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Karla Michell Arias Marín

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Évaluation énergétique de l'extraction du pétrole : Efficacité et durabilité du secteur pétrolier privé du Equateur

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M. Arnaud ABAD, INRAE	Examinateur
M. Pedro ALARCÓN, Professeur à FLACSO	Co-Director
M. Stéphane BLANCARD, Professeur à Agrosup Dijon	Rapporteur
M. Hervé BLANCHARD, Professeur à Université de Perpignan Via Domitia	Examinateur
M. Jean-Philippe BOUSSEMART, Professeur à l'Université de Lille 3	Rapporteur
M. Walter BRIEC, Professeur à l'Université de Perpignan	Directeur
M. Vincent LIGNON, Professeur à l'Université de Perpignan	Co-Director
M. Roman MESTRE, Maître de Conférences à l'Université de Perpignan	Examinateur
Mme. Françoise SEYTE, Maître de Conférences à l'Université de Perpignan	Examinateur

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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.

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 (D. 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, Thermoeconomic Analysis 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, British Petroleum 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

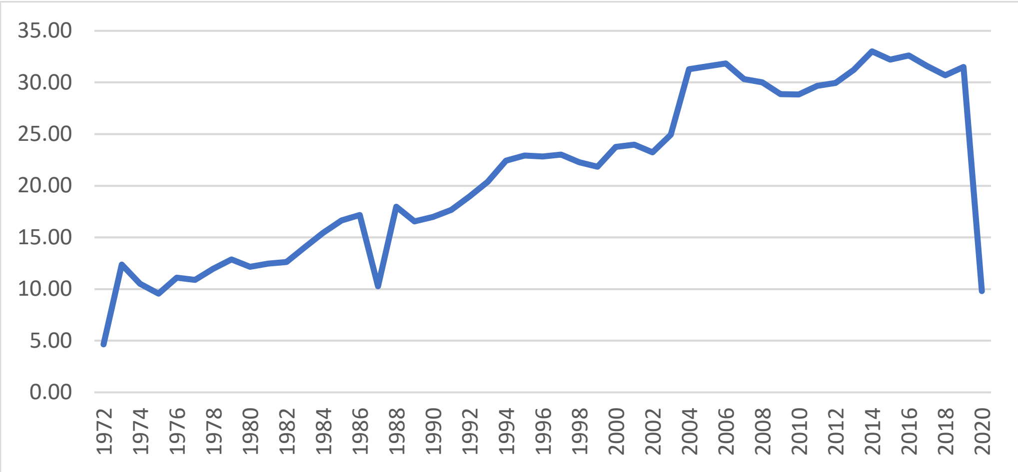
1.1. Introduction

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 3.1.

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.

1.2. 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).

1.2.1. 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 3.1. 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 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.

	EXCEM quantity. Mass and energy are conserved. Exergy and cost are not conserved, as exergy cannot increase while cost cannot decrease.		
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 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.	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 electrical generating station.
Thermoeconomics and exergo-economics	Exergoeconomics and thermoeconomics are exergy-based economic methods (Sciubba 2001).	Exergy accounting utilizes exergy costs and is useful for diagnosing energy systems and accounting for	There are several scientific papers showing the theoretical foundations and applications of exergy cost accounting and thermoeconomics

	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 (A. 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, Lozano, et al. 1986).	natural exergy resources (A. 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).	such as the work developed by (Yantovski 1994, Sciubba 2001, A. 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	The approach allows direct quantitative comparisons of factors like labor, environmental impact, and externalities (Ayres, Brockway and Aramendia 2019).	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

	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).	Thermodynamics and economics are integrated to obtain exergy-based indicators of sustainable development (Ferrari, Genoud and Lesourd 2001) The method allows firms and governments to set environmental goals and programs (Rosen 2008).	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)

1.2.3. 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 thermoeconomic methods to analyze environmental and economic issues has helped to increase the interest in this field around 1993 (A. 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

[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.

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 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.

1.2.4. 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

[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).

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.

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

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

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 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).

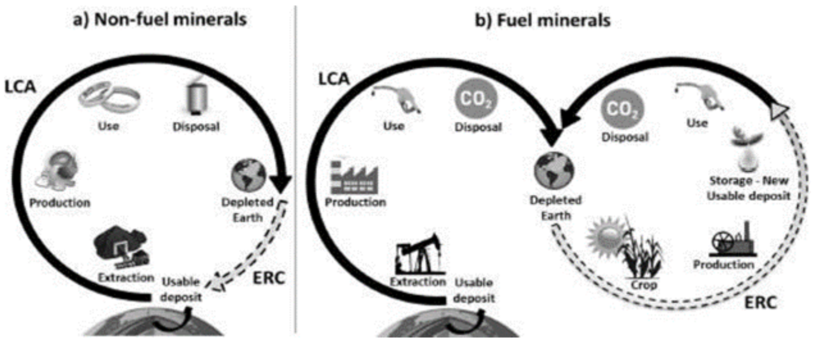
The second suggestion the "Lisboa school" make to clarify the definition of ERC is to focus on fossil fuel, and it imply considering "Nature´s ability through photosynthesis to provide a usable deposit that fulfills the function of fossil fuels, in the form of biomass" (Whiting, et al. 2017, 17). there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

> Valero and Valero (2014) 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) 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, Calvo, et al. 2018b, Palacios, Calvo, et al. 2018a) national (Carmona, Whiting,, et al. 2017, Valero and Torres 2006, Calvo, et al. 2021), and product scale (A. 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).

1.2.5. 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.

1.3. 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.

1.3.1. 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 3.2. For this study I will use the HHV of fuel-2 calculated by Valero & Valero (2014), showed in Table 3.2.

1.3.2. Chemichal 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).

1.3.3. 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:

$$EROI = \frac{Energy\ returned}{Energy\ invested} \tag{3}$$

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 (Capellán-Pérez, Castro and González 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.

1.3.4. 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:

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

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

$$Energy\ cost = \ \Delta(Eq. 5) \times Ext. \quad (6)$$

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

$$Site\ degradation = \ \Delta(Ext.) \times \big(1 + (Eq. 5)\big) \quad (7)$$

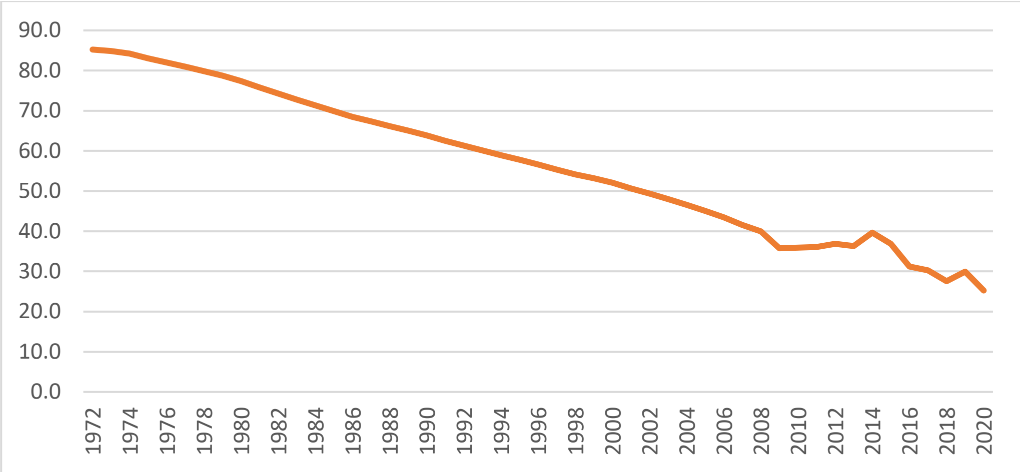
Having clear the procedure to be followed in the next section the results are presented.

1.4. 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 CO_2 and therefore cannot be reconcentrated. In terms of exergy replacement cost (ERC), Valero and Valero (2014) determined the ERC for fuel minerals (Table 3.3). 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



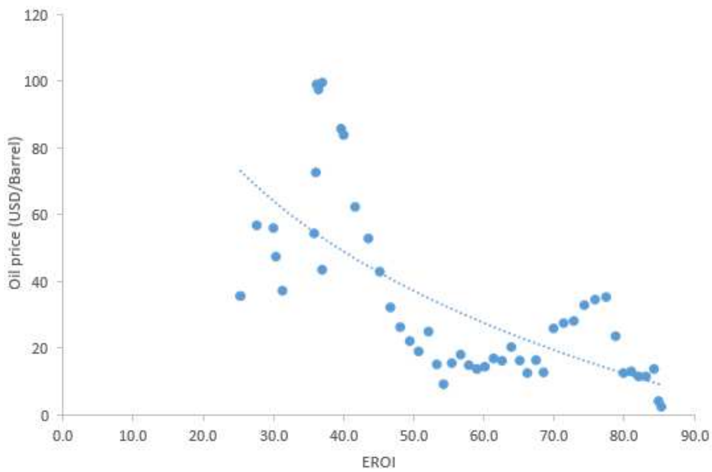
Elaborated by the author

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 prices in Ecuador 1972-2040



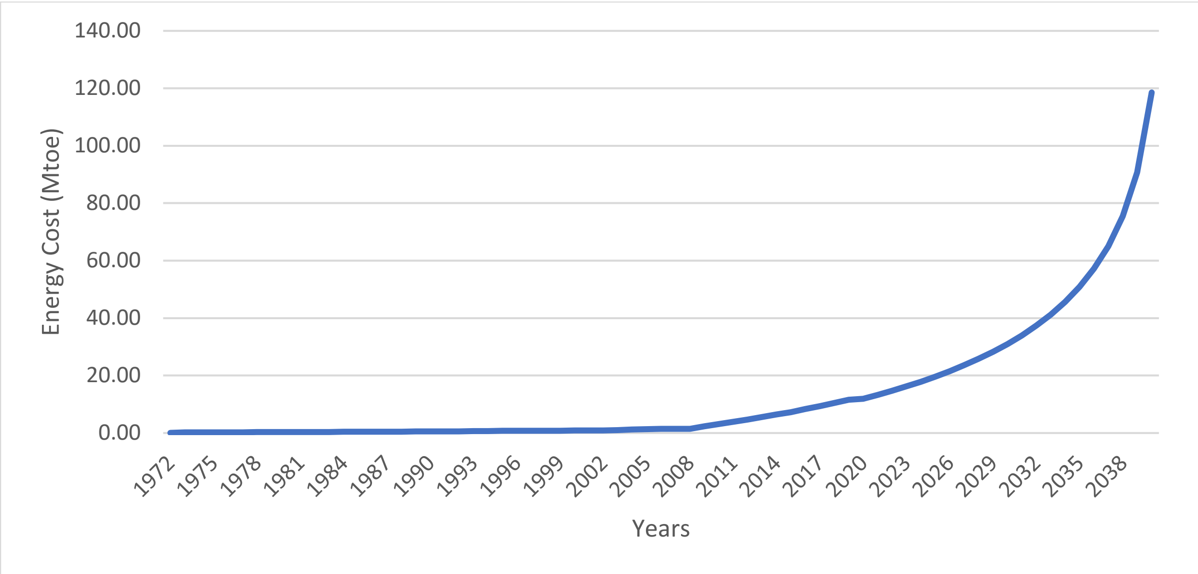
Source: Elaborated by the author

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.

1.4.1. 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 3.1, the energy cost follows an exponential path, this follows the results obtained for non-fuel minerals presented in Valero and Valero (2014).

