA model

Among the energy efficiency assessment models, the nonparametric approach Data Envelopment Analysis (DEA) has gained popularity in measuring efficiency (Iqbal, et al. 2019). Some researchers have focused specifically on energy efficiency in firms, while others have focused on the energy activities of geographical regions or countries regarding global climate change. Most of these studies concentrated on oil extraction's economic value and environmental impact (measured in CO2 emissions). However, very few studies examine the economic impact of the loss of the quality of fuels due to extraction. Therefore, the current study employs a stochastic DEA model, with constant returns to scale (CRS) considering undesirable and desirable outputs and calculating the stochastic cross-efficiency scores between oil-producing countries in the Latin American and African regions. Additionally, this study uses a nonparametric frontier approach to measure productivity, such as the Malmquist index.

Tone (2001) developed a modified “Slack Base Measure- Data Envelopment Analysis” (SMB DEA) method suitable for handling undesirable productions. Following Tone (2001) and Tachega et al. (2021), assuming there are n Latin American countries with both biophysical and monetary inputs defined for $x \in Rn$, the desirable output for $Y \in R_s$ for a $DMU(x_0, y_0)$. The correspondent product function is expressed as:

$$P = \left\{ \left(x_0, y_0^g, y_0^b \right) x \geq X\lambda, y^g \leq Y^g, L \leq e\lambda \leq U, \lambda \geq 0 \right\} \tag{12}$$

Where:

λ = intensity factor

$L =$ lower bound of intensity vector

$U =$ upper bound of intensity vector

Th methodology states that a $DMU\left(x_0, y_0^g, y_0^b\right)$ is efficient when there is no vector $\left(x_0, y_0^g, y_0^b\right) \in P$, such that $x_0 \geq x, y_0^g \leq y^g, y_0^b \leq y^b$ with a least one strict inequality.

According to Chambers et al. (1978) and Färe and Grosskopf (2009), formulated a new variant of the SBM model based on directional distance function with no orientation which was, in fact, a new generalization of the SBM model under the variable returns to scale technology. The directional distance function on *P* can be defined as:

$$g = (g_1, \ldots\ldots, g_{m,}\ g_{m+1,} \cdots\cdots, g_{m+s}) \neq 0$$

And solving the following problem for each DMU:

$$\varphi_0 = \max \beta$$

s.t.$\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{i0} - \beta g_i\,,\ i = 1, \ldots., m$

$$\sum_{j=1}^{n} \lambda_j y_{ij} \ \geq\ y_{i0} - \beta g_{r0}, \qquad i = 1, \ldots., s$$

$$\lambda_j \geq 0\ \ j = 1, \ldots., n, \qquad \beta \geq 0$$

The non-radial SMB—DEA in the presence of undesirable output is given as:

$$[SBM]p^* = min \frac{1 - \frac{1}{m} \sum_{i=1}^{m} \frac{s_{i0}^{-}}{x_{i0}}}{1 + \frac{1}{m}\left(\sum_{r=1}^{s_1} \frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{r0}^b}\right)} \tag{13}$$

Subject to:

$$x_0 = X\lambda + S^-$$

$$y_0^g = Y\lambda - S^g$$

$$y_0^b = Y\lambda + S^b$$

The vectors S^{-} and S^{b} show an oversupply of inputs and undesirable outputs, and S^{g} represents excess desirable outputs. Therefore, a DMU is considered energy efficient if $p^{*} = 1$ or S^{-}, S^{b} and S^{g} are non-existent.

Malmquist Index

To analyze and compare the dynamic efficiency of energy productivity among the Latin America and African countries the Malmquist Productivity Index (MPI) has been adopted. The MPI approach assesses the multi-faceted and multi-output environmental impact of time frame changes, this method relies on the same distance function described previously, but has some advantages compare to the traditional SBM DEA: first, there is no need to estimate the DUM efficiency in advance, and the initial data does not need dimensionless processing, which can effectively avoid errors and make the calculation results true and reliable. Second, there is no strict data requirement, multi-input-multi-output or multi-input-unit output can be measured. Finally, the efficiency measured by this method can reflect its dynamic changes, and the results are more comprehensive and objective. This approach decomposes Total Factor Productivity of numerous inputs and outputs into Technical Progress Change ($TPCH$) and Technical Efficiency Change (TC), pure technical efficiency change (EC), to further explain the standpoint of technological progress and technical efficiency of DMUs of a firm. The Malmquist index can be estimated as:

$$\begin{aligned} MPI = TEC * TPCH = M(x^{t+1}, y^{t+1}, x^{t}, y^{t}) \\ = \frac{D^{t}(x^{t+1}, y^{t+1})}{D^{t}(x^{t}, y^{t})} \times \left[\frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^{t}(x^{t+1}, y^{t+1})} * \frac{D^{t+1}(x^{t}, y^{t})}{D^{t}(x^{t}, y^{t})} \right] \end{aligned} \tag{14}$$

Where:

$(x^{t}, y^{t}), (x^{t+1}, y^{t+1})$ are outputs and inputs vectors in t and $t+1$

D^{t}, D^{t+1} are the distance functions between t and $t+1$

$TEC =$ represents the “catching up effect” between t and $t+1$

3.3.3. Data in brief

The study covered fourteen of the most important oil-producing countries in Latin America and Africa for 2006–2020 in terms of supply and proven reserves. The fourteen economies are Colombia, Argentina, Brazil, Ecuador, México, Bolivia, Perú, Gabon, South Africa, Argelia, Angola, Egypt, and Equatorial Guinea. The data was collected from World Development Indicators (WDI) of the World Bank, U.S. Energy Information Administration (EIA), and own calculations.

The analysis focused on aggregate economic and energy efficiency indicators using multiple inputs to produce a desirable output (GDP and Life expectancy) and an undesirable output (CO2 and energy depletion). In energy efficiency analysis, inputs and output indexes are employed. The input index is grouped into energy inputs and non-energy inputs. The output index comprises one economic output indicator and one pollutant indicator Table 3.1. lists all the variables used in this study:

Table 3.1. Variable definitions

Type	Variable	Unit	Source
Input	Gross Capital Formation	Constant USD 2005	WDI
	Labor	Per 1000 Workers	WDI
	Oil and Gas production	Mbd	EIA
	Energy consumption	Quad BTU	EIA
Output	CO2 emissions (undesirable)	Millions of tons	WDI
	Energy depletion (undesirable)	Current USD dollars	WDI
	GDP (desirable)	Constant	WDI

	USD 2005	
Life expectancy (desirable)	Years	WDI

Elaborated by the author

Also, it is assumed that energy efficiency means deploying economic, energy, and natural resources to induce economic growth and decrease CO2 emissions simultaneously (Liu and Liu 2016). Consequently, the non-energy inputs indicators are capital stock, while the energy inputs are natural gas, crude oil, and electricity consumption. Installed capacity is used as a proxy for capital, as used by Yang, Wei and Chengzhi (2009).