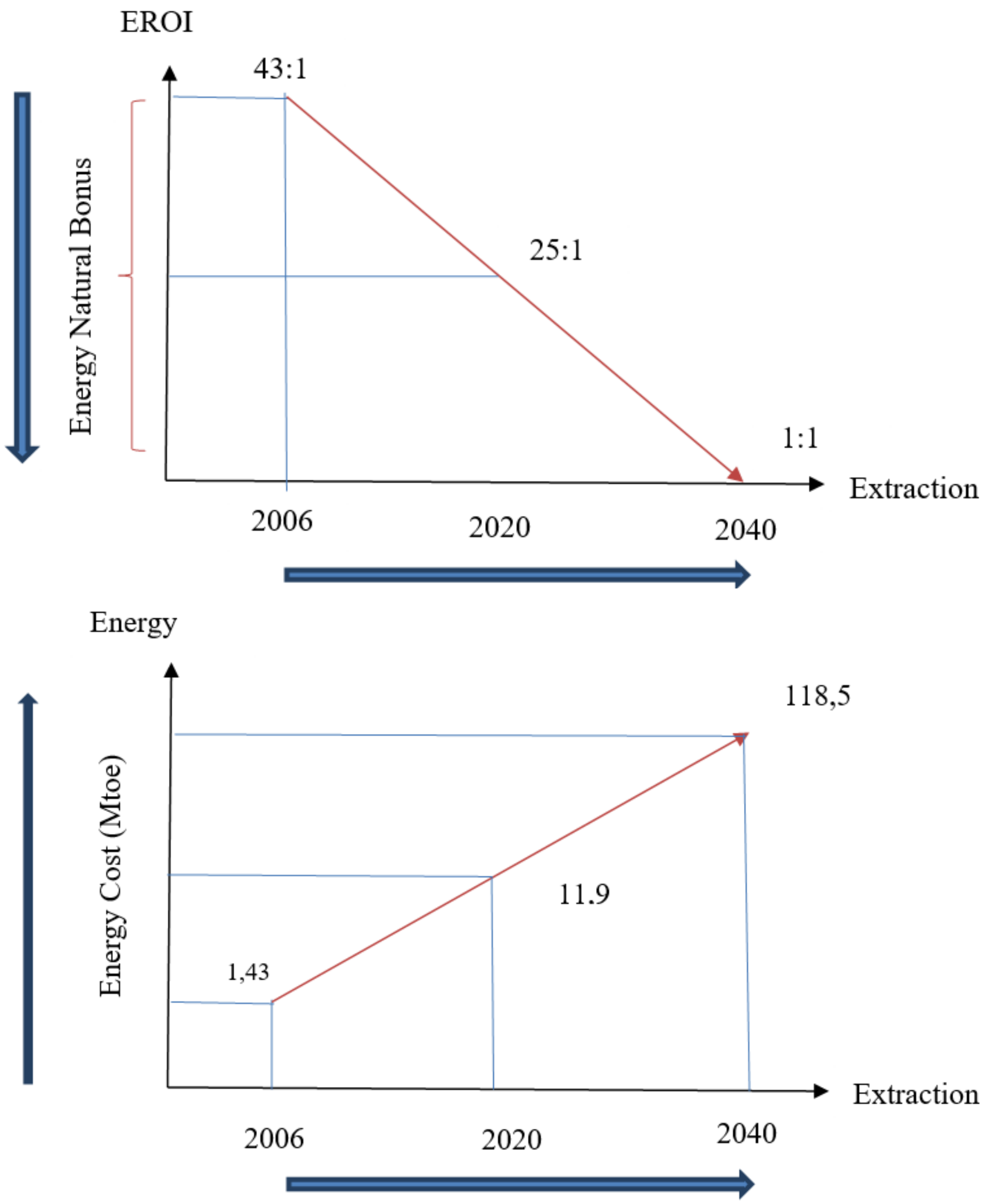
Figure 1.5. Energy cost of oil in Ecuador (1972-2040)



Source: Elaborated by the author

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 3.6. 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)



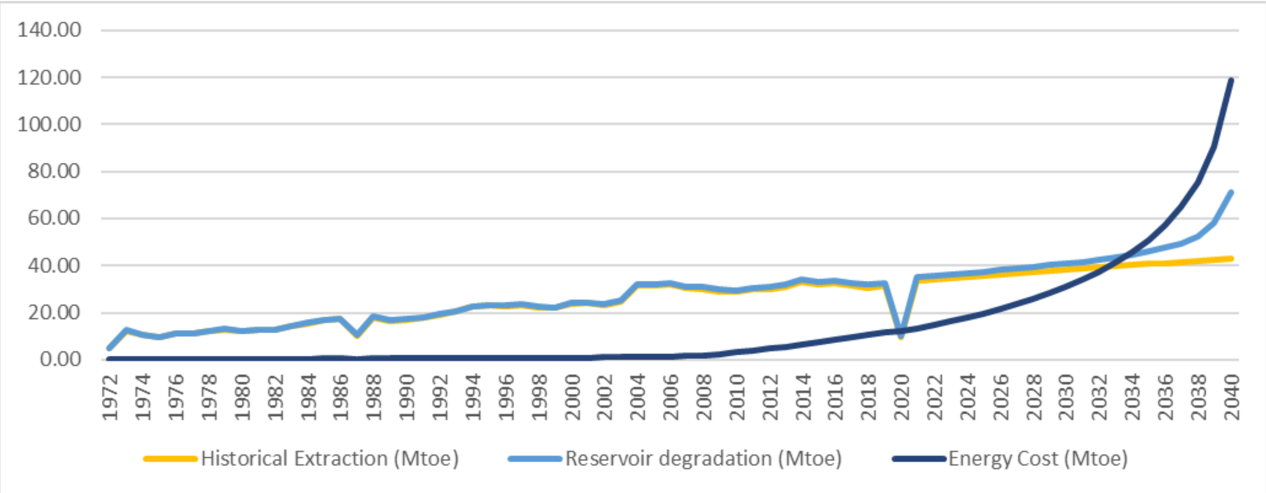
Source: *Elaborated by the author*

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.

1.4.2. 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 author

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.

1.4.3. 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 (Capellán-Pérez, Castro and González 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.

1.5. 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

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 (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, Mokhtari, Sharabi, and Zarrin (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.

$$For\ any\ (x_t,\ y_t) \in\ R_+^{n+m}, where\ y_{\ t} = \left(y_t^d, y_t^u\right) \in\ R_+^m\ , the\ multplication\ adjusted\ distance\ function, D^{\emptyset} :\ R_+^m\ \rightarrow R\ \cup \infty\ is\ defined\ below: \tag{8}$$

$$D^{\emptyset}(\ x,y)\ = \begin{cases} inf_{\beta}\left\{\beta\in[0,1]:\left(\beta^{\alpha}x_t\ ,\beta^{\gamma^d}{y_t}^d,\beta^{\gamma^u}{y_t}^u\right)\epsilon T\right\} \\ if\ \left(\beta^{\alpha}x_t\ ,\beta^{\gamma^d}{y_t}^d,\beta^{\gamma^u}{y_t}^u\right)\epsilon T, \beta > 0 \\ else \\ \infty \end{cases}$$

$$where\ \emptyset = (\alpha, \gamma^d, \gamma^u)\epsilon\{0,1\}^{m^d}x\{0,1\}^{m^u}$$

The multiplicative pollution adjusted function is employed to compute the Malmquist index. According to Nishimizu and Page (1982), 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:

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

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 Compañias, 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-Mogro and Bermudez-Barrezueta (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) CO_2 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 CO_2 emissions (tons of CO_2 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 Tables 2.3. and 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.

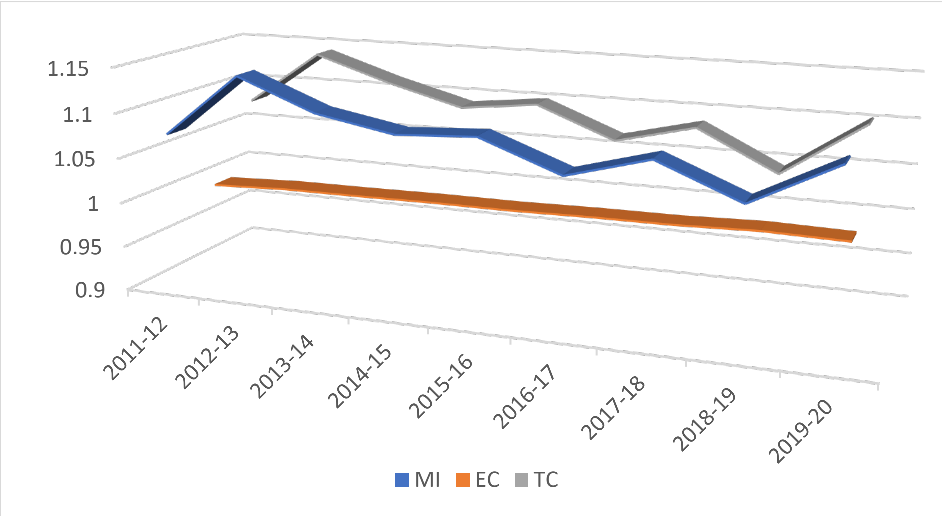
Table 2.4. Ranking of oil companies according to Malmquist Index

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	1,19	ERINCORP S.A.	0,57

PETROLEROS CIA. LTDA.			
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 figure 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.

2.5.3. Tobit Panel Regression results

Having obtained the PMI analysis, we want to find the primary economic indicators that affect efficiency scores. The Hausman test[7] 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)

[7]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.

CO2 emissions	-0,00334
	(0,00307)
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.

2.5.4 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 CO_2 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 Figure 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 (Figure 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 CO_2 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

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[8].

[8] This chapter has been accepted for publication in the “The Handbook of Energy and Economic Growth” which will be published by Edward Elgar Publishing Ltd in 2023.

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 (Navarro-Chávez, Delfín and Guardado 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) (P. Stern 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 (B. Keskin 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, CO_2 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:

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

Where:

λ = intensity factor

L = lower bound of intensity vector

U = upper bound of intensity vector

Th methodology states that a $DMU(x_0, y_0^g, y_0^b)$ is efficient when there is no vector $(x_0, y_0^g, y_0^b) \in P$, 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:

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

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:

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

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 1.1. lists all the variables used in this study:

Table 3.1. Variable definitions

Type	Variable	Unit	Source
Input	Gross Capital	Constant	WDI

	Formation	USD 2005	
	Labor Oil and Gas production Energy consumption	Per 1000 Workers Mbd Quad BTU	WDI EIA EIA
Output	CO_2 emissions (undesirable)	Millions of tons	WDI
	Energy depletion (undesirable)	Current USD dollars	WDI
	GDP (desirable) Life expectancy (desirable)	Constant USD 2005 Years	WDI 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 CO_2 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

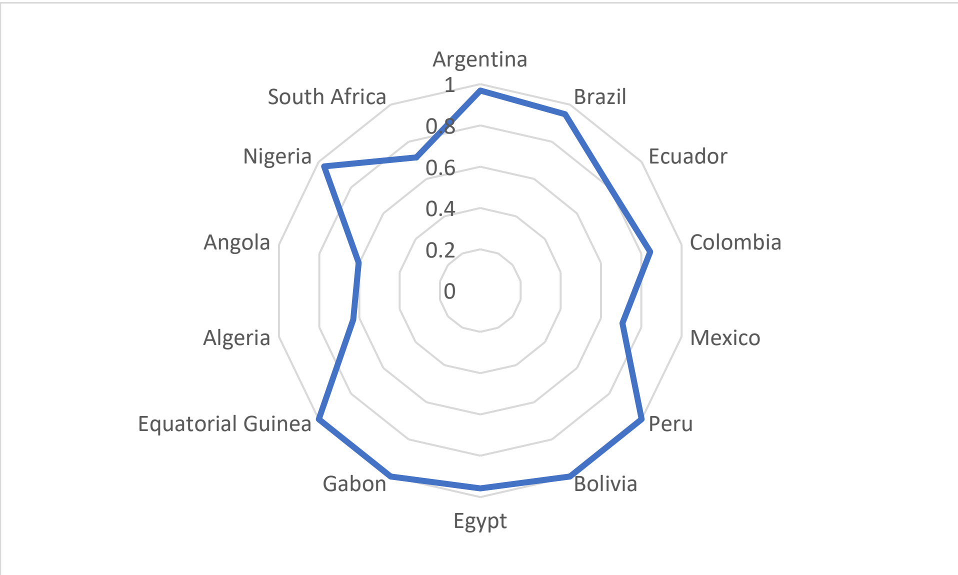
Countries /Score	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average
Argentina	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.534	0.969
Brazil	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.738	1.000	1.000	1.000	1.000	1.000	1.000	0.484	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 stepping stones 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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6. 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

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

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

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

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

Elaborated by the author

THÈSE

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Karla Michell Arias Marín

TITRE DE LA THESE

Évaluation énergétique de l'extraction du pétrole : Efficacité et durabilité du secteur pétrolier privé du Equateur

Soutenue le 5 du juillet devant le jury composé de

M. Arnaud ABAD, INRAE	Examinateur
M. Pedro ALARCÓN, Professeur à FLACSO	Co-Director
M. Stéphane BLANCARD, Professeur à Agrosup Dijon	Rapporteur
M. Hervé BLANCHARD, Professeur à Université de Perpignan Via Domitia	Examinateur
M. Jean-Philippe BOUSSEMART, Professeur à l'Université de Lille 3	Rapporteur
M. Walter BRIEC, Professeur à l'Université de Perpignan	Directeur
M. Vincent LIGNON, Professeur à l'Université de Perpignan	Co-Director
M. Roman MESTRE, Maître de Conférences à l'Université de Perpignan	Examinateur
Mme. Françoise SEYTE, Maître de Conférences à l'Université de Perpignan	Examinateur

Résume

La présente étude vise à étudier la littérature sur l'efficacité et la durabilité de l'extraction du pétrole dans les pays en développement. Cette étude est divisée en trois chapitres qui répondent à différentes questions autour de ce sujet. Le premier chapitre applique un modèle d'analyse par enveloppement des données basé sur les glissements de terrain (SBM-DEA) qui maximise les bénéfices obtenus des puits de pétrole et minimise les produits indésirables : les émissions de carbone et la dégradation de l'énergie.

Le premier chapitre examine les questions d'épuisement et de durabilité des ressources naturelles en intégrant l'idée de dégradation de la qualité et en utilisant des indicateurs tels que le coût de remplacement exergétique (ERC) et le retour énergétique sur investissement (EROI). Ces indicateurs ont été calculés à partir des données des compagnies pétrolières privées en Équateur de 1972 à 2020. Il a été constaté que les prix du pétrole ont augmenté à mesure que l'EROI diminue. Il a également été constaté qu'à partir de 2034, il ne sera plus rentable de continuer à extraire du pétrole en Équateur puisque la qualité des gisements aura diminué jusqu'à ce que les coûts énergétiques dépassent largement les gains énergétiques.

Le deuxième chapitre prend un échantillon de 18 compagnies pétrolières privées opérant en Équateur de 2011 à 2020 pour étudier les principaux facteurs d'efficacité et de productivité d'un point de vue industriel. Un indice de productivité de Malmquist ajusté aux polluants et une régression par panel ont été employés dans cette recherche. Les principaux résultats de ce chapitre suggèrent que les pertes d'efficacité et de productivité sont soumises au niveau de consommation d'énergie et à l'absence de changement technique dans les entreprises pour la période analysée.

En outre, le troisième chapitre applique l'indice de productivité de Malmquist (MPI) afin d'analyser et comparer les efficacités dynamiques de la productivité énergétique des différents pays d'Amérique latine et d'Afrique. Les résultats du modèle SBM-DEA indiquent que parmi un échantillon de 14 pays d'Afrique et d'Amérique latine sur la période 2006-2020, des pays comme la Guinée équatoriale, le Gabon, le Pérou et la Bolivie ont une efficacité énergétique plus élevée que leurs homologues en Angola, en Algérie, au Mexique, en Équateur et en Colombie. La principale conclusion de ce chapitre est que les pays ayant des taux d'extraction plus élevés sont moins efficaces, ce qui signifie que les impacts environnementaux sont plus élevés que les bénéfices économiques qu'ils tirent de l'extraction.

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L'étude des questions liées à l'énergie a pris de l'importance pour les économistes du développement depuis les deux chocs pétroliers mondiaux (1973-1974 et 1979-1980), mais l'étude de l'importance de l'énergie en économie trouve ses racines dans l'histoire. Podolinsky (2008) est l'un des premiers précurseurs de l'économie de l'énergie et a été le premier à examiner explicitement le processus économique, y compris les aspects liés à la thermodynamique. Nicolas Georgescu-Rogen (1971) a affirmé l'importance de l'énergie dans la détermination de la valeur économique, et Ayres (1998) a conclu que l'énergie et la matière constituent la base du processus de production. Odum (1973) a affirmé que le seul critère d'efficacité économique est l'énergie, c'est-à-dire que plus l'énergie nette obtenue par un processus est grande, plus ce processus sera efficace. La manière d'aborder la relation entre l'énergie et l'économie a également évolué au fil du temps. L'énergie a été étudiée depuis son rôle comme l'un des principaux intrants pour produire des biens et services (Cook 1976), depuis son impact sur la croissance économique (Stern 2011), et a même été considérée comme un quatrième facteur de production (Pokrovski 2003).

La thermodynamique analyse le comportement de certains processus énergétiques en vue de leur optimisation ultérieure, par exemple en maximisant le travail utile obtenu par la combustion de combustibles fossiles. Une contribution importante de la thermodynamique à l'analyse économique est l'incorporation de l'idée d'irréversibilité. Selon Machrafi (2019), un processus irréversible est défini comme un processus qui ne peut ramener à la fois le système et l'environnement à leurs conditions initiales. Toute activité économique implique l'utilisation de ressources; l'utilisation de ces ressources entraîne une perte irréversible d'une partie de cette ressource, qui doit être quantifiée et incluse dans les analyses économiques (Valero & Torres 2006). Cette idée est très importante car elle montre la "finalité" (l'efficacité) au cœur de la thermodynamique. L'efficacité mesure donc la qualité d'un processus, et elle nécessite une comparaison du produit obtenu avec les ressources nécessaires pour l'obtenir (Marmolejo-Correa & Gundersen 2012).

L'une des questions centrales étudiées par l'économie de l'énergie est l'efficacité énergétique.

L'idée d'efficacité énergétique est intrinsèquement liée à celle de service énergétique (Fell 2017), ou d'énergie utile. Selon Oikonomou et al. (2006), l'efficacité énergétique concerne le rapport entre le volume d'énergie consommé et le total des services énergétiques disponibles (par exemple le chauffage, l'éclairage, le refroidissement, la mobilité, la cuisson, etc.) L'efficacité énergétique est donc liée à presque toutes les activités humaines, tant au niveau microéconomique des ménages et des entreprises qu'au niveau macroéconomique de la gestion des ressources et des externalités environnementales.

Compte tenu de l'importance de l'énergie pour le système socio-économique, il est important de souligner la persistance du rôle que les combustibles fossiles ont joué dans la relation énergie-économie en tant que sources d'énergie primaire les plus importantes au cours du siècle dernier. Le pétrole représente 31% des sources de consommation d'énergie dans le monde, suivi du charbon 27% et du gaz naturel 24% (British Petroleum 2022). L'extraction de pétrole est passée de 3 158 Mt en 1990 à 4 221 Mt en 2021, ce qui représente une augmentation d'environ 42 % (IEA 2020a; British Petroleum 2022). Parallèlement, la consommation de pétrole est passée de 2 890 Mt en 1990 à 2 180 Mt pour atteindre 4 399 Mt en 2021, ce qui représente une croissance de 34%. Le World Energy Outlook 2021 affirme que l'énergie générée par les combustibles fossiles restera la source principale et devrait encore répondre à environ 75% de la demande énergétique en 2030 (IEA 2021). Cependant, on sait que l'approvisionnement mondial en pétrole finira par atteindre sa limite de production et entamer un déclin à long terme.

En outre, les pays exportateurs de pétrole sont confrontés à certains défis mondiaux qui nécessitent la transformation de ce secteur. Premièrement, le changement climatique est l'un des problèmes les plus pressants de notre époque. L'accord de Paris, qui vise à maintenir le réchauffement de la planète en dessous de 1,5 C par rapport aux niveaux préindustriels, reconnaît, bien que de manière non explicite, le rôle de l'utilisation des combustibles fossiles dans la modification du climat mondial et encourage donc la transition vers des sources d'énergie renouvelables. Deuxièmement, l'accès à des vecteurs énergétiques abordables et de qualité (tels que l'électricité) est l'un des principaux objectifs pour assurer le bien-être dans le Nord et réduire la pauvreté énergétique dans le Sud. Troisièmement, la sécurité et la souveraineté énergétiques ont été ramenées en tête de l'agenda politique international en raison de la guerre en Ukraine et des tensions croissantes entre l'Occident et la Russie (Alarcón 2023). Dans un contexte de demande énergétique croissante déclenchée par la reprise de la pandémie et un secteur pétrolier qui nécessite une transformation, l'un des sujets qui a commencé à prendre de l'ampleur dans la littérature académique est l'épuisement du pétrole et le rôle que l'efficacité énergétique pourrait jouer dans la promotion du développement durable.

L'épuisement des réserves de pétrole est un problème qui a été étudié de manière approfondie et sous différents angles, notamment en tant que problème environnemental. Cependant, ces analyses se sont concentrées sur la perte de quantité plutôt que de qualité. Ce projet de recherche s'inspire plutôt des applications de la thermodynamique en économie et aborde donc le problème de l'épuisement du pétrole comme un problème d'efficacité. Comme elle reconnaît l'importance de l'idée d'efficacité énergétique en thermodynamique, cette recherche vise à contribuer à une compréhension plus large des implications de la perte irréversible de qualité des ressources énergétiques, dans ce cas le pétrole, pour les pays, l'industrie et la société. À cette fin, cette étude est divisée en trois chapitres.

Ce premier chapitre entend contribuer à la littérature académique en identifiant les coûts énergétiques de l'épuisement du pétrole dans un pays exportateur à faible revenu et dans quelle mesure il serait efficace de continuer à extraire du pétrole. À cette fin, j'analyse le cas de l'Équateur. En ce sens, la question à laquelle il faudra répondre sera : Jusqu'à quelle année est-il efficace et durable de continuer l'extraction du pétrole en Equateur ? Cette étude permettra d'expliquer pourquoi il est important de considérer d'autres variables que le prix du pétrole lors de la conception de politiques publiques.

Le deuxième chapitre vise à contribuer au corpus de connaissances de l'analyse de l'efficacité énergétique au niveau industriel en fournissant des preuves empiriques pour les entreprises pétrolières privées en Équateur et en examinant comment les moteurs et les obstacles à l'efficacité énergétique opèrent dans ce secteur et dans le contexte d'un pays en développement. Ce chapitre cherche à fournir des informations pertinentes sur la manière d'utiliser au mieux les ressources dans les entreprises du secteur pétrolier afin de maximiser leurs profits et de minimiser les émissions qu'elles produisent.

Le chapitre trois cherche à évaluer l'efficacité énergétique et les améliorations de la productivité énergétique dans les pays en développement exportateurs de pétrole. Tout d'abord, l'efficacité énergétique est évaluée en utilisant l'approche DEA-SMB. Ensuite, l'approche de l'indice de productivité de Malmquist est mise en œuvre pour estimer l'amélioration de la productivité énergétique. La nouveauté de cette étude est l'introduction de l'épuisement énergétique en tant que production indésirable dans les estimations DEA et Malmquist. La plupart des études sur l'efficacité dans le secteur pétrolier ont été développées dans les pays du Nord, mais les études dans les pays en développement sont rares. Par conséquent, l'objectif de ce chapitre est de contribuer à la littérature académique en présentant des informations sur la façon dont les activités extractives pourraient avoir un impact sur l'efficacité énergétique et les améliorations de la productivité énergétique dans les pays du Sud.

Chapitre I

Le "vrai" coût de l'extraction du pétrole en Equateur

1.1. Introduction

L'énergie et les matériaux sont essentiels pour le système socio-économique ; ils soutiennent la production alimentaire, le transport, l'expansion des stocks de matériaux (infrastructures) et, en général, le bien-être de la société (Valero & Valero, 2014). L'extraction de combustibles fossiles et de ressources minérales a connu une croissance exponentielle depuis la révolution industrielle, et loin de ralentir, elle devrait augmenter dans les décennies à venir (Holdren & Ehrlich, 1974). L'extraction des ressources naturelles a un impact significatif sur la qualité des gisements de pétrole dans un pays. En théorie, l'extraction du pétrole devrait offrir aux gouvernements une chance de stimuler la croissance économique et de réduire les inégalités. En pratique, cela conduit souvent à la stagnation économique, aux conflits sociaux, à la dégradation de l'environnement et à l'épuisement de l'énergie (Ross, 2004).

Lorsque nous parlons de l'efficacité et des impacts économiques de l'épuisement énergétique, il est important de comprendre la dynamique de cette question. C'est une question complexe car elle implique plusieurs dimensions. La quantité totale de ressources minérales énergétiques et non énergétiques sur Terre est probablement inexplicable. En termes généraux, le minéral impliqué peut être suffisamment abondant sur toute échelle de temps raisonnable. Il y aura des gisements non découverts ailleurs ou des développements technologiques qui permettront d'accéder à de nouveaux gisements et matériaux (Hannesson, 2001). Cependant, l'impact sera différent du point de vue d'un pays exportateur de ressources minérales. Faire face à la raréfaction des gisements miniers sur son territoire, ou en tout cas à la raréfaction des gisements de bonne qualité, pourrait affecter significativement ses revenus et augmenter les coûts énergétiques.

L'évaluation de l'épuisement énergétique n'est pas une tâche simple. Les implications de l'épuisement du pétrole pour les économies développées et sous-développées sont différentes. Dans le cas de l'Equateur, il y a une double dépendance au pétrole. Sur le plan économique, les revenus pétroliers constituent la principale recette de l'État. Sur le plan énergétique, le pétrole constitue toujours la principale source primaire de la matrice énergétique. Selon l'EIA (2020), l'Équateur est le cinquième producteur de pétrole d'Amérique du Sud, derrière le Brésil, la

Colombie, l'Argentine et le Venezuela. Les réserves de pétrole de l'Équateur sont les troisièmes plus importantes d'Amérique latine, après celles du Venezuela et du Brésil. L'Équateur possède 8,3 milliards de barils de réserves prouvées de pétrole brut.

Pendant ce temps, en termes d'exergie, l'exergie des réserves prouvées de pétrole de l'Équateur est de 937,3 (Mtep). L'évolution de la production pétrolière en Équateur en termes d'exergie est illustrée à la figure 3.5. L'exergie est la quantité maximale de travail utile qui peut être obtenue lorsqu'une certaine forme d'énergie est transformée (Gool et Hoogendoorn 1990). Toutes les formes d'énergie n'ont pas la même qualité, car elles ne produisent pas la même quantité maximale de travail utile (Whiting et al. 2017). L'exergie peut être comprise comme une mesure de valeur car l'exergie est une mesure de la qualité de l'énergie, les sources à haute exergie produisent un travail plus utile (Szargut 2005, 192). Et par conséquent, ils sont plus "précieux" que ceux qui produisent un travail moins utile, car on aura besoin de moins de ressources (c'est-à-dire d'énergie) pour produire le même résultat.