The output variables are divided into two desirable outputs and two undesirable outputs. Gross domestic product (GDP) an Live expectancy are the desirable output, and CO2 emissions and natural degradation are undesirable outputs. GDP is an indicator of the economy's health and vastly use in literature, and life expectancy is an essential measure of financial performance for non-renewable resource-dependent economies (Davis, Fedelino and Ossowski 2003).

Nonetheless, only a few studies consider natural degradation as undesirable output; Halkos and Papageorgiou (2014) included waste generation as an environmental inefficiency among the European regions. In this case, energy depletion is a proxy for natural degradation. According to World Bank (2010), energy depletion is the ratio of the value of the stock of energy resources to the remaining reserve lifetime (capped at 25 years). It covers coal, crude oil, and natural gas. The equation to calculate this indicator is:

$$V_t = \sum_{i=1}^{t+T-1} \frac{\pi_i q_i}{(1+r)^{(i-t)}} \tag{15}$$

Where:

$\pi_i q_i$ = economic profit of total rent in i

$r =$ social discount rate

$T =$ is the lifetime of the natural resource (capped at 25)

3.3.4. Descriptive statistics of the variables

Appendix A details the summary statistics of the considered variables used in this study. It is observed that Brazil and Mexico have more investment (gross capital formation than the other countries) during the study period. Brazil, Mexico, South Africa, and Nigeria use more crude oil input. With the undesirable output-CO_2, Brazil tops the other countries, and Ecuador has most higher values of energy depletion. From the mean values calculation of the energy inputs illustrated, it is observed that the average mean values of crude oil production have fluctuated during the whole study period. For the outputs, the GDP mean value has consistently increased while the values of CO_2 fluctuated and finally gained ascendancy.

3.3.5. Correlation matrix

Appendix B presents the correlation matrix between the Outputs and the Inputs. Generally, the variables selected as inputs are highly correlated with the outputs conferring validity to our empirical strategy. The high correlation found also confirms the association between the selected inputs and outputs as statistically significant at a 95% level (except for Life expectancy and oil and gas production), with satisfies one of the properties of DEA analysis which says that output should not decrease with an increase in input.

3.4. Results

3.4.1. Energy efficiency analysis with undesirable inputs and outputs

To proceed to an analysis of energy efficiency, this study employed the SMB-DEA to account for the undesirable output and to measure the efficiency of the oil and gas-producing countries from 2006 to 2020 in different Latin American and African countries. The results section also showed the evolution of technical efficiency (SMB C) and variable returns to scale (SMB V) efficiency scores. Furthermore, as a robustness check, once calculated, the super-efficiency model SMB is non-oriented to show the diversity in the efficient DMUs and to rank them. In addition, several countries' characteristics might be related to efficiency needs, such as the quality of oil fields, the country's size, geographical differences, and macro-energy policy. The results suggest that, in the mean, countries exhibit increasing returns to scale during the analysis period. However, there is no significant improvement in efficiency compared year after year during the analysis in oil and gas-producing countries in Latin America and the African region.

Table 3.2. Total factor energy efficiency 2006-2020

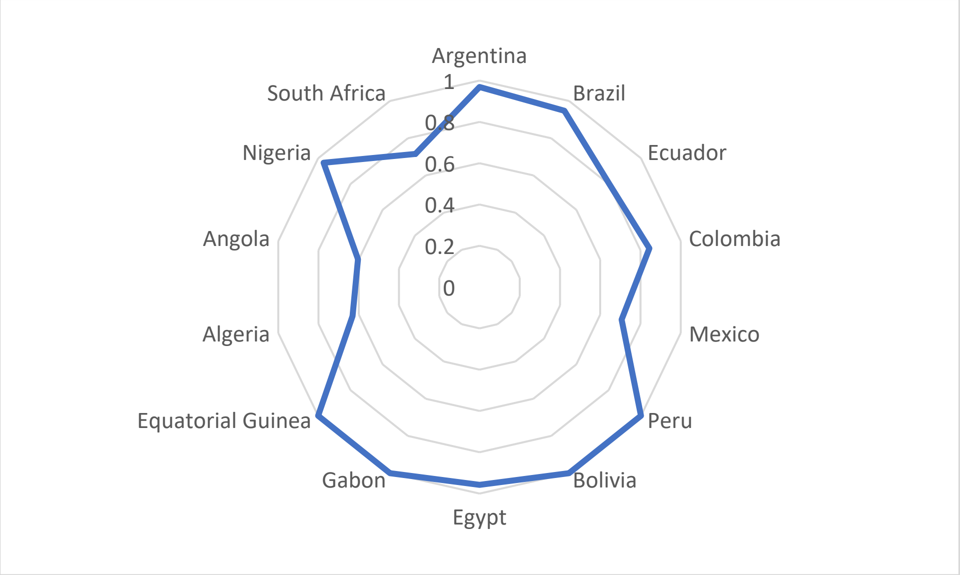
Countries /Score	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average
Argentina	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.534	0.969
Brazil	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.738	1.000	1.000	1.000	1.000	1.000	1.000	0.484	0.948
Ecuador	0.702	1.000	1.000	1.000	0.860	1.000	1.000	0.847	0.884	0.809	0.690	0.592	0.562	0.552	0.545	0.803
Colombia	0.941	0.921	1.000	0.921	1.000	1.000	0.942	0.865	0.826	0.793	0.731	0.754	0.751	0.690	0.527	0.844
Mexico	0.659	0.726	0.735	0.726	0.742	0.719	0.710	0.721	0.734	0.718	0.717	0.726	0.745	0.717	0.498	0.706
Peru	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Bolivia	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Egypt	1.000	1.000	0.842	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.524	0.958
Gabon	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Equatorial Guinea	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Algeria	0.696	0.629	0.614	0.629	0.632	0.665	0.715	1.000	0.651	0.565	0.547	0.538	0.533	0.528	0.521	0.631
Angola	0.566	0.528	0.523	0.528	0.600	0.602	0.705	1.000	0.675	0.621	0.558	0.552	0.543	0.534	0.528	0.604

Nigeria	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.492	0.966
South Africa	0.691	0.716	0.712	0.716	0.747	0.736	0.741	0.737	0.757	0.744	0.750	0.732	0.759	0.696	0.499	0.715

Elaborated by the author

The implication for the countries with a score of 1 (Equatorial Guinea and Gabon) is that these countries are energy efficient. They use technology, production processes, and inputs effectively to produce a balanced GDP growth, emit CO2 emission, life expectancy increase, and low energy depletion values than the other countries. Angola is the least inefficient country (0.604), followed by Algeria (0.63) and Mexico (0.705). Across the years, the mean efficiency estimates of the 14 selected countries went from 0.875 in 2006 to 0.837. This decrease in productivity can be associated with the fall in oil rent and the Latin American energy efficiency policies that enable countries to be on top of their games. The results for 2020 might be because of the intrusion of Covid-19, which affected many countries. The loss of productivity from 2015 to 2020 could be the result of global economic crises in Latin America and Africa that have made countries with weak economic systems vulnerable to losses in productivity.