Cette recherche vise à déterminer en quelle année il est efficace et durable de poursuivre l'extraction de pétrole en Équateur. Pour répondre à cette question, deux problèmes principaux doivent être résolus : l'épuisement de la ressource et la perte de qualité et d'efficacité de l'utilisation de cette ressource. Pour résoudre le premier problème, j'adapterai le coût de remplacement de l'exergie (ERC), y compris l'EROI comme indicateur de perte de qualité. L'objectif principal de l'utilisation de cette approche dans l'analyse est d'évaluer la question de l'épuisement et de la durabilité des ressources naturelles et d'intégrer la dégradation de la qualité dans l'analyse. L'utilisation de ressources naturelles non renouvelables comme intrant de nombreux processus économiques implique une perte ; dans ce cas, nous quantifions cette perte en termes d'exergie (travail utile). L'exergie devient un indicateur approprié pour analyser la durabilité en termes de "forte durabilité" car il n'y a pas de substituabilité possible une fois que l'entropie détruit l'exergie, le pétrole est un bon exemple pour comprendre cela car contrairement aux minéraux non combustibles, une partie importante du pétrole brûle et se transforme en CO_2 et une fois que cela se produit, il est impossible de le recycler ou de le récupérer.

1.2. Revue de littérature

Des méthodes analytiques intégrant l'exergie et l'économie ont été développées au cours des dernières décennies, la plupart d'entre elles suivant les pas de Georgescu-Rogen qui est considéré comme le pionnier dans le domaine de la thermodynamique de l'économie (Rosen, 2008). La plupart des méthodes économiques basées sur l'exergie ont des caractéristiques communes telles que celles (Tsatsaronis et Valero 1989) : 1) Elles associent l'exergie et l'analyse économique pour atteindre des objectifs thermodynamiques et économiques, tels que l'optimisation ; 2) Ils reconnaissent que l'exergie représente la « valeur » dans un système, ils attribuent donc des coûts et/ou des prix aux variables liées à l'exergie ; 3) Ils évaluent la faisabilité économique et la rentabilité ; 4) Ils permettent de déterminer les coûts réels des sorties et des prix précis ; 5) Ils déterminent les allocations appropriées des ressources économiques ; 6) L'optimisation est une application particulièrement importante des techniques économiques basées sur l'exergie.

Rosen (2008) a déterminé quatre catégories principales de méthodologies économiques basées sur l'exergie en prenant comme base les formes suivantes : 1) la comptabilité des coûts exergétique-économiques, 2) l'analyse du calcul exergique-économique, 3) le nombre de similarité exergétique-économique, et 4) rapport produit/coût.

1.2.1. L'ERC comme mesure de l'efficacité énergétique et de l'épuisement des ressources naturelles

Le coût de remplacement de l'exergie (ERC) quantifie l'exergie nécessaire pour reconcentrer les minéraux extraits (combustibles et non combustibles) de l'environnement de référence (RE) à l'état de concentration trouvé dans la mine via la meilleure technologie disponible (Domínguez, Valero et Valero 2013).

La méthode ERC a été principalement appliquée aux minéraux non combustibles jusqu'à récemment, car l'approche méthodologique proposée par Valero et Valero (2013) se concentre sur l'incapacité actuelle de la société à accélérer les processus géologiques pour fournir des combustibles fossiles plutôt que sur la capacité de la nature à fournir un gisement utilisable qui remplit la fonction des combustibles fossiles. Les travaux universitaires actuels comprennent la comptabilisation de l'épuisement des minéraux non combustibles au niveau mondial (Valero et Valero 2010 ; Valero et Valero 2006), régional national (Carmona et al. 2014 ; Valero et Valero, 2015 ; Calvo et al. 2015) et produit échelle (Valero et al. 2016). C'est pourquoi la contribution de Whiting et al. (2017) offre également la possibilité de développer une analyse de l'épuisement des minéraux combustibles.

Cet article vise à contribuer à cette approche méthodologique en proposant une adaptation de l'ERC utilisant EROI pour tenir compte de la perte de qualité. De plus, j'appliquerai l'approche ERC en tenant compte de la suggestion faite par "Lisboa School" d'utiliser l'ER en tenant compte de l'exergie nécessaire pour fournir un gisement artificiel utilisable et non Thanatia.

En ce sens, l'"EROI" est un indicateur physique proposé qui est utilisé comme proxy de la qualité des ressources énergétiques en tant que retour énergétique sur (l'énergie) investie (d'où vient son acronyme EROI), qui, comme son homologue financier return on l'investissement (ROI) est un rapport entre les extrants et les intrants (Cleveland et al. 1984). Nous définissons l'EROI comme le rapport qui mesure l'énergie produite par rapport à l'énergie utilisée pour la créer (Fizaine et Court 2016 ; Murphy et Hall 2006). La théorie économique de base conduit à s'attendre à ce qu'un EROI en baisse puisse être associé à une augmentation du coût marginal de production et, en fin de compte, à une augmentation du prix auquel le produit (l'énergie) est échangé (Heun et Wit 2012).

1.3. Cadre méthodologique

Cette section développe quatre étapes : 1) collecte de données sur les minéraux combustibles (pétrole) pour la période 2000-2020 ; 2) conversion en termes d'exergie chimique ; 3) calcul de l'EROI comme indicateur de dégradation pour la même période ; 4) calcul du coût énergétique de l'extraction du pétrole en Equateur.

Pour convertir l'extraction de barils en tonnes, j'ai utilisé le facteur de conversion du "Manual Estadística Energética" (2017) fourni par l'Organisation latino-américaine de l'énergie (OLADE). Une fois que nous aurons la valeur du pétrole en termes d'exergie, je calculerai le facteur de dégradation EROI. Pour inclure le facteur de « dégradation », nous utiliserons le retour énergétique sur investissement (EROI) du pétrole en Equateur pour la période 2006-2020. Pour déterminer l'EROI de l'extraction de pétrole en Equateur, j'utiliserai la méthodologie proposée par Amores et al. (2020) expliqué précédemment.

1.3.1. EROI comme indicateur de dégradation

Pour déterminer l'EROI de l'extraction de pétrole en Equateur, la méthodologie proposée par Amores et al. (2020) est utilisé.

Ces auteurs effectuent un calcul préliminaire de l'EROI du pétrole équatorien, au niveau du pays et par blocs, obtenant des résultats préliminaires EROI pour les blocs de production pétrolière 7, 10, 15, 16, 21, 46, 47, 56, 57, 60, 61, 62 et 67. Par conséquent, d'après Amores et al. (2020) et Muphy (2014) EROI peut être exprimé par l'équation suivante $EROI_{1d}$:

$$EROI = \frac{E_o}{E_i} \qquad (1)$$

Où:

E_o= consommation de combustibles pour la production d'électricité.

E_i = le volume de la production à l'échelle, en termes d'énergie en tonnes d'équivalent pétrole (TEP), qui est mesuré avant d'entrer dans le système d'oléoduc transéquatorial (SOTE) et l'oléoduc de pétrole brut lourd (OCP) par le biais du transfert de garde automatique de location (LACT) et les unités de transfert de garde automatique (ACT).

1.3.2. Évolution du coût de l'énergie

Pour tenir compte du coût de l'énergie, j'ai utilisé les étapes suivantes :

Tout d'abord, j'utilise l'EROI pour calculer le pourcentage d'énergie supplémentaire nécessaire chaque année à l'aide de l'équation suivante :

$$\left(\frac{\frac{1}{EROI}t_1 - \frac{1}{EROI}t_0}{\frac{1}{EROI}t_0}\right) \times 100 \qquad (2)$$

Deuxièmement, pour déterminer le coût énergétique, je multiplie le % d'énergie supplémentaire (Équation 9) par le taux d'extraction historique (Ext) :

$$Energy\ cost = \Delta(Eq.2) \times Ext. \qquad (3)$$

Enfin, je multiplie l'extraction historique (Ext) en termes d'exergie chimique (Mtep) par (1+ % d'énergie supplémentaire) pour déterminer la "dégradation" du site (Mtep) :

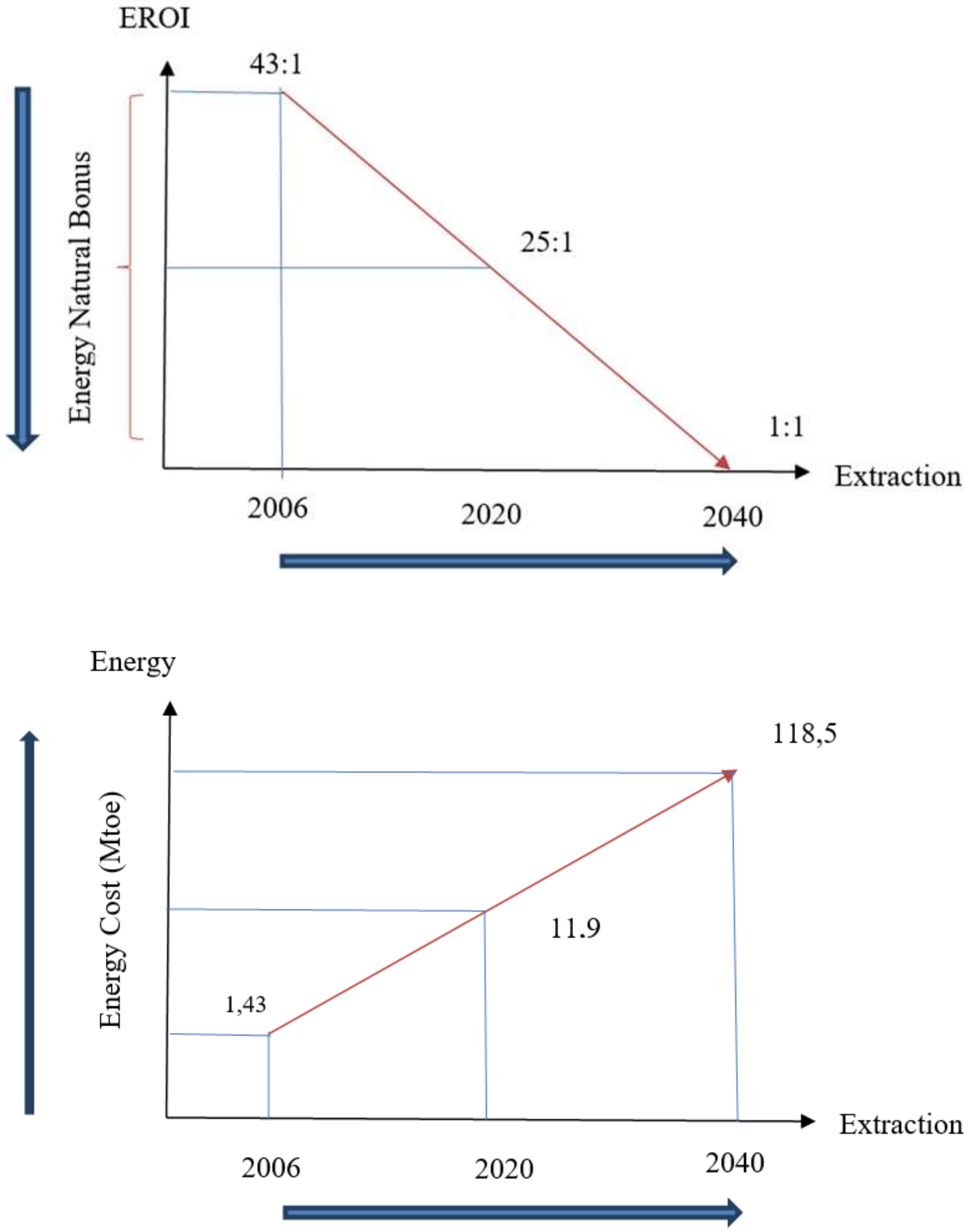
$$Site\ degradation = \Delta(Ext.) \times \left(1 + (Eq.2)\right) \qquad (4)$$

Après avoir dégagé la procédure à suivre dans la section suivante, les résultats sont présentés.

1.4. Résultats et conclusion

Dans le cas de l'Équateur, en 1972, lorsque le boom pétrolier a commencé, l'EROI était de 85,2, il convient de noter que ces données ont certaines limites puisque jusqu'en 2006, il n'était pas obligatoire pour toutes les entreprises de déclarer des données sur les opérations. Les lacunes de l'information. Depuis 2006, il est obligatoire pour toutes les entreprises de déclarer des informations sur les opérations et les coûts, afin que davantage d'informations soient disponibles et que le calcul de l'EROI soit plus rigoureux. Avec ces précisions, on peut voir qu'en 2006, l'EROI était de 43,5 et a diminué à 25,25 en 2020. Ces calculs suivraient la tendance à la baisse montrée dans d'autres études sur l'EROI dans le monde. Par exemple, au Royaume-Uni (Correa et al. 2017 ; Hall, 2017), aux États-Unis (Cleveland, 2005 ; Heun et Wit 2012), en Chine (Xu et al. 2014 ; Feng et al. 2017) et dans les pays en développement (Lambert 2014).

Figure 1.1: Baisse du bonus énergétique naturel par rapport à l'augmentation du coût de l'énergie (2006-2040)



D'autre part, lors de l'analyse de la relation entre l'EROI et le prix du pétrole en Équateur, il existe une relation significative et négative. Cela implique qu'à mesure que l'EROI diminue, les prix du pétrole ont tendance à augmenter au fil du temps en raison de l'augmentation des coûts d'extraction (voir la figure 3.8). En d'autres termes, il faut investir davantage d'énergie pour obtenir de l'énergie, ce qui a un impact direct sur les prix. De plus, selon Hall (2014), la tendance des prix élevés a conduit les producteurs de pétrole à se relayer dans des champs de mauvaise qualité situés dans des endroits difficiles ainsi que la récupération améliorée du pétrole des champs existants qui augmentent la consommation d'énergie, donc le niveau d'EROI baisse. (Figure 3.8).

Enfin, l'augmentation des coûts énergétiques affecte les générations futures qui devront investir davantage d'énergie pour maintenir un mode de vie similaire à celui d'aujourd'hui. L'analyse des coûts énergétiques contribue à la discussion sur la durabilité dans une perspective de durabilité forte, puisque le bonus énergétique perdu avec l'extraction est irréparable et affecte la qualité de vie des générations futures. En ce sens, plusieurs auteurs ont parlé de l'EROI minimum requis pour maintenir une société durable.

Chapitre II

Efficacité énergétique et productivité environnementale : analyse des compagnies pétrolières équatoriennes

2.1. Introduction

Les études sur la productivité environnementale ont pris de l'ampleur ces dernières années en raison de la nécessité de favoriser la croissance industrielle tout en réduisant les émissions de GES. Comme il s'agit d'un sujet récent, les études dans ce domaine sont rares et la plupart d'entre elles ont été développées dans les pays développés et en Asie. Compte tenu de l'importance de ce sujet pour promouvoir la réduction des GES dans les industries hautement polluantes, cette étude se concentrera sur les entreprises privées du secteur pétrolier et gazier. En outre, cette étude vise à contribuer à la littérature en analysant l'efficacité énergétique et la productivité environnementale dans un pays en développement exportateur de pétrole. J'ai choisi l'Équateur comme cas d'étude parce que cela dépend fortement des revenus des exportations de pétrole et qu'il dépend également fortement du pétrole dans sa matrice énergétique.

L'Équateur est le cinquième producteur de pétrole d'Amérique du Sud, avec une production moyenne de 27,94 millions de tonnes de 2011 à 2020. Parmi tous les secteurs industriels, l'industrie pétrolière intéresse particulièrement l'Équateur en raison de son importance économique et environnementale. Sur la base de la valeur ajoutée de la production au cours de la période 2011-2020, l'industrie pétrolière représente 8,53% du PIB équatorien. Le pétrole est également important pour le secteur énergétique équatorien ; en 2018, il y avait une production d'énergie primaire de 216 millions de BEP. L'approvisionnement énergétique national est composé de 86,9 % de pétrole en 2018. L'industrie de l'énergie est un contributeur important aux émissions de GES dans le pays, en particulier pour la combustion de combustibles fossiles. En 2012, cette activité représentait 36 822,54 Gg (CO2e), ce qui représente 97,95 % des émissions du secteur de l'énergie.

Ainsi, les compagnies pétrolières doivent être plus efficaces et trouver un équilibre entre l'atténuation de la pollution et le succès économique. Certaines études montrent l'importance de l'efficacité énergétique dans l'amélioration de la performance économique des compagnies pétrolières en réduisant les coûts (Midor et al. 2021 ; Yáñez et al. 2018 ; Longwell 2002). Cependant, la plupart des études ont souvent ignoré les aspects environnementaux lors de l'évaluation de l'efficacité énergétique. Ainsi, peu d'études portent sur la performance environnementale des compagnies pétrolières (Hou, 2019 ; Jung, 2001). À la connaissance de l'auteur, aucune étude n'a été développée dans laquelle l'évolution de la productivité économique et environnementale dans le secteur pétrolier est évaluée en Amérique latine, et aucune étude de cas spécifique n'a été réalisée dans le secteur pétrolier dans un pays de la région. La présente étude vise à évaluer l'évolution de la productivité économique et environnementale des compagnies pétrolières équatoriennes. Pour cette étude, un échantillon de 18 sociétés pétrolières privées équatoriennes associées aux activités d'extraction et de raffinage du pétrole brut en Équateur a été considéré dans la base de données de SCV sur la période 2011-2020 pour estimer l'indice de productivité PM.

Le reste de ce chapitre est structuré comme suit. La section 2 présente les études qui abordent le moteur de l'efficacité énergétique et les modèles non paramétriques pour estimer l'efficacité énergétique. L'approche paramétrique et non paramétrique est présentée dans la section 3. L'illustration empirique est fournie dans la section 4. Enfin, la section 5 se concentre sur la discussion et les conclusions de cette recherche.

2.2. Revue de littérature

Récemment, de nombreuses études ont porté sur l'efficacité environnementale et les variations de productivité dans le secteur pétrolier ; voir, par exemple, Tavana et al. (2020), Wegener et Amin (2019), Sueyoshi et Wang (2018, 2014), Bezerra et al. (2017), Azedeh et al. (2015), Song et al., (2015), Sueyoshi et Goto (2015), entre autres. De plus, les méthodes de programmation mathématique non paramétrique pour l'analyse de la production sont largement appliquées pour définir des études d'efficacité et de productivité environnementales (Sueyoshi et al., 2017 ; Zhou et al., 2008). Dans ce chapitre, le modèle non paramétrique de production de coques à élimination libre (Tulkens, 1993) est appliqué comme approche pratique pour évaluer le changement de productivité ajusté à la pollution des compagnies pétrolières équatoriennes. Cette modélisation n'a pas besoin de spécifier explicitement une forme mathématique pour la fonction de production. De plus, il permet d'évaluer l'efficacité environnementale des unités de production multi-entrées et multi-sorties en relâchant la propriété de convexité des technologies génératrices de pollution.

Compte tenu de ce qui précède, cette étude empirique a proposé une modélisation DEA et un modèle paramétrique pour analyser l'efficacité énergétique et la productivité de l'industrie pétrolière avec des sorties indésirables dans les entreprises privées en Équateur.

2.3. Cadre méthodologique

Cette section présente le cadre théorique adopté tout au long du chapitre. Dans ce contexte, des indices d'efficacité et de productivité ajustés en fonction de la pollution sont introduits en tant que modèle économétrique.

2.3.1. Modèle non paramétrique : indices d'efficacité et de productivité ajustés en fonction de la pollution

Cette section affiche les indices d'efficacité et de productivité ajustés en fonction de la pollution. De plus, les principaux éléments de la variation de la productivité ajustée en fonction de la pollution sont présentés. Les fonctions de distance multiplicatives sont devenues des outils standard pour définir des mesures d'efficacité technique (Debreu 1951 ; Farrell 1957 ; Shephard 1953). Ces fonctions à distance complètent les processus de production d'entrées-sorties multiples. La définition suivante présente la fonction de distance multiplicative ajustée en fonction de la pollution (Abad 2018).

Définition 1

$$For\ any\ (x_t,\ y_t) \in\ R_+^{n+m}, where\ y_t = \left(y_t^d, y_t^u\right) \quad (1)$$

$\in\ R_+^m$, $the\ multplication\ adjusted\ distance\ function, D^{\emptyset}\ :\ R_+^m \to R\ \cup \infty\ is\ defined\ below$:

$$D^{\emptyset}(\,x, y) \ = \begin{cases} inf_{\beta\left\{\beta \in\,[0,1]:\,\left(\beta^{\alpha}x_t\,, \beta^{\gamma^d}{y_t}^d, \beta^{\gamma^u}{y_t}^u\right) \epsilon T\right\}} \\ if\ \left(\beta^{\alpha}x_t\,, \beta^{\gamma^d}{y_t}^d, \beta^{\gamma^u}{y_t}^u\right) \epsilon T, \beta > 0 \\ else \\ \infty \end{cases}$$

$$where\ \emptyset = (\alpha, \gamma^d, \gamma^u) \epsilon \{0,1\}^{m^d} x \{0,1\}^{m^u}$$

Le résultat suivant affiche l'indice de productivité corrigé de la pollution de Malmquist (Abad et Ravelojaona, 2021).

$$PM_t^{\emptyset}\left(x_{t,t+1}, y_{t,t+1}\right) = \frac{D_t^{1,-1,0}\left(x_{t+1}, y_{t+1}^d, y_{t+1}^u\right)}{D_t^{1,-1,0}(x_t,\ y_t)}\ x \frac{D_t^{1,0,1}\left(x_{t+1}, y_t^d, y_{t+1}^u\right)}{D_t^{1,0,1}(x_t,\ y_t)} \quad (2)$$

Et

Si l'efficacité change en ${EC^{\emptyset}}_{t,t+1}$ est supérieur à 1, alors le progrès d'efficacité se produit sur les périodes (t) et (t + 1). De plus, l'amélioration technologique se produit entre les périodes (t) et (t + 1) lorsque $TC^{\emptyset}{}_{t,t+1}$.

Où :

$(x^t, y^t), (x^{t+1}, y^{t+1})$ Sont des vecteurs de sorties et d'entrées dans t et $t + 1$

D^t, D^{t+1} Sont les fonctions de distance entre t et $t + 1$

2.3.2 Modèle paramétrique : régression de panel

J'ai étudié la relation entre l'indice de productivité et les variables économiques à l'aide d'un modèle de régression de panel Tobit pour spécifier les effets DMU individuels et les points communs des données transversales (Liu et al., 2017), également en tant que rob. La relation entre les pratiques énergétiques et les compagnies pétrolières et le score d'efficacité est décrite à l'aide du modèle ci-dessous :

$$MI_{it} = \beta_0 + \beta_1 Energy_{it} + \beta_2\ Capital_{it} + \beta_3 Employment_{it} + \beta_4 Emmisions_{it} + \beta_5 Oilproduction_{it} + \varepsilon_{it} \quad (3)$$

Où *MI* est la variable dépendante, représentant les scores obtenus à partir de l'évaluation de l'efficacité. Les émissions représentent les émissions de $CO2$ par habitant, introduites en logarithmes et le *capital* en niveau, mesuré par le ratio *capital/travail* ; Emploi et est la main-d'œuvre, mesurée en personne, et Énergie est la mesure de la consommation d'énergie en kwts/heure.

2.4. Données en bref

Un échantillon de 18 compagnies pétrolières privées en Équateur est considéré sur la période 2011-2020. L'ensemble de données utilisé dans cette recherche est construit avec la population des entreprises pétrolières formelles équatoriennes enregistrées, construite à partir des bilans et des états financiers enregistrés sur le site officiel de la Superintendencia de Compañias, Valores y Seguros (SCVS). Ces informations sont communiquées chaque année directement par les entreprises au SCVS.

Trois entrées sont sélectionnées : (i) le nombre d'employés formels de chaque entreprise et (ii) les immobilisations corporelles nettes (capital social). Les informations sur le nombre d'employés légalement enregistrés (i) sont déclarées par chaque entreprise. Nous considérons une sortie souhaitable, (iii) le nombre de barils de pétrole, et une sortie indésirable représentée par (iv) les émissions de CO2.

Tableau 2.1. Statique descriptive des variables d'entrée et de sortie

Variables	Min	Max	Médiane	S.D.	Moyenne
La main d'oeuvre	0	6.55	2.30	2.06	2.73
Capital	7.47	18.97	13.26	2.12	13.48
Consommation d'énergie	8.14	19.85	15.64	2.89	14.89
Production de pétrole	5.95	16.44	12.89	2.30	12.27
CO2 émissions	1.31	22.41	8.79	4.93	9.75

Source : propre élaboration

2.4.2. Matrice de corrélation

Ce tableau représente la matrice de corrélation des variables d'entrée et de sortie dans l'échantillon. Les variables sélectionnées comme entrées sont fortement corrélées avec les sorties conférant une validité à notre stratégie empirique. La forte corrélation trouvée confirme également l'association entre les entrées et les sorties sélectionnées comme statistiquement significatives au niveau de 90 % (sauf pour l'emploi et la consommation d'énergie), ce qui satisfait l'une des propriétés de l'analyse DEA qui dit que la production ne devrait pas diminuer avec une augmentation de contribution.