Figure 3.1. Mean energy efficiency scores of the 14 selected countries from 2006 to 2020



Source: Elaborated by the author

Note: Averages are determined by computing the relative efficiency for each country as calculated in this thesis."

3.4.2. Malmquist Productivity Index results

Malmquist productivity index was employed to measure the energy technical efficiency change index, pure efficiency change index, super efficiency change index, and total factor productivity change index from 2006 to 2020. The productivity of the various economies operated on the assumption that for a DMU to be deemed efficient. Scores below the 1 or 100% threshold are deemed inefficient. Comparing the significant improvement of all the economies on a year-to-year basis, the total factor productivity was decomposed into TC and EC. This ignited that most of the nine countries were inefficient, and that energy consumption and use have been inefficient in improving productivity. Details of TEC indicated the index climbed from 0.781 in 2007–2008 to 1.032 in 2019–2020. The same trend was recorded for EC in 2007–2008, reduced to 0.789 in 2019–2020. The decrease in average efficiency more significant than (1) from 2013 to 2020 indicates a lower energy efficiency level and improvement by countries over the past ten years ending 2020 (Table 3.3). The Energy Efficiency over the past ten years ending 2020 was far below the with an entry efficiency level of 0.67 in 2006–2007 to 0.66 in 2019–2020, and slight improvements in 2009 (0.70) and 2010 (0.72).

Table 3.3. Malmquist Productivity Index results 2007-2020

	Argentina	Brazil	Ecuador	Colombia	Mexico	Peru	Bolivia	Egypt	Gabon	Equatorial Guinea	Algeria	Angola	Nigeria	South Africa	Average
2006-2007	1.00	1.13	1.00	1.00	1.00	1.07	0.99	0.93	0.90	0.98	1.00	1.00	1.01	1.02	0.69
2007-2008	1.00	1.21	0.99	1.00	1.00	0.93	1.02	1.00	1.00	1.01	1.00	0.99	1.00	1.02	0.70
2008-2009	1.01	0.65	1.00	1.00	1.00	0.86	1.01	1.01	1.09	0.98	0.99	0.99	1.00	0.94	0.72
2009-2010	1.00	1.36	1.00	1.00	1.00	1.17	0.99	1.00	0.66	1.01	1.00	1.00	1.00	1.10	0.69
2010-2011	1.00	1.18	1.00	1.00	1.00	1.14	0.99	1.00	0.94	0.96	1.00	1.00	1.01	1.01	0.67
2011-2012	1.00	0.81	1.00	1.00	1.00	0.96	0.97	1.00	0.95	1.00	1.00	1.00	1.00	0.98	0.68
2012-2013	1.00	1.01	1.00	1.00	1.00	0.84	0.99	1.00	0.96	0.97	1.00	1.00	0.99	1.00	0.65

2013-2014	1.00	0.87	1.00	1.00	1.00	0.78	0.98	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.62
2014-2015	1.00	0.73	1.00	1.00	0.99	0.88	0.95	1.00	1.05	1.02	1.00	1.01	1.00	0.95	0.63
2015-2016	1.00	1.14	1.00	1.00	1.02	1.19	1.00	1.00	1.03	1.01	1.00	1.00	1.00	1.02	0.64
2016-2017	1.00	1.05	1.00	1.00	1.00	1.17	0.99	1.00	0.99	0.99	1.00	1.00	1.00	1.00	0.65
2017-2018	1.00	1.00	1.00	1.00	1.00	1.06	1.00	1.00	1.42	1.28	1.00	1.00	1.00	1.00	0.67
2018-2019	1.00	0.94	1.00	1.00	1.00	0.77	1.00	1.00	2.01	1.00	1.00	1.00	1.00	1.02	0.67
2019-2020	1.00	0.95	1.01	1.01	1.00	0.80	1.01	1.01	1.28	1.02	1.00	1.00	1.00	1.03	0.67

Elaborated by the author

3.5. Conclusions

This study conducted an extensive analysis of energy efficiency in oil and gas-producing countries in Latin America and Africa from 2006 to 2020, utilizing the SMB DEA model to account for undesirable outputs and measure efficiency. The results encompassed the evolution of technical efficiency (SMB C) and variable returns to scale (SMB V) efficiency scores. Additionally, a SMB model was applied to rank and identify diverse efficient Decision-Making Units (DMUs). The study also explored potential relationships between country characteristics, such as the quality of oil fields, country size, geographical variations, and macro-energy policies, and their efficiency levels.

The findings indicate that, on average, these countries exhibited increasing returns to scale during the analysis period. However, there was no significant year-over-year improvement in efficiency. This suggests that oil and gas-producing countries in Latin America and Africa faced challenges in enhancing their energy efficiency over time, despite varying country-specific characteristics.

The countries that achieved a score of 1 (Equatorial Guinea and Gabon) demonstrated remarkable energy efficiency, effectively utilizing technology, production processes, and inputs to achieve balanced GDP growth, lower CO2 emissions, increased life expectancy, and reduced energy depletion compared to other countries. Angola emerged as the least inefficient country (0.604), followed by Algeria (0.63) and Mexico (0.705). However, the mean efficiency estimates of the 14 selected countries decreased from 0.875 in 2006 to 0.837, indicating a declining trend in productivity. This decline may be attributed to factors such as the fall in oil rents and energy efficiency policies in Latin America.

The results for 2020 may also be influenced by the impact of the Covid-19 pandemic, which affected many countries and disrupted various economic activities. The observed loss of productivity from 2015 to 2020 may be linked to global economic crises in Latin America and Africa, leaving countries with weaker economic systems vulnerable to productivity losses.

The study further employed the Malmquist productivity index to assess energy technical efficiency change, pure efficiency change, super efficiency change, and total factor productivity change from 2006 to 2020. The results highlighted that most of the analyzed countries were inefficient, indicating that energy consumption and utilization had not been effectively harnessed to improve productivity.

In conclusion, the study underscores the challenges faced by oil and gas-producing countries in Latin America and Africa in enhancing energy efficiency. It points to the need for sustained efforts and policies to address these inefficiencies, particularly in the context of changing economic conditions and global events like the Covid-19 pandemic. Furthermore, the study's findings offer a substantial foundation for future research endeavors and policy development initiatives aimed at driving improvements in energy efficiency within these regions. It is imperative that governments, industry stakeholders, and researchers collaboratively work to identify specific bottlenecks and implement targeted interventions to enhance energy efficiency. These actions should not only consider technological advancements but also encompass robust regulatory frameworks, investment in sustainable practices, and a commitment to reducing environmental impacts.

As the global community grapples with the imperatives of sustainability, climate change mitigation, and energy security, the oil and gas-producing countries in Latin America and Africa find themselves at a crucial crossroads. Addressing inefficiencies in their energy sectors is not only vital for economic stability and growth but also for their contribution to global efforts to combat climate change. The study's insights serve as a valuable compass, guiding these nations towards a more sustainable and energy-efficient future, one that is better equipped to navigate the complexities of a rapidly changing world.