Tableau 2.2. Matrice de corrélation

Variables	La main d'oeuvre	Capital	Consommation d'énergie	Production de pétrole	CO2 émissions
La main d'oeuvre	1				
Capital	0.4442***	1			
Consommation d'énergie	0.0285	0.4267***	1		
Production de pétrole	0.3079 ***	0.5080 ***	0. 7483 ***	1	

CO2 émissions	0.1361***	0.2045***	0.2839 ***	0.5132 ***	1

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

Source : propre élaboration

2.5 Résultats

2.5.1. Productivité ajustée en fonction de la pollution de l'indice de Malmquist

Les résultats présentés dans le tableau révèlent les scores des indices de productivité PM et leurs décompositions sur la période 2011-2020. Plus précisément, la troisième colonne à partir de la droite affiche les scores de l'indice de productivité ajusté en fonction de la pollution de Malmquist. Les deux premières colonnes à partir de la droite montrent les principaux moteurs du changement de productivité corrigé de la pollution, à savoir le changement technologique et les composantes de variation de l'efficacité, respectivement

Table 2.3. Malmquist Index scores for 2011-2020

2011			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	MI	EC	TC
1.01	1.01	1.00	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
0.35	1.00	0.35	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
1.91	0.94	2.02	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
0.92	1.06	0.87	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
0.50	1.00	0.50	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
2.91	1.00	2.91	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
0.81	1.00	0.81	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
0.86	1.00	0.86	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
0.52	1.00	0.52	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
2.12	1.00	2.12	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
1.09	1.00	1.09	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
0.56	0.98	0.57	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
1.42	1.02	1.39	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
0.90	0.98	0.92	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
1.13	1.02	1.11	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
0.45	1.00	0.45	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
1.09	1.00	1.09	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
0.80	0.93	0.86	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

Source : propre élaboration

Le tableau 2.3 présente les indices de productivité annuels moyens des MP sur la période analysée. Pendant la majeure partie de la période 2011-2020, les indices de productivité des particules indiquent des améliorations de la productivité ajustées en fonction de la pollution, en particulier en 2014-2015. Pendant ce temps, dans les périodes 2013-2014 et 2016-2017, il y a une baisse de la productivité corrigée de la pollution. La combinaison des variations de productivité polluantes et non polluantes nous permet de montrer les principaux moteurs de la variation de la productivité corrigée de la pollution. Les gains de productivité ajustés en fonction de la pollution sur 2017-2018 et 2012-2013 proviennent de l'augmentation de la productivité dans les composants non polluants. En effet, pour ces périodes, une perte de productivité polluante apparaît. Cependant, la croissance de la productivité non polluante compense la baisse de la productivité polluante pour les périodes 2017-2018 et 2012-2013.
Concernant les périodes 2014-2015 et 2015-2016, les résultats inverses se produisent. Dans de tels cas, le progrès de la productivité corrigée de la pollution provient de l'augmentation de la productivité en polluant. Remarquons que sur la période 2013-2014, la baisse de la productivité non polluante ne compense pas l'amélioration de la productivité polluante de sorte qu'une baisse de la productivité corrigée de la pollution se produit. De la même manière, la perte de productivité corrigée de la pollution se produit sur la période 2016-2017. Cette baisse de productivité résulte à la fois de la baisse de la productivité polluante et non polluante. Globalement, les valeurs moyennes des indices de productivité de Malmquist sur la période 2012-2018 indiquent une croissance de la productivité corrigée de la pollution, qui provient essentiellement de l'augmentation de la productivité des composants polluants.

2.5.2. Résultats de la régression de panel

Après avoir obtenu l'analyse PMI, nous voulons trouver les principaux indicateurs économiques qui affectent les scores d'efficacité. Le test de Hausman est utilisé pour choisir entre les modèles à effets fixes et à effets aléatoires, adaptés à l'analyse de régression par panel. Les résultats indiquent que le modèle à effets aléatoires convient mieux à l'évaluation de régression par panel.

Tableau 2.4. Résultats de la régression du panel

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)
Observations	180
Number of n	18

Note: Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Source : propre élaboration

Ainsi, dans l'étape suivante, nous utilisons le modèle à effets aléatoires pour mesurer l'impact des indicateurs sur le PMI. Selon l'analyse, l'IM a une faible corrélation négative avec la consommation d'énergie à un niveau de signification de 10 %. Et une relation négative avec l'emploi à un seuil de signification de 1 %. Ces résultats suggèrent que pour l'Équateur, l'efficacité énergétique et industrielle des compagnies pétrolières dépend de leur stratégie de main-d'œuvre et de la consommation de combustibles fossiles dans leurs activités extractives.

2.6. Conclusion

Ce chapitre analyse les principaux moteurs de l'efficacité et de la productivité des compagnies pétrolières privées en Équateur. De plus, les principales sources de variation de la productivité ajustée en fonction de la pollution sont fournies en considérant les parties polluantes et non polluantes de la variation de la productivité. Un échantillon de 18 compagnies pétrolières équatoriennes de 2011 à 2020 est sélectionné. Un modèle non paramétrique et un indice de Malmquist ont été développés pour évaluer l'efficacité énergétique et la productivité des compagnies pétrolières privées en Équateur.

La décomposition de la productivité corrigée de la pollution permet d'aller plus loin dans le détail. En affichant les principaux moteurs de la productivité polluante et non polluante variantes. Au cours de la période analysée, le changement de productivité ajusté en fonction de la pollution provient surtout de la variation technologique et des composantes de changement d'efficacité d'échelle, ce qui pourrait induire l'infaisabilité. Par ailleurs, la variation de productivité corrigée de la pollution apparaît neutre par rapport à la variation d'efficacité. Des travaux ultérieurs pourraient considérer le processus de production multiplicatif non convexe (Banker et Mandiratta, 1986) pour définir le une analyse.

Les résultats ont montré que les facteurs polluants et non polluants affectaient les scores d'efficacité au cours de la période analysée. Plus précisément, la taille et l'évolution technologique ont un impact plus important sur les entreprises qui utilisent des intrants plus polluants dans leur processus de production. De plus, dans la période analysée, en moyenne, les entreprises ne montrent pas de changements positifs dans leur efficacité et leur productivité, sauf pour les périodes 2013-2014 et 2017-2018, où de légères augmentations sont identifiées. Les résultats du modèle paramétrique suggèrent que l'efficacité et la productivité des entreprises ont une relation négative mais significative avec la consommation d'énergie et l'emploi. Ceci est cohérent avec les résultats présentés dans d'autres études, telles que Managi (2011). Ces résultats suggèrent la nécessité de promouvoir des politiques publiques visant à réduire la consommation d'énergie de ce type d'entreprises, ainsi qu'une éventuelle suppression des subventions à l'électricité qui encourageraient une consommation plus efficace et consciente.

Chapitre III

Efficacité et épuisement énergétique dans les pays en développement exportateurs de pétrole

3.1. Introduction

Les activités économiques dépendent de la consommation d'énergie, créant des défis de durabilité environnementale (Adom et al. 2019). Ces défis sont plus importants pour les pays exportateurs de pétrole qui ont besoin d'énergie pour répondre aux besoins de la société et dépendent des revenus générés par l'extractivisme pétrolier. Une voie pour relever les défis de la durabilité consiste à atteindre et à améliorer l'efficacité énergétique, car l'efficacité est au cœur du développement environnemental durable. Il est donc urgent de donner la priorité à l'efficacité énergétique, en particulier dans les pays en développement, car ces pays connaissent des problèmes économiques et environnementaux liés à là sur extraction de pétrole.

Ce chapitre vise à aborder deux principaux problèmes environnementaux auxquels sont confrontés les pays pétroliers en développement : la pollution de l'environnement et l'épuisement du pétrole. Premièrement, le secteur de l'énergie essaie de réduire la participation des combustibles fossiles dans la production d'énergie pour atteindre les objectifs en matière de changement climatique. Le secteur de l'énergie est l'un des plus importants contributeurs au changement climatique en brûlant des combustibles fossiles. Selon Olivier, Peters, & Schure (2017), environ 70 % des émissions mondiales totales de GES sont sous forme de CO2 en raison de la combustion de combustibles fossiles. Pour suivre une trajectoire régulière vers les objectifs de 1,5°C, le monde devra réduire la production de combustibles fossiles d'environ 6 % par an entre 2020 et 2030. Cela se traduit par une réduction des investissements dans le développement de projets pétroliers, une réduction des redevances, et donc une réduction des revenus des exportations de pétrole dans les pays en développement. Il est généralement admis que la manière stratégique d'atténuer le réchauffement climatique consiste à adopter une politique de réduction des émissions de carbone, une utilisation efficace de l'énergie (Iqbal et al., 2019) et à découpler la demande énergétique et la pollution de l'environnement (Adom et al. 2019). Par conséquent, il est important d'évaluer régulièrement les performances d'utilisation de l'énergie pour obtenir des preuves personnalisées pour l'analyse comparative et le suivi des améliorations en matière de réduction des émissions de carbone.

Le deuxième défi est l'épuisement du pétrole, plus précisément la réduction de la qualité des gisements qui se traduit par l'augmentation des coûts énergétiques. Lorsque nous parlons d'épuisement du pétrole, trois tendances se produisent dans le monde : la production des champs pétrolifères existants diminue, les nouveaux champs ne sont pas aussi vastes ou productifs que les anciens champs, et les zones dotées de ressources conventionnelles sont de plus en plus interdites aux investissements des compagnies pétrolières indépendantes (Brandt et al. 2017). Les champs de meilleure qualité sont les premiers à être consommés, il faut donc plus d'énergie pour extraire l'énergie; cela se traduit par une augmentation des coûts économiques et énergétiques. La nature de l'épuisement du pétrole est généralement étudiée à l'aide de statistiques agrégées telles que les courbes de production régionales (Brandt et al. 2007). En raison du manque de données accessibles au public, peu de recherches ont été effectuées sur les effets spécifiques de l'épuisement du pétrole sur l'efficacité énergétique et la performance environnementale (Brant et al., 2017 ; Cleveland 2005 ; Murphy & Hall, 2011).

Malgré les impacts des émissions de CO2 et de l'épuisement du pétrole sur les performances économiques et énergétiques des pays en développement exportateurs de pétrole, peu d'études ont été menées. En fait, à la connaissance de l'auteur, aucune étude n'a été développée qui inclut les émissions de CO2, l'épuisement du pétrole et la croissance économique du point de vue de la performance/efficacité dans les pays en développement exportateurs de pétrole. À cet égard, cette étude vise à contribuer à la littérature dans ce domaine en analysant les problèmes environnementaux susmentionnés dans un groupe de pays exportateurs de pétrole d'Amérique latine et d'Afrique.

Certains pays d'Amérique latine et d'Afrique sont d'excellents exemples pour étudier cette question. En ce sens, le Brésil, le Mexique et le Venezuela dominent l'extraction pétrolière latino-américaine. Ces pays sont responsables d'environ 75 % de la production totale de la région et sont des géants sur la scène internationale. Pendant ce temps, en 2019, environ 10% de la demande mondiale de pétrole était extraite en Afrique, ce qui donne une idée de la richesse des ressources naturelles du continent. En outre, en Afrique, il existe cinq pays centraux exportateurs de pétrole dans le monde, l'Angola, le Nigéria, l'Algérie, la Libye et l'Égypte (IEA, 2020a). Ces pays sont fortement dépendants de la rente pétrolière et sont vulnérables aux chocs de prix.

Ce chapitre est divisé en quatre parties. La première section présente une revue de la littérature dans laquelle j'introduis les principaux concepts et travaux empiriques développés dans ce domaine. La deuxième section décrit le cadre méthodologique utilisé dans cette étude, ici, je présente les données utilisées pour le modèle et la spécification du modèle SMB-DEA appliqué dans cette étude. La troisième section présente les principaux résultats de cette enquête. Et la dernière section conclut et propose des recommandations politiques.

3.2. Revue de littérature

D'après l'examen de la littérature, il a été constaté que l'efficacité énergétique est considérée comme un objectif essentiel dans les pays en développement (Popkova et Sergi, 2021). En outre, dans le cas des pays pétroliers, l'efficacité énergétique est essentielle car elle est fortement liée à la sécurité commerciale et énergétique, ainsi qu'aux avantages environnementaux tels que la réduction des émissions de CO2 et l'épuisement des ressources énergétiques (Li et Tao, 2017). Pour mesurer et étudier le changement dynamique de l'efficacité énergétique, la plupart des chercheurs ont appliqué les modèles DEA traditionnels et l'indice de productivité de Malmquist (Zhou et al., 2018). Ces méthodes ont été utilisées pour la recherche sur l'efficacité énergétique dans les pays de l'OCDE (Fidanoski et al., 2021), en Asie (Kim et al., 2015) et aux États-Unis (Grösche, 2009). Bien qu'il existe de la littérature sur l'évaluation de l'efficacité énergétique dans les pays d'Amérique latine et d'Afrique, nombre de ces études se concentrent sur un secteur ou un pays particulier de l'industrie énergétique (Navarro-Chávez, 2020) ou ne tiennent pas compte des caractéristiques spécifiques qui peuvent contribuer à ou aggraver la mise en œuvre de politiques énergétiques dans cette région (Popkova et Sergi, 2021). De plus, il existe peu de preuves empiriques dans les pays en développement qui tiennent compte d'autres facteurs environnementaux défavorables en dehors des émissions de CO2 impliquées dans la production d'énergie.