Chapter 4. Final Reflections and Discussion

Centered around the research question, "Are energy resources, particularly oil, being optimally utilized in Ecuador and similar developing nations?", this chapter delves into the synthesis of findings from the preceding three chapters. Its aim is to provide an in-depth exploration of the multifaceted repercussions stemming from the decline in oil quality and the subsequent decrease in efficiency – both at the organizational and national levels. Moreover, this chapter endeavors to propose viable strategies that can counteract the potential ramifications.

By weaving together, the insights derived from the prior chapters, this section strives to illuminate the economic, environmental, and social dimensions of the challenges posed by diminishing oil quality. These challenges extend beyond mere technical concerns, warranting a comprehensive understanding of their ripple effects on economies, ecosystems, and societies. The interplay between these facets highlights the urgency of adopting effective measures to address the overarching issue.

Furthermore, within the context of firms and countries, this chapter explores the cascading impacts of reduced oil quality on efficiency, considering aspects such as resource allocation, production processes, and overall performance. This analysis seeks to underscore the intricate connections between energy quality, efficiency, and sustained growth while simultaneously revealing vulnerabilities that demand mitigation strategies.

The chapter concludes by delineating potential pathways to mitigate the impending consequences, considering the complexities presented. Drawing upon empirical evidence and theoretical frameworks, it aspires to offer actionable solutions that can help steer Ecuador and similar developing nations toward a more resilient and sustainable trajectory. These solutions aim to safeguard against the adverse outcomes stemming from declining oil quality and eroding efficiency through a combination of policy interventions, technological innovations, and strategic investments.

4.1. Oil Quality Deterioration: Economic and environmental implications

4.1.1. Economic Impacts and Possible Solutions

The diminishing quality of extracted oil extends beyond a mere technical concern; it reverberates through multifaceted dimensions, impacting various aspects of the economy and society. Economically, the decline in oil quality creates a chain reaction of challenges that ripple across different sectors.

On an economic level, the reduced quality of oil decreases its market value and demand, leading to lower revenues for the government. This reduction in revenue can have a cascading effect on various public services and government finances. Additionally, the vulnerability of export earnings due to lower-quality oil can disrupt the delicate balance of the nation's balance of payments, potentially leading to trade deficits and economic instability. The reliance on oil-derived income to formulate budgets necessitates a fundamental recalibration to address the potential revenue shortfalls caused by diminishing oil quality. This, in turn, might necessitate adjustments in fiscal policies, potentially affecting social programs and infrastructural projects. The need to make such adjustments could prompt a thorough reassessment of national priorities, urging a shift towards more diversified and sustainable sources of revenue. Moreover, the diminishing quality of oil can dent investor confidence, which is a cornerstone of sustained economic growth. A decline in investor confidence might deter foreign direct investment and capital inflows, which are crucial for economic development and stability. In conclusion, the implications of declining oil quality are far-reaching, affecting economic stability, government finances, social programs, infrastructure projects, and investor confidence. This underscores the urgency for Ecuador to explore and invest in alternative, renewable energy sources to mitigate these challenges and ensure a more sustainable and prosperous future.

Diversifying the economic landscape of Ecuador and nurturing the growth of new industries is paramount in addressing the challenges posed by diminishing oil quality. This approach goes hand in hand with the imperative to explore and invest in alternative, renewable energy sources for long-term sustainability and prosperity.

By embracing a diversified approach to the country's economic activities, Ecuador can reduce its heavy dependence on oil-related revenues. This involves fostering the growth of new sectors such as technology, manufacturing, agriculture, tourism, and services. Each of these sectors not only brings additional revenue streams but also contributes to employment generation, skills development, and a more resilient economy.

Investing in renewable energy sources like solar, wind, geothermal, and hydropower not only mitigates the negative economic consequences of declining oil quality but also aligns with global efforts to combat climate change. Transitioning to a cleaner energy mix not only reduces greenhouse gas emissions but also positions Ecuador as a forward-looking nation in the international arena. Furthermore, the development of renewable energy industries can spur innovation and create a ripple effect in related sectors. It can catalyze research and development efforts, foster the growth of local expertise, and attract foreign investment from companies seeking sustainable energy solutions. The success story of countries like Iceland, which leveraged its geothermal resources to transform its economy, serves as a compelling example of the potential benefits of such endeavors.

In conclusion, diversifying Ecuador's economic structure and prioritizing the development of renewable energy industries are essential steps in overcoming the challenges posed by declining oil quality. By doing so, Ecuador not only ensures its economic resilience but also contributes to global sustainability efforts while paving the way for a brighter and more prosperous future for its citizens.

4.1.2. Environmental Ramifications: Unveiling the Ecological Consequences

Environmental ramifications reverberate in response to the decline in oil quality, unmasking a sequence of interconnected challenges that necessitate a resolute commitment to sustainable practices and environmental stewardship. As the quality of extracted oil diminishes, the processing trajectory embarks on a precarious course. Lower-quality oil necessitates more energy-intensive methods for extraction and refining. This cascade effect increases energy consumption during extraction processes while refining procedures become more resource-intensive. The augmented energy demands drive greenhouse gas emissions, as conventional extraction and refining techniques and lower-quality oil contribute disproportionately to the sector's overall ecological footprint.

This stark reality precipitates a poignant juncture. Urgency envelops the imperative to redefine industry standards, pivoting towards sustainable practices to assuage the sector's burgeoning environmental impact. The transformation calls for integrating cutting-edge technologies, innovative extraction methods, and stringent emission reduction protocols. A multipronged approach comes to the fore, entailing the adoption of advanced technologies that optimize extraction efficiency and minimize energy consumption. Concurrently, refining processes must be refined themselves, aligning with eco-friendly benchmarks to curb emissions. Investing in research and development becomes instrumental, fostering the birth of novel techniques that marry resource efficiency with environmental preservation.

Furthermore, collaborative initiatives among governmental bodies, industry stakeholders, and environmental organizations assume significance. The collective pursuit of sustainable practices requires cohesive frameworks that amalgamate expertise, resources, and policy enforcement. Incentives for companies to transition towards greener methodologies and financial support for research into cleaner extraction techniques can expedite the transformation.

Ultimately, the environmental ramifications cascade beyond the oil sector, intertwining with the broader fabric of global sustainability. Ecuador's commitment to ecological conservation can resonate on the international stage, embodying a proactive stance in the face of climate challenges. As the oil industry navigates these environmental crosscurrents, it beckons an era of responsibility, innovation, and collaboration—a clarion call to mend the ecological tapestry for generations to come.

Environmental ramifications follow suit. The processing of lower-quality oil could entail escalated energy consumption and elevated emissions during extraction and refining processes. This lends urgency to bolstering sustainable practices to mitigate the sector's ecological footprint.