3.3. Cadre méthodologique

3.3.1. SMB- DEA model

Pour analyser la question de l'efficacité énergétique et de l'épuisement énergétique dans les pays en développement exportateurs de pétrole, cette recherche utilise le modèle SBM-DEA. La méthode DEA est une méthode d'évaluation de l'efficience basée sur le concept d'efficacité relative. Le SMB-DEA, un modèle DEA non radial et non orienté en input ou en output qui utilise directement les inputs et les outputs pour déterminer la mesure de l'efficacité des DMU. Conformément à l'objectif de cette étude, le modèle SMB-DEA avec production indésirable est appliqué pour estimer l'efficacité énergétique de 14 économies productrices de pétrole en Amérique latine et en Afrique. Cette étude n'intègre que des variables dont les valeurs peuvent être modifiées dans un délai raisonnable par les unités décisionnelles (Çelen, 2013), et qui permettent de maximiser les bénéfices de l'extraction pétrolière et de minimiser les sorties indésirables, qui sont dans ce cas les émissions de carbone et l'épuisement énergétique dès l'utilisation des puits de pétrole. Pour analyser et comparer l'efficacité dynamique de la productivité énergétique entre les pays d'Amérique latine et d'Afrique, l'indice de productivité de Malmquist (IPM) est adopté. L'approche MPI évalue l'impact environnemental à multiples facettes des changements de période. Cette approche est utilisée pour tenir compte des variations dans l'efficacité des politiques, avec l'avantage de ne pas postuler de relation fonctionnelle entre les intrants et les extrants. Les approches Malmquist et DEA sont parmi les outils les plus utilisés pour estimer l'efficacité énergétique (Zhou et al., 2007; Zheng, 2021).

Tone (2001) a développé une méthode modifiée « Slack Base Measure-Data Envelopment Analysis » (SMB - DEA) adaptée à la gestion des productions indésirables.

Suivant Tone (2001) et Tachega et al., (2020), en supposant qu'il y a n pays d'Amérique latine avec des intrants biophysiques et monétaires définis par $x \in R^n$, des outputs désirables par $Y \in R_s$ pour un $DMU(x_0, y_0)$. La correspondance en output s'exprime par:

$$P = \{(x_0, y_0^g, y_0^b)x \geq X\lambda, y^g \leq Y^g, L \leq e\lambda \leq U, \lambda \geq 0\} \quad (1)$$

Où:

λ = facteur d'intensité

L = limite inférieure du vecteur d'intensité

U = limite supérieure du vecteur d'intensité

La méthodologie indique qu'un $DMU(x_0, y_0^g, y_0^b)$ est efficace lorsqu'il n'y a pas de vecteur $(x_0, y_0^g, y_0^b) \in P$, tel que $x_0 \geq x, y_0^g \leq y^g, y_0^b \leq y^b$ avec au moins une inégalité stricte.

Selon Chambers et al. (1998) et F*ä*re and Grosskopf (2009), la fonction de distance directionnelle sur *P* peut être défini comme :

$$g = (g_1, \ldots, g_m, g_{m+1}, \ldots, g_{m+s}) \neq 0 \quad (2)$$

Et résoudre le problème suivant pour chaque DMU :

$$\varphi_0 = \max \beta$$

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

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

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

Le SMB—DEA non radial en présence d'output indésirable est donné par :

$$[SBM]p^* = min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_{i0}^-}{x_{i0}}}{1 + \frac{1}{m}\left(\sum_{r=1}^{s_1} \frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{r0}^b}\right)} \tag{3}$$

Sujet à:

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

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

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

Les vecteurs S^- et S^b montrer une offre excédentaire d'entrées et de sorties indésirables, et S^g représente les extrants souhaitables en excès. Par conséquent, une DMU est considérée comme économe en énergie si $p^* = 1$ or S^-, S^b et S^g sont inexistants.

3.3.2. Indice de Malmquist

Pour analyser et comparer l'efficacité dynamique de la productivité énergétique entre les pays d'Amérique latine et d'Afrique, l'indice de productivité de Malmquist (IPM) a été adopté. L'approche Malmquist DEA est l'un des outils les plus puissants pour estimer l'efficacité énergétique. Cette approche tient compte des variations d'efficacité des politiques, avec l'avantage d'estimer l'association fonctionnelle entre les intrants et les extrants.

L'approche de l'indice de Malmquist évalue l'impact environnemental multi-output des changements de période. Des auteurs tels que Sarpong et al. (2022), Shah et al. (2022) affirment que la méthode DEA est appropriée pour évaluer la relation entre l'énergie et la productivité.

Cette approche décompose la productivité totale des facteurs de nombreux intrants et extrants en changement de progrès technique (TPCH) et changement d'efficacité technique (TECH), changement d'efficacité technique pur (PECH) pour mieux expliquer le point de vue du progrès technologique et l'efficacité technique des DMU d'une entreprise. L'indice de Malmquist peut être estimé comme suit :

$$MPI = TECH * TPCH = M(x^{t+1}, y^{t+1}, x^t, y^t)$$
$$= \frac{D^t(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \times \left[\frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^{t+1}, y^{t+1})} * \frac{D^t(x^t, y^t)}{D^t(x^t, y^t)}\right] \tag{4}$$

Où:

$(x^t, y^t), (x^{t+1}, y^{t+1})$ Sont des vecteurs de sorties et d'entrées dans t et $t+1$

D^t, D^{t+1} Sont les fonctions de distance entre t et $t+1$

$TECH =$ Représente « l'effet de rattrapage » entre t et $t+1$

3.3.3. Données en bref

L'étude a couvert quatorze des plus importants pays producteurs de pétrole d'Amérique latine et d'Afrique pour la période 2006-2020 en termes d'approvisionnement et de réserves prouvées. Les quatorze économies sont la Colombie, l'Argentine, le Brésil, l'Équateur, le Mexique, la Bolivie, le Pérou, le Gabon, l'Afrique du Sud, l'Algérie, l'Angola, l'Égypte et la Guinée équatoriale. Les données ont été recueillies à partir des indicateurs de développement dans le monde (WDI) de la Banque mondiale, de l'Energy Information Administration (EIA) des États-Unis et de leurs propres calculs.

L'analyse s'est concentrée sur des indicateurs économiques et d'efficacité énergétique agrégés utilisant plusieurs intrants pour produire un output désirable (PIB et espérance de vie) et une sortie indésirable (épuisement du CO2 et de l'énergie).

Dans l'analyse de l'efficacité énergétique, des indices d'intrants et d'extrants sont utilisés. L'indice des intrants est regroupé en intrants énergétiques et en intrants non énergétiques. L'indice de production comprend un indicateur de production économique et un indicateur de polluant. Le tableau 1.1 liste toutes les variables utilisées dans cette étude :

Tableau 1. 1 : Définitions des variables

Type	Variable	Unité	Source
Input	Gross Capital Formation	Constante USD 2005	WDI
	La main d'oeuvre	Pour 1000 travailleurs	WDI
	Production de pétrole et de gaz	Mbd	EIA
	Consommation d'énergie	Quad BTU	EIA
Output	CO2 émissions (Indésirable)	Millions of tons	WDI

Épuisement énergétique (indésirable)	Current USD dollars	WDI
PIB (désirable)	Constante USD 2005	WDI
Espérance de vie (désirable)	Years	WDI

Source : propre élaboration

3.4. Résultats

3.4.1. Analyse de l'efficacité énergétique avec entrées et sorties indésirables

Pour procéder à une analyse de l'efficacité énergétique, cette étude a utilisé le SMB-DEA pour tenir compte de la production indésirable et pour mesurer l'efficacité des pays producteurs de pétrole et de gaz de 2006 à 2020 dans différents pays d'Amérique latine et d'Afrique. La section des résultats a également montré l'évolution des scores d'efficacité technique (SMB-C) et des rendements d'échelle variables (SMB-V). De plus, à titre de contrôle de robustesse, une fois calculé, le modèle de super-efficacité SMB est non orienté pour montrer la diversité des DMU efficaces et les classer. En outre, les caractéristiques de plusieurs pays pourraient être liées aux besoins d'efficacité, telles que la qualité des gisements de pétrole, la taille du pays, les différences géographiques et la politique macro-énergétique. Les résultats suggèrent qu'en moyenne, les pays affichent des rendements d'échelle croissants au cours de la période d'analyse. Cependant, il n'y a pas d'amélioration significative de l'efficacité comparée année après année lors de l'analyse dans les pays producteurs de pétrole et de gaz d'Amérique latine et de la région africaine.

Tableau 1.2 : Efficacité énergétique totale du facteur 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

Source : propre élaboration

L'implication pour les pays avec un score de 1 (Guinée équatoriale et Gabon) est que ces pays sont économes en énergie. Ils utilisent efficacement la technologie, les processus de production et les intrants pour produire une croissance équilibrée du PIB, émettre des émissions de CO2, augmenter l'espérance de vie et des valeurs d'épuisement énergétique plus faibles que les autres pays. L'Angola est le pays le moins inefficace (0,604), suivi de l'Algérie (0,63) et du Mexique (0,705). Au fil des ans, les estimations d'efficacité moyenne des 14 pays sélectionnés sont passées de 0,875 en 2006 à 0,837. Cette baisse de productivité peut être associée à la baisse de la rente pétrolière et aux politiques d'efficacité énergétique latino-américaines qui permettent aux pays d'être au top de leur forme. Les résultats pour 2020 pourraient être dus à l'intrusion du Covid-19, qui a touché de nombreux pays. La perte de productivité de 2015 à 2020 pourrait être le résultat de crises économiques mondiales en Amérique latine et en Afrique qui ont rendu les pays dotés de systèmes économiques faibles vulnérables aux pertes de productivité.

3.4.2. Résultats de l'indice de productivité de Malmquist

L'indice de productivité de Malmquist a été utilisé pour mesurer l'indice de changement d'efficacité technique énergétique, l'indice de changement d'efficacité pure, l'indice de changement de super efficacité et l'indice de changement de la productivité totale des facteurs de 2006 à 2020. La productivité des différentes économies fonctionnait sur l'hypothèse que (TECH> 1, et TFPCH>1) pour qu'une DMU soit jugée efficace. Les scores inférieurs au seuil de 1 ou 100 % sont réputés inefficaces. En comparant l'amélioration significative de toutes les économies sur une base annuelle, la productivité totale des facteurs a été décomposée en TECH, PECH et TFPCH. Cela a révélé que la plupart des neuf pays étaient inefficaces et que la consommation et l'utilisation de l'énergie ont été inefficaces pour améliorer la productivité. Les détails de TECH ont indiqué que TECH est passé de 0,781 en 2007-2008 à 1,032 en 2019-2020. La diminution de l'efficacité moyenne plus importante que (1) de 2013 à 2020 indique une baisse du niveau d'efficacité énergétique et une amélioration par pays au cours des dix dernières années se terminant en 2020 (tableau 1.3). La productivité totale des facteurs au cours des dix dernières années se terminant en 2020 était bien inférieure à avec un niveau d'efficacité d'entrée de 0,67 en 2006-2007 à 0,66 en 2019-2020, et de légères améliorations en 2009 (0,70) et 2010 (0,72).

Tableau 1.3 : Résultats de l'indice de productivité de Malmquist de 2007 à 2020

Source : propre élaboration

	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

3.5. Conclusions

Ces résultats suggèrent que les décideurs devraient accorder une attention particulière aux politiques qui encouragent la réduction de la consommation d'énergie dans le secteur pétrolier et gazier, car cela a un impact positif sur l'efficacité énergétique dans les pays en développement exportateurs de pétrole. Il a également été démontré que les politiques visant à modifier les modèles de consommation d'énergie dans cette industrie ont un impact positif sur les réductions d'émissions de CO2.

Quant à l'indicateur d'épuisement énergétique, les résultats montrent qu'il diminue avec le temps, ce qui implique que les pays analysés reçoivent moins de revenus pour la même quantité de ressources énergétiques extraites. Cela pourrait s'expliquer par la perte de qualité de l'énergie dans les champs pétroliers. Cela implique qu'à mesure qu'un baril de pétrole est extrait, le gisement de pétrole perd non seulement en quantité mais aussi en qualité de production d'énergie. Il faut investir plus d'énergie pour extraire le baril suivant. Cette question n'est pas explorée en profondeur dans cette étude ; pour plus d'explications à ce sujet, se référer à Arias, 2023. Ceci suggère que les décideurs devraient analyser la pertinence de poursuivre l'extraction des ressources énergétiques puisque, dans plusieurs cas, cette activité n'est plus rentable ou efficace. Elle génère plus de pertes que de bénéfices pour le pays.

Enfin, les résultats de l'indice de productivité de Malmquist pour l'Afrique et l'Amérique latine montrent que la plupart des pays ont des niveaux d'efficacité énergétique inférieurs à 1. Cela implique qu'aucun pays n'a montré d'amélioration en termes de productivité au cours de la période analysée. Ces résultats témoignent du retard important de ces pays en termes de capacités productives et technologiques. Cela suggère que ce groupe de pays devrait encourager les investissements dans la science et la technologie pour améliorer l'efficacité énergétique dans le secteur pétrolier et gazier.

Chapitre IV

Réflexions finales

Cette thèse est motivée par l'importance de l'efficacité énergétique dans la réalisation d'avantages économiques et environnementaux dans les pays en développement exportateurs de pétrole. En ce qui concerne les avantages économiques, l'amélioration de l'efficacité énergétique encourage une meilleure utilisation des ressources énergétiques, ce qui peut réduire la consommation d'énergie et diminuer les coûts énergétiques dans le secteur pétrolier. En ce qui concerne les avantages environnementaux, les mesures d'efficacité énergétique peuvent réduire les émissions de gaz à effet de serre et contribuer aux efforts mondiaux pour atténuer le changement climatique.