4.2. Beyond 2034: Navigating the Post-Oil Horizon

The possible obsolescence of profitable oil extraction post-2034 imposes a critical juncture for Ecuador's long-term prosperity. Amidst the challenges, a canvas of opportunities unfurls, guiding the trajectory toward a diversified, resilient, and sustainable future. Foremost, a comprehensive economic diversification strategy becomes paramount. Reliance on oil beyond its profitability would court financial instability and curtail the emergence of nascent economic sectors. The vacuum left by diminishing oil revenues necessitates innovative policies to nurture industries outside the oil spectrum.

The evolution towards renewable energy sources emerges as an imperative. As the oil chapter draws close, the potential to catalyze a green energy revolution gains prominence. Investments in clean technologies and sustainable practices lay the groundwork for an energy-independent future, underscoring Ecuador's commitment to global climate objectives. Ecuador holds an immense generation potential rooted in renewable sources, encompassing a variety of primary sources such as photovoltaic, wind, geothermal, and hydropower. Encouraging public and private investments in these technologies could diminish the nation's energy reliance on oil and pave the way for a burgeoning industry within the country, thereby decreasing its economic dependence on oil.

The development of the renewable industry in Ecuador is not only possible but also feasible; it simply requires a strong political commitment to foster this new sector. Consider the case of Iceland, where the advancement of geothermal energy served as the cornerstone for the nation's development. Iceland's GDP per capita surged from 28,897.4 in 2001 to 72,903 in 2022 (World Bank 2023), a growth catalyzed by the abundance of geothermal and hydroelectric resources. These resources attracted foreign investments in the aluminum sector, propelling economic expansion and stirring interest from high-tech firms seeking to establish data centers fueled by cost-effective green energy (Gylfason 2014).

The recalibration of Ecuador's geopolitical positioning warrants scrutiny. As the nation transforms from an oil exporter to a diversified economy, international relations and trade dynamics demand astute navigation to safeguard diplomatic and economic interests.

In conclusion, the waning quality of oil reserves and the impending obsolescence of profitable extraction unfurl a pivotal chapter in Ecuador's history. Strategic investments diversified economic structures, renewable energy pursuits, and proactive policy reforms collectively chart a course toward a resilient, sustainable, and economically vibrant nation. As the sun sets on the oil era, Ecuador's dawn of transformation beckons, carrying the promise of a brighter and greener future.

4.2.1. The role of policy reform in the Post-Oil Horizon

Policy reforms are pivotal in steering Ecuador's transition away from oil-dominated policies and fostering a robust, inclusive economic ecosystem. This transformation necessitates a comprehensive overhaul of legislative frameworks to accommodate the changing dynamics of the economy.

One crucial aspect of this transformation is the development of policies focused on energy efficiency, spanning both the supply and demand sides. On the supply side, incentivizing and promoting efficient energy production methods, especially in the context of renewable sources, can yield significant benefits. This includes investing in advanced technologies, optimizing resource utilization, and streamlining energy distribution systems. By doing so, Ecuador can enhance the overall productivity of its energy sector while minimizing waste and environmental impact.

On the demand side, policies aimed at promoting energy efficiency among consumers and industries can lead to substantial gains. Implementing energy-efficient building codes, promoting the use of energy-efficient appliances, and creating awareness campaigns can all contribute to reducing energy consumption and lowering overall costs. This not only benefits individuals and businesses by lowering their energy bills but also reduces the strain on the energy infrastructure and contributes to sustainability goals.

Moreover, as Ecuador shifts its economic focus and seeks to diversify revenue streams, the government's role in ensuring the continuity of social welfare programs becomes paramount. This involves strategic resource allocation, where revenues from non-oil sectors are directed towards sustaining these essential programs. These efforts require careful planning, as the transition away from oil-related revenues may lead to budgetary adjustments. However, by aligning welfare policies with the new economic realities, Ecuador can safeguard the well-being of its citizens while facilitating the broader economic transformation.

In summary, comprehensive policy reforms are pivotal in navigating Ecuador's transition towards a more diverse and sustainable economic landscape. By prioritizing energy efficiency, both on the supply and demand sides and strategically reallocating resources to uphold social welfare programs, Ecuador can effectively address the challenges brought about by declining oil quality and chart a course towards a prosperous and resilient future.

4.2.2. Navigating the Jevons Paradox: Harnessing Energy Efficiency for Sustainable Development in Private Oil Companies and Developing Oil-Exporting Nations

In the context of a Post-oil Horizon, the implementation of energy efficiency policies emerges as a pivotal strategy in addressing the Jevons Paradox, thereby fostering a sustainable and responsible energy consumption paradigm. This is particularly pertinent for private oil companies and developing oil-exporting nations alike.

Private oil companies can proactively adopt measures to enhance energy efficiency throughout their operations. By investing in advanced technologies that minimize energy losses during extraction, refining, and transportation processes, these companies can curtail wastage and optimize energy utilization. Furthermore, integrating eco-friendly practices, such as utilizing renewable energy sources for auxiliary operations, can further bolster their commitment to efficient energy use. Notably, these actions not only align with environmental stewardship but also contribute to improved long-term profitability by reducing operational costs and enhancing corporate social responsibility.

For developing oil-exporting nations, the strategic deployment of energy efficiency policies can circumvent the Jevons Paradox and promote sustainable development. By channeling revenues from oil exports into initiatives that promote energy diversification, such as investing in renewable energy infrastructure, these nations can reduce their reliance on oil while catering to growing energy demands. Concurrently, incentivizing industries to adopt energy-efficient practices through regulatory frameworks and economic incentives can temper the demand surge that often accompanies efficiency improvements. This harmonization of policies can lead to a more balanced energy landscape, safeguarding against the pitfalls of increased energy consumption that can counteract efficiency gains.

In essence, both private oil companies and developing oil-exporting nations stand to gain by proactively navigating the Jevons Paradox through the prism of energy efficiency policies well designed and that consider social and environmental objectives. By embracing these measures, they align with global sustainability objectives and fortify their resilience in an evolving energy landscape, ensuring a harmonious coexistence between economic growth and responsible resource utilization.

4.3. Strategies and Policy recommendations

Regarding the loss of quality of oil fields and increment of energy cost due to oil extraction in developing countries, there are some strategies that governments can implement. 1) Governments can provide incentives to oil companies to adopt energy-efficient practices. This can include tax breaks, subsidies, or other financial incentives to encourage companies to invest in energy-efficient equipment or practices (García-Quevedo & Jové-Llopis, 2021). 2) Governments can implement regulations that require oil companies to adopt energy-efficient practices, such as using energy-efficient equipment, reducing energy waste, or improving energy management (Shi & Sun, 2017). 3) Promoting the use of energy-saving technologies, such as energy-efficient lighting, HVAC systems, and insulation, to reduce the energy consumption of oil extraction facilities. Overall, governments can play an essential role in reducing the energy cost of oil extraction in developing countries by implementing policies and programs that encourage energy efficiency and promote sustainable energy practices.

The results obtained in chapter two suggest that oil and gas companies in developing countries can implement several recommendations to improve energy efficiency, such as: 1)

Conducting energy audits can help identify areas where energy efficiency improvements can be made. The audits should focus on identifying areas where energy is being wasted and recommend solutions to reduce energy consumption (Moya, et al., 2016). 2) Investing in renewable energy sources can help oil and gas companies reduce their carbon footprint and energy consumption (IEA 2022). 3) Implementing energy management systems can help firms monitor and manage their energy consumption more effectively. This can include monitoring energy use in real-time, setting energy consumption targets, and implementing energy-saving measures (Javied et al. 2015). 4) Improving operational efficiency through process optimization, equipment upgrades, and regular maintenance can help reduce energy consumption and costs. This can also improve productivity and profitability (Hohne et al. 2020). 5) Training employees on energy efficiency best practices can help create a culture of energy conservation within the company. This can include training on energy-efficient equipment usage, energy-saving techniques, and reducing energy consumption (Henriques & Catarino 2016). Furthermore, 6) Collaborating with the government and other stakeholders to access resources, funding, and technical expertise to implement energy efficiency measures. It can also help create a regulatory environment that promotes energy efficiency and encourages investment in renewable energy (Berry 2020).

Results found in chapter three suggests that improving energy efficiency has a positive impact in reducing energy consumption and CO2 emissions in the oil and gas sector in oil-exporting developing countries.

There are several strategies that oil-exporting developing countries can adopt to improve their energy efficiency and achieve sustainability goals. Some recommendations are 1) Implementing Energy Efficiency Standards, governments can set minimum energy efficiency standards for buildings, appliances, and industrial processes. These standards can be backed by incentives or penalties to encourage compliance (Bertoldi 2022). 2) Governments can incentivize the adoption of renewable energy technologies through tax breaks, subsidies, or other financial incentives. Promoting renewable energies projects can reduce dependence on fossil fuels and increase energy efficiency (IEA 2022). 3) Stimulating Energy Conservation, governments can promote energy conservation by implementing awareness campaigns, providing energy audits, and encouraging the use of energy-efficient appliances and practices (Moya et al. 2016). 4) Improving Energy Infrastructure, developing countries can improve their energy infrastructure by upgrading their transmission and distribution systems, reducing transmission losses, and investing in innovative grid technologies (Neffati et al., 2021). 5)

Governments can encourage private sector investment in energy efficiency by creating a supportive policy and regulatory environment that incentivizes investment in energy efficiency and by establishing partnerships with the private sector to develop energy-efficient technologies and practices (Owusu-Manu 2021). 6) Developing countries can implement carbon pricing mechanisms such as a carbon tax or emissions trading system to incentivize energy efficiency and reduce greenhouse gas emissions (Haites 2018). 7) Enhance international cooperation by collaborating with international organizations, such as the United Nations Development Program (UNDP) or the International Energy Agency (IEA), to access financing, technical assistance, and knowledge-sharing opportunities to support their energy efficiency efforts.

4.4. Limitation of the study

While this study has contributed valuable insights, it is important to acknowledge its limitations, which influence the scope and depth of the findings. The following points highlight key limitations that warrant consideration:

Holistic Approach to Variables: The decision to utilize physical variables exclusively or monetary variables alone can be reductionist. Focusing solely on one category of variables risks omitting important nuances. The intention of this study was to lay the groundwork for future comprehensive models. The inclusion of both physical and monetary variables would offer a more holistic understanding of the complex relationships and trade-offs between efficiency improvements, economic outcomes, and environmental impacts.

Limited Scope of Impacts: The chosen methodology, while insightful, falls short in encompassing the full spectrum of impacts associated with oil extraction. Notably absent are considerations of ecosystem services and the socioeconomic effects on communities in proximity to extraction sites. These unaddressed dimensions may influence the overall sustainability assessment and should be incorporated in future studies to provide a more complete picture.

Neglecting Uncertainty and Volatility: The models employed in this study omit variables that account for the uncertainty and volatility inherent in oil price variations. As a result, the projections provided are rooted solely in historical data. In reality, the oil market is characterized by fluctuations influenced by geopolitical events, market dynamics, and unforeseen factors. Integrating variables that capture such uncertainty could lead to a more realistic depiction of potential outcomes.

Exclusion of Public Companies: This study focused solely on private oil companies, omitting the insights that could be gleaned from analyzing public oil companies. Expanding the analysis to encompass public entities offers an opportunity for future research, which could shed light on the differences in efficiency strategies, impacts, and implications for public policy.

In essence, while this study contributes valuable insights to the discourse on energy efficiency and its implications, it is crucial to acknowledge its limitations. These limitations, although inherent, serve as steppingstones for future research endeavors, enabling more comprehensive, nuanced, and contextually rich analyses that account for the multifaceted nature of energy extraction and its impacts.

4.5. Final remark and future research

While this study has undoubtedly made significant headway in unraveling the potential impacts arising from inefficient energy resource utilization, as well as in elucidating the pivotal role of energy efficiency in enhancing the economic and environmental dimensions within oil companies and developing oil-exporting nations, there remains a realm of uncharted territory that beckons exploration. This uncharted territory, particularly within the dynamic realm of Latin American and Caribbean (LAC) countries, holds immense promise for shedding light on hitherto unexplored aspects. With insights garnered from the present study serving as the guiding compass, the groundwork is firmly established for an ambitious future research agenda that seeks to plumb the depths of the intricate nexus between energy efficiency and its transformative effects across both traditional and renewable energy sectors within the expansive LAC region. Considering these the possible research lines that could be develop are:

1**. Extending the Geographic Context:**

The study of energy efficiency's influence on economic and environmental aspects remains an ongoing pursuit, especially within the diverse and dynamic landscape of LAC countries. A logical progression would be to expand the research's geographic scope to encompass a broader array of nations within the region. By doing so, a more comprehensive understanding of regional variations, policy dynamics, and industry-specific challenges can be achieved.

2. Comprehensive Evaluation of Strategies:

Building upon the findings of this study, the next phase of research could involve a meticulous evaluation of strategies aimed at enhancing energy efficiency and environmental performance across both traditional and renewable energy sectors. This evaluation should encompass an array of dimensions, including technological advancements, regulatory frameworks, investment incentives, and the adoption of sustainable practices.

3. Comparative Analysis:

A comparative analysis between traditional and renewable energy companies in the LAC region can yield valuable insights into the effectiveness of energy efficiency strategies across different energy sources. Understanding how these strategies translate within different sectors can offer tailored insights for policy formulation and industry development.

4. Socioeconomic Implications:

Beyond economic and environmental aspects, future research can delve into the socioeconomic implications of energy efficiency strategies. This includes assessing their effects on job creation, community development, and local empowerment, particularly within the context of LAC countries where energy industries often intersect with vulnerable populations.