Afin d'étudier le rôle de l'efficacité énergétique dans l'amélioration des performances économiques et environnementales des pays en développement exportateurs de pétrole, cette thèse est divisée en trois chapitres.

4.1 Résultats et conclusions

Le premier chapitre aborde le problème de la perte de qualité du réservoir, comprise comme le bonus d'énergie naturelle gratuite fourni par la nature pour avoir le pétrole concentré dans les champs au lieu d'être dispersé dans l'atmosphère (Valero & Valero, 2019), et comment cela entraîne une augmentation des coûts énergétiques en Equateur. Ce chapitre applique une adaptation de l'ERC utilisant EROI pour tenir compte de la perte de qualité des champs pétrolifères et de l'augmentation des coûts énergétiques. Les résultats ont montré que l'EROI des champs pétrolifères avait diminué en Équateur de 43: 1 en 2006 à 25: 1 en 2020. Les prévisions montrent que d'ici 2040, les champs pétrolifères en Équateur atteindront un EROI de 1: 1. Cela implique que pour chaque baril de pétrole investi, on obtient un baril de pétrole, donc après ce point, il n'est plus efficace de continuer à extraire des termes énergétiques. Cela a des implications importantes sur les coûts énergétiques car, en 2006, l'Équateur a investi 1,43 Mtep pour obtenir 1 baril de pétrole, et en 2020, le pays a investi 11,9 Mtep pour obtenir le même baril. D'ici 2040, l'Equateur devra investir 118,5 Mtep pour obtenir du baril (1 baril = 45,5 Mtep). De plus, il est essentiel de mentionner que ce résultat concorde avec l'étude d'Espinoza et al. (2019), qui ont développé des modèles basés sur Hubbert pour projeter l'extraction future de pétrole en Équateur, et ils ont conclu que l'Équateur pourrait devenir un importateur net de pétrole entre 2024 et 2035, selon le modèle et le scénario de demande. Ces résultats ont montré comment l'extraction des ressources génère des coûts qui ne sont pas pris en compte dans le prix, tels que les coûts énergétiques. Ce chapitre a également servi d'introduction aux deux chapitres suivants, qui analysent si les compagnies pétrolières et les pays exportateurs de pétrole utilisent efficacement leurs ressources énergétiques.

Le deuxième chapitre vise à contribuer à la connaissance de l'analyse de l'efficacité énergétique au niveau industriel en fournissant des preuves empiriques des compagnies pétrolières privées en Équateur et en examinant comment les moteurs et les obstacles à l'efficacité énergétique fonctionnent dans ce secteur dans le contexte d'un pays en développement. Ce chapitre prétend donner des informations pertinentes sur la manière d'utiliser au mieux les ressources des entreprises du secteur pétrolier pour maximiser leurs profits et minimiser les émissions qu'elles produisent. Ce chapitre a évalué l'efficacité énergétique à l'aide de l'approche SMB-DEA. Il a également mis en œuvre l'approche de l'indice de productivité de Malmquist pour estimer l'amélioration de la productivité environnementale de 2011 à 2020. Les résultats ont révélé que les facteurs liés à la baisse des investissements et au manque d'avancées techniques sont essentiels pour expliquer le ralentissement de la productivité et la mauvaise performance des entreprises pétrolières en termes d'efficacité énergétique.

De plus, dans la période analysée, en moyenne, les entreprises ne montrent pas de changements positifs dans leur efficacité et leur productivité, sauf pour les périodes 2013-2014 et 2017-2018, où de légères augmentations sont identifiées. Au cours des deux sous-périodes, comme mentionné précédemment, le gouvernement équatorien a pris des mesures de politique publique pour attirer davantage d'investissements privés dans l'industrie pétrolière et augmenter la production. L'augmentation de la production, selon les résultats du modèle DEA, a été générée en maintenant la même relation entre les entrées et les sorties, de sorte qu'une légère augmentation de la productivité au cours de ces années peut être mise en évidence. Les résultats du modèle paramétrique suggèrent que l'efficacité et la productivité des entreprises ont une relation négative mais significative avec la consommation d'énergie et l'emploi. Cela signifie que les entreprises ayant des emplois moins qualifiés pourraient devenir plus inefficaces au fil du temps. Selon Managi (2011), en termes d'efficacité, il vaut mieux avoir moins d'employés mieux qualifiés que plus d'employés peu qualifiés.

Le troisième chapitre évalue l'efficacité énergétique et les améliorations de la productivité dans les pays en développement exportateurs de pétrole. Ce chapitre évalue l'efficacité énergétique à l'aide de l'approche SMB-DEA. Il met également en œuvre l'approche de l'indice de productivité de Malmquist pour estimer l'amélioration de la productivité énergétique de 2006 à 2020. La nouveauté du chapitre un est l'introduction de l'épuisement de l'énergie comme résultat indésirable dans les estimations DEA et Malmquist. Les résultats du modèle SBM-DEA indiquent que des pays tels que la Guinée équatoriale, le Gabon, le Pérou et la Bolivie ont des efficacités énergétiques supérieures à celles de leurs homologues en Angola, en Algérie, au Mexique, en Équateur et en Colombie, ce qui signifie qu'ils investissent moins d'énergie dans le pétrole et extraction de gaz. Le niveau d'efficacité des pays était assez bon, avec une augmentation de la productivité de 8% en 2007 et progressivement réduite à 2% en 2010. Il est essentiel de mentionner que la Guinée équatoriale et le Gabon ont également la plus faible moyenne de consommation d'énergie des pays.

En ce qui concerne les émissions, la Guinée équatoriale a une émission totale moyenne de 8 027 GT, ce qui est inférieur à la moyenne de tous les pays analysés, 153 602 GT. Les résultats de l'indice de productivité de Malmquist pour l'Afrique et l'Amérique latine montrent que la plupart des pays ont un niveau d'efficacité énergétique inférieur à 1. Cela implique qu'aucun pays n'a montré d'amélioration en termes de productivité sur la période analysée. Ces résultats témoignent du retard important de ces pays en termes de capacités productives et technologiques. Les résultats suggèrent que ce groupe de pays devrait encourager les investissements dans la science et la technologie pour améliorer l'efficacité énergétique dans le secteur pétrolier.

Les résultats trouvés ont des implications politiques importantes qui pourraient aider à améliorer l'efficacité énergétique au niveau des pays et des entreprises. Voici quelques stratégies et recommandations de politiques publiques qui pourraient être utiles pour les études de cas de cette recherche.

4.2 Stratégies et recommandations politiques

En ce qui concerne la perte de qualité des gisements de pétrole et l'augmentation du coût de l'énergie due à l'extraction du pétrole dans les pays en développement, il existe certaines stratégies que les gouvernements peuvent mettre en œuvre. 1) Les gouvernements peuvent inciter les compagnies pétrolières à adopter des pratiques éconergétiques. Cela peut inclure des allégements fiscaux, des subventions ou d'autres incitations financières pour encourager les entreprises à investir dans des équipements ou des pratiques économes en énergie (García-Quevedo & Jové-Llopis, 2021). 2) Les gouvernements peuvent mettre en œuvre des réglementations qui obligent les compagnies pétrolières à adopter des pratiques économes en énergie, telles que l'utilisation d'équipements économes en énergie, la réduction du gaspillage d'énergie ou l'amélioration de la gestion de l'énergie (Shi & Sun, 2017). 3) Promouvoir l'utilisation de technologies économes en énergie, telles que l'éclairage éconergétique, les systèmes de CVC et l'isolation, pour réduire la consommation d'énergie des installations d'extraction de pétrole. Dans l'ensemble, les gouvernements peuvent jouer un rôle essentiel dans la réduction du coût énergétique de l'extraction du pétrole dans les pays en développement en mettant en œuvre des politiques et des programmes qui encouragent l'efficacité énergétique et promeuvent des pratiques énergétiques durables.

Les résultats obtenus au chapitre deux suggèrent que les sociétés pétrolières et gazières des pays en développement peuvent mettre en œuvre plusieurs recommandations pour améliorer l'efficacité énergétique, telles que : 1) La réalisation d'audits énergétiques peut aider à identifier les domaines dans lesquels des améliorations de l'efficacité énergétique peuvent être apportées. Les audits doivent se concentrer sur l'identification des domaines où l'énergie est gaspillée et recommander des solutions pour réduire la consommation d'énergie (Moya, et al., 2016). 2) Investir dans les sources d'énergie renouvelables peut aider les sociétés pétrolières et gazières à réduire leur empreinte carbone et leur consommation d'énergie (IEA, 2022). 3) La mise en œuvre de systèmes de gestion de l'énergie peut aider les entreprises à surveiller et à gérer plus efficacement leur consommation d'énergie. Cela peut inclure la surveillance de la consommation d'énergie en temps réel, la définition d'objectifs de consommation d'énergie et la mise en œuvre de mesures d'économie d'énergie (Javied et al., 2015). 4) L'amélioration de l'efficacité opérationnelle grâce à l'optimisation des processus, aux mises à niveau des équipements et à la maintenance régulière peut contribuer à réduire la consommation d'énergie et les coûts. Cela peut également améliorer la productivité et la rentabilité (Hohne et al., 2020). 5) La formation des employés aux meilleures pratiques en matière d'efficacité énergétique peut aider à créer une culture d'économie d'énergie au sein de l'entreprise. Cela peut inclure une formation sur l'utilisation d'équipements éconergétiques, les techniques d'économie d'énergie et la réduction de la consommation d'énergie (Henriques et Catarino, 2016). En outre, 6) Collaborer avec le gouvernement et d'autres parties prenantes pour accéder aux ressources, au financement et à l'expertise technique pour mettre en œuvre des mesures d'efficacité énergétique. Cela peut également contribuer à créer un environnement réglementaire qui

favorise l'efficacité énergétique et encourage les investissements dans les énergies renouvelables (Berry, 2020).
Les résultats du chapitre trois suggèrent que l'amélioration de l'efficacité énergétique a un impact positif sur la réduction de la consommation d'énergie et des émissions de CO2 dans le secteur pétrolier et gazier des pays en développement exportateurs de pétrole.

Il existe plusieurs stratégies que les pays en développement exportateurs de pétrole peuvent adopter pour améliorer leur efficacité énergétique et atteindre leurs objectifs de durabilité. Certaines recommandations sont 1) En mettant en œuvre des normes d'efficacité énergétique, les gouvernements peuvent établir des normes minimales d'efficacité énergétique pour les bâtiments, les appareils et les processus industriels. Ces normes peuvent être soutenues par des incitations ou des sanctions pour encourager la conformité (Bertoldi, 2022). 2) Les gouvernements peuvent encourager l'adoption de technologies d'énergie renouvelable par le biais d'allégements fiscaux, de subventions ou d'autres incitations financières. La promotion de projets d'énergies renouvelables peut réduire la dépendance aux combustibles fossiles et accroître l'efficacité énergétique (AIE, 2022). 3) En stimulant la conservation de l'énergie, les gouvernements peuvent promouvoir la conservation de l'énergie en mettant en œuvre des campagnes de sensibilisation, en réalisant des audits énergétiques et en encourageant l'utilisation d'appareils et de pratiques économes en énergie (Moya et al., 2016). 4) Améliorer les infrastructures énergétiques, les pays en développement peuvent améliorer leurs infrastructures énergétiques en modernisant leurs systèmes de transmission et de distribution, en réduisant les pertes de transmission et en investissant dans des technologies de réseau innovantes (Neffati, et al., 2021). 5) Les gouvernements peuvent encourager les investissements du secteur privé dans l'efficacité énergétique en créant un environnement politique et réglementaire favorable qui incite à investir dans l'efficacité énergétique et en établissant des partenariats avec le secteur privé pour développer des technologies et des pratiques économes en énergie (Owusu-Manu, 2021). 6) Les pays en développement peuvent mettre en œuvre des mécanismes de tarification du carbone tels qu'une taxe sur le carbone ou un système d'échange de droits d'émission pour encourager l'efficacité énergétique et réduire les émissions de gaz à effet de serre (Haites, 2018). 7) Renforcer la coopération internationale en collaborant avec des organisations internationales, telles que le Programme des Nations Unies pour le développement (PNUD) ou l'Agence internationale de l'énergie (AIE), pour accéder au financement, à l'assistance technique et aux opportunités de partage des connaissances afin de soutenir leurs efforts d'efficacité énergétique.

L'étude du rôle de l'efficacité énergétique dans l'amélioration des performances économiques et environnementales reste à explorer, notamment dans les pays d'Amérique latine et des Caraïbes. Compte tenu des résultats de cette étude, la prochaine étape de mon programme de recherche consistera à évaluer les stratégies d'amélioration de l'efficacité énergétique et des performances environnementales des entreprises énergétiques de l'ALC (traditionnelles et renouvelables).

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