5. Longitudinal Studies:

Conducting longitudinal studies to track the implementation and impacts of energy efficiency strategies over time would provide a more comprehensive understanding of their long-term effectiveness. This approach can uncover trends, adaptation strategies, and potential challenges that emerge as policies and technologies evolve.

In essence, the exploration of energy efficiency's intricate ties to economic and environmental performance is an ongoing journey with vast potential. By focusing on the specific landscape of LAC and other developing countries and extending research into the strategies and implications of energy efficiency across different energy sectors, this future research agenda can significantly contribute to sustainable energy practices, policy formulation, and the overall well-being of the world.

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Appendix

Pollution generating process.

Assume that the outputs are separated into economic (desirable) and polluting (undesirable) components[2]. Let $\mathtt{I}$ and $\mathtt{O}$ be the input and output sets such that $\mathtt{I} = [n]$ and $\mathtt{O} = (\mathtt{O}^{\mathtt{d}}, \mathtt{O}^{\mathtt{u}}) = [m]$, where $[n] = \#\mathtt{I}$ and $[m] = \#\mathtt{O}^{\mathtt{d}} + \#\mathtt{O}^{\mathtt{u}}$. The input and output vectors for the period (t) are defined as $(x_t, y_t) \in \mathbb{R}_+^{m+n}$.

The pollution-generating technology is defined as follows,

$$T = \left\{(x_t, y_t) \in \mathbb{R}_+^{n+m} : x_t \text{ can produce } (y_t^{\mathtt{d}}, y_t^{\mathtt{u}})\right\}. \tag{6.1}$$

Usual characterisations of T are the output set, $P : \mathbb{R}_+^n \mapsto 2^{\mathbb{R}_+^m}$, and the input correspondence, $L : \mathbb{R}_+^m \mapsto 2^{\mathbb{R}_+^n}$,

$$P(x_t) = \left\{(y_t^{\mathtt{d}}, y_t^{\mathtt{u}}) \in \mathbb{R}_+^m : (x_t, y_t) \in T\right\} \tag{6.2}$$

and

$$L(y_t^{\mathtt{d}}, y_t^{\mathtt{u}}) = \left\{x_t \in \mathbb{R}_+^n : (x_t, y_t) \in T\right\}. \tag{6.3}$$

In this chapter, alternative characterisations of the pollution-generating processes are considered through the undesirable set, $\mathcal{Q} : \mathbb{R}_+^{m^{\mathtt{d}}} \mapsto 2^{\mathbb{R}_+^{n+m^{\mathtt{u}}}}$, and the desirable correspondence, $\mathcal{Z} : \mathbb{R}_+^{m^{\mathtt{u}}} \mapsto 2^{\mathbb{R}_+^{n+m^{\mathtt{d}}}}$,

$$\mathcal{Q}(y_t^{\mathtt{d}}) = \left\{(x_t, y_t^{\mathtt{u}}) \in \mathbb{R}_+^m : (x_t, y_t) \in T\right\} \tag{6.4}$$

and

$$\mathcal{Z}(y_t^{\mathtt{u}}) = \left\{(x_t, y_t^{\mathtt{d}}) \in \mathbb{R}_+^m : (x_t, y_t) \in T\right\}. \tag{6.5}$$

$$\left.\begin{array}{l} x_t \in L(y_t^{\mathtt{d}}, y_t^{\mathtt{u}}) \\ (y_t^{\mathtt{d}}, y_t^{\mathtt{u}}) \in P(x_t) \\ (x_t, y_t^{\mathtt{d}}) \in \mathcal{Z}(y_t^{\mathtt{u}}) \\ (x_t, y_t^{\mathtt{u}}) \in \mathcal{Q}(y_t^{\mathtt{d}}) \end{array}\right\} \Leftrightarrow (x_t, y_t) \in T \tag{6.6}$$

Assume that the pollution-generating technology satisfies the following usual properties (Färe et al., 1985):

$\mathcal{A}1$: *No free lunch and Inaction*; $(0,0) \in T$, $(0, y_t) \in T \Rightarrow y_t = 0$.
$\mathcal{A}2$: *Boundedness*; $T(x_t, y_t) = \{(x_t, v_t) \in T : v_t \leq y_t\}$ is bounded for all $y_t \in \mathbb{R}_+^m$.
$\mathcal{A}3$: *Closedness*; T is closed.

Let C be the convex cone such that: $\mathrm{C} = \{y_t \in \mathbb{R}^m : y_t^u \leq 0 \text{ and } y_t^d \geq 0\}$. In addition of the traditional axioms $\mathcal{A}1 - \mathcal{A}3$, suppose that the pollution-generating process satisfies the B-disposal assumption (Abad and Briec, 2019):

$\mathcal{A}4$: *B-disposability*; $T = \Big(\big(T + (\mathbb{R}_+^n \times -\mathbb{R}_+^m)\big) \cap \big(T + (\mathbb{R}_+^n \times -\mathrm{C})\big)\Big) \cap (\mathbb{R}_+^m \times \mathbb{R}_+^n)$.

The theoretical model based upon the properties $\mathcal{A}1 - \mathcal{A}4$ permits to define the pollution-generating process as an intersection of sub-technologies (Abad and Briec, 2019): $T + (\mathbb{R}_+^n \times -\mathbb{R}_+^m) \cap (\mathbb{R}_+^m \times \mathbb{R}_+^n)$ and $T + (\mathbb{R}_+^n \times -\mathrm{C}) \cap (\mathbb{R}_+^m \times \mathbb{R}_+^n)$. As in the by-production framework (Murty and Russell, 2020), the intended production activities of firms satisfy the usual strong disposability assumption; *ie.* $T + (\mathbb{R}_+^n \times -\mathbb{R}_+^m) \cap (\mathbb{R}_+^m \times \mathbb{R}_+^n)$. Moreover, a partially reversed free disposal axiom applies for the polluting residuals generation; *ie.* $T + (\mathbb{R}_+^n \times -\mathrm{C}) \cap (\mathbb{R}_+^m \times \mathbb{R}_+^n)$. It is worth noting that axioms $\mathcal{A}1 - \mathcal{A}4$ define a fairly weak axiomatic framework such that the convexity assumption is not required to define pollution-generating processes[3]

Table 0.1. PM productivity index under FDH production technology

	Mean	S.D.	Min	Max
Algeria				
Employment	16.254	0.806	15.194	17.390
Capital	11.812	0.193	11.511	12.051
CO_2 emissions	24.950	0.297	24.287	25.255
Oil and gas production	7.475	0.099	7.247	7.585
Life expectancy	4.324	0.015	4.297	4.345
ENERGY DEPLETION	9.338	0.071	9.226	9.434
GDP	0.601	0.031	0.540	0.633
Energy consumption				
Angola	16.232	0.806	15.171	17.367
ENERGY DEPLETION	10.073	0.190	9.715	10.362
CO_2 emissions	24.115	0.146	23.764	24.330
Capital	7.448	0.112	7.184	7.581
Oil and gas production	4.047	0.060	3.935	4.119
Life expectancy	9.269	0.157	9.019	9.504
Employment	0.383	0.054	0.259	0.450
GDP				
Energy consumption	*20.390*	*0.457*	*19.508*	*21.259*
Argentina	12.057	0.057	11.951	12.131
ENERGY DEPLETION	25.252	0.142	25.005	25.436
CO_2 emissions	6.737	0.067	6.650	6.860
Capital	4.326	0.008	4.312	4.337
Oil and gas production	9.841	0.043	9.782	9.925
Life expectancy	0.723	0.019	0.696	0.749
Employment				
GDP	19.618	0.787	17.478	20.622
Energy consumption	10.765	0.196	10.337	10.948
Bolivia	22.421	0.369	21.719	22.867

ENERGY DEPLETION	4.369	0.224	4.025	4.710
CO_2 emissions	4.237	0.028	4.188	4.274
Capital	8.501	0.079	8.383	8.639
Oil and gas production	0.289	0.044	0.226	0.338
Life expectancy				
Employment	22.737	0.495	21.823	23.531
GDP	12.952	0.129	12.724	13.145
Energy consumption	26.493	0.161	26.276	26.740
Brazil	7.977	0.169	7.698	8.246
ENERGY DEPLETION	4.308	0.017	4.277	4.331
CO_2 emissions	11.476	0.044	11.407	11.556
Capital	0.977	0.019	0.936	1.000
Oil and gas production				
Life expectancy	20.594	0.591	19.748	21.413
Employment	11.172	0.132	10.963	11.323
GDP	24.762	0.216	24.334	24.980
Energy consumption	6.711	0.222	6.303	6.941
Colombia	4.331	0.013	4.311	4.350
ENERGY DEPLETION	10.056	0.101	9.882	10.177
CO_2 emissions	0.573	0.021	0.538	0.595
Capital				
Oil and gas production	17.949	0.717	15.883	18.634
Life expectancy	10.520	0.107	10.313	10.641
Employment	23.885	0.164	23.562	24.104
GDP	6.247	0.050	6.179	6.331
Energy consumption	4.327	0.012	4.308	4.346
Ecuador	8.873	0.100	8.769	9.025
ENERGY DEPLETION	0.526	0.017	0.492	0.555
CO_2 emissions				
Capital	18.777	1.492	16.562	20.632

Oil and gas production	12.277	0.118	12.048	12.427
Life expectancy	24.603	0.220	24.192	25.056
Employment	6.502	0.624	4.263	6.837
GDP	4.261	0.012	4.243	4.279
Energy consumption	10.222	0.060	10.088	10.284
Egypt	0.745	0.014	0.714	0.765
ENERGY DEPLETION				
CO$_2$ emissions	13.948	0.580	12.872	14.959
Capital	8.965	0.240	8.585	9.209
Oil and gas production	21.891	0.849	19.838	22.885
Life expectancy	5.656	0.284	5.124	5.971
Employment	4.038	0.026	4.001	4.079
GDP	5.913	0.194	5.593	6.181
Energy consumption	0.089	0.024	0.045	0.126
Equatorial Guinea				
ENERGY DEPLETION	14.918	0.968	13.452	16.241
CO$_2$ emissions	8.619	0.074	8.505	8.767
Capital	22.071	0.418	21.457	22.821
Oil and gas production	5.476	0.351	5.153	6.691
Life expectancy	4.146	0.044	4.071	4.200
Employment	6.310	0.152	6.063	6.512
GDP	0.057	0.032	0.006	0.094
Energy consumption				
Gabon	21.814	0.437	21.183	22.602
ENERGY DEPLETION	13.045	0.027	13.013	13.095
CO$_2$ emissions	26.243	0.087	26.060	26.339
Capital	7.885	0.220	7.558	8.219
Oil and gas production	4.318	0.002	4.316	4.321
Life expectancy	10.829	0.075	10.700	10.944

Employment	0.917	0.007	0.900	0.926
GDP				
Energy consumption	16.093	1.399	13.469	18.075
Mexico	11.508	0.136	11.251	11.655
ENERGY DEPLETION	24.955	0.107	24.783	25.131
CO_2 emissions	7.766	0.074	7.658	7.892
Capital	3.953	0.038	3.888	4.008
Oil and gas production	10.915	0.078	10.785	11.039
Life expectancy	0.589	0.053	0.502	0.648
Employment				
GDP	22.488	0.464	21.244	23.051
Energy consumption	9.779	0.249	9.326	10.053
Niger	24.355	0.269	23.711	24.602
ENERGY DEPLETION	5.389	0.189	5.024	5.628
CO_2 emissions	4.320	0.016	4.293	4.343
Capital	9.714	0.065	9.602	9.842
Oil and gas production	0.504	0.026	0.450	0.535
Life expectancy				
Employment	21.759	0.644	20.521	22.637
GDP	12.956	0.045	12.847	13.012
Energy consumption	24.785	0.096	24.538	24.892
Peru	7.496	0.131	7.264	7.711
ENERGY DEPLETION	4.094	0.063	3.985	4.165
CO_2 emissions	9.925	0.071	9.843	10.043
Capital	0.701	0.014	0.663	0.718
Oil and gas production				
Life expectancy	18.826	2.959	12.872	23.531
Employment	11.178	1.413	8.505	13.145
GDP	24.342	1.384	19.838	26.740
Energy consumption	6.652	1.095	4.025	8.246

South Africa	4.216	0.132	3.888	4.350
ENERGY DEPLETION	9.370	1.545	5.593	11.556
CO_2 emissions	0.548	0.265	0.006	1.000
Capital	12.956	0.045	12.847	13.012
Oil and gas production	7.496	0.131	7.264	7.711
Life expectancy	4.094	0.063	3.985	4.165
Employment	3.417	2.713	2.090	13.110
GDP	19.609	0.074	19.459	19.698
Energy consumption	0.701	0.014	0.663	0.718

Note: All the variables are in logarithms.

Elaborated by the author.

Table 0.2. Output-Input correlation matrix

Variables	Energy depletion	CO_2 emissions	Capital	Oil and gas production	Life expectancy	Employment	Energy consumption
Energy depletion	1.000						
CO_2 emissions	0.603 (0.000)	1.000					
Capital	0.607 (0.000)	0.838 (0.000)	1.000				
Oil and gas production	0.179 (0.009)	0.669 (0.000)	0.786 (0.000)	1.000			
Life expectancy	0.540 (0.000)	0.318 (0.000)	0.384 (0.000)	-0.078 (0.263)	1.000		
Employment	0.658 (0.000)	0.827 (0.000)	0.900 (0.000)	0.652 (0.000)	0.309 (0.000)	1.000	
Energy consumption	0.688 (0.000)	0.925 (0.000)	0.943 (0.000)	0.695 (0.000)	0.459 (0.000)	0.911 (0.000)	1.000

Note: significance levels in parenthesis. All the variables are in logarithms.

Elaborated by the author