UNIVERSIDADE FEDERAL DE VIÇOSA

Macroeconomics of Energy Transition: Two Essays on the Biophysical Approach to Economic Growth

Jéssica de Lima da Vida Pellenz
Doctor Scientiae

VIÇOSA - MINAS GERAIS
2025

JÉSSICA DE LIMA DA VIDA PELLENZ

Macroeconomics of Energy Transition: Two Essays on the Biophysical Approach to Economic Growth

Thesis submitted to the Applied Economics Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

Adviser: Ian Michael Trotter

VIÇOSA - MINAS GERAIS
2025

Ficha catalográfica elaborada pela Biblioteca Central da Universidade Federal de Viçosa - Campus Viçosa

T

P386m
2025

Pellenz, Jéssica de Lima da Vida, 1990-

A macroeconomia da transição energética: uma abordagem biofísica do crescimento econômico / Jéssica de Lima da Vida Pellenz. – Viçosa, MG, 2025.

1 tese eletrônica (85 f.): il. (algumas color.).

Inclui apêndice.
Orientador: Ian Michael Trotter.
Tese (doutorado) - Universidade Federal de Viçosa, Departamento de Economia Rural, 2025.
Referências bibliográficas: f. 74-85.
DOI: https://doi.org/10.47328/ufvbbt.2025.071
Modo de acesso: World Wide Web.

1. Desenvolvimento econômico. 2. Investimento em energia limpa - Estatísticas. I. Trotter, Ian Michael, 1983-. II. Universidade Federal de Viçosa. Departamento de Economia Rural. Programa de Pós-Graduação em Economia Aplicada. III. Título.

CDD 22. ed. 338.9

Bibliotecário(a) responsável: Euzébio Luiz Pinto CRB-6/3317

JÉSSICA DE LIMA DA VIDA PELLENZ

Macroeconomics of Energy Transition: Two Essays on the Biophysical Approach to Economic Growth

Thesis submitted to the Applied Economics Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

APPROVED: February 7, 2025.

Assent:

Jéssica de Lima da Vida Pellenz
Author

Ian Michael Trotter
Adviser

Dedico esta tese ao meu tio José, cuja voz ainda ecoa, suave e firme, pedindo-me simples e profundamente para ser feliz – um pedido que se faz bússola em minha jornada. Ao meu avô Neto, que um dia, com olhos cheios de fé e amor, enxergou em mim a grande mulher que eu ainda me tornaria. Ambos, agora silêncios eternizados, habitam cada momento de coragem que encontro em mim.

E à minha mãe, minha raiz e meu refúgio, que me deu mais do que a vida – presenteou-me com olhos de poesia para enxergar além do que é visível, para sentir além do que é tangível e para viver mais do que é possível sonhar (esta é pra ti, "menina pequena, pequena menina").

ACKNOWLEDGMENTS

Esta tese não teria chegado a bom porto sem a colaboração, estímulo e empenho de várias pessoas. Com isso, gostaria de agradecer a todos que, direta ou indiretamente, contribuíram para que esta tarefa chegasse ao final com sucesso. A todos, meus sinceros e cordiais agradecimentos. Algumas pessoas merecem que esse agradecimento seja feito de forma específica, tamanha a importância que tiveram para que esta etapa de minha vida se concretizasse.

Inicialmente, agradeço ao meu orientador, Professor Ian, cuja orientação e apoio incansáveis foram fundamentais para a realização deste projeto. Suas palavras de encorajamento e sua visão crítica transformaram este trabalho em algo muito além do que eu imaginei ser possível. Obrigada por acreditar em mim, mesmo quando a dúvida parecia tomar conta, e por me desafiar a ir além dos limites do conhecimento.

À professora Viviani, minha sincera gratidão não só pelos ensinamentos valiosos, mas, sobretudo, pelo carinho e pelas palavras de incentivo nos momentos mais desafiadores. Agradeço profundamente pela compreensão diante dos atrasos em meus compromissos e pela paciência que sempre demonstrou. Sua solidariedade e apoio foram fundamentais para que eu seguisse adiante, e são parte essencial desta conquista.

Agradeço imensamente ao Programa de Pós-Graduação em Economia Aplicada da Universidade Federal de Viçosa (UFV) pela formação acadêmica excepcional, pelo suporte contínuo e pelo ambiente intelectual estimulante que proporcionou ao longo desta jornada. O programa foi fundamental para o meu crescimento acadêmico e profissional, e sou grata pela oportunidade de fazer parte dessa comunidade. Agradeço também à CAPES pelo financiamento que tornou possível a realização desta pesquisa.

Agradeço imensamente à minha família, que sempre esteve ao meu lado, tanto nas horas de conquistas quanto nas de dificuldades. Ao meu tio José, cujos conselhos continuarão ecoando em minha vida e cuja ausência será sempre sentida com saudade. Ao meu avô Neto, o maior exemplo de homem que conheço, a quem devo as raízes do meu caráter e perseverança, e de quem jamais esquecerei o legado de força e dignidade que deixou. À tia Fátima, tia, madrinha e eterna apoiadora, agradeço profundamente por todo o suporte, carinho e atenção que sempre me dispensou.

À minha mãe, a quem amo com todo o meu coração e com um olhar repleto de admiração e gratidão. Àquela que, com coragem, escolheu me proporcionar a oportunidade de estar aqui, mesmo sabendo das dificuldades que esse "aqui" traria. Suas lições têm sido meu guia e continuam a me orientar, moldando minha trajetória com sabedoria e amor incondicional. Ela é meu porto seguro, o abraço para o qual faço questão de sempre retornar, onde encontro força e renovação para seguir adiante.

Agradeço profundamente aos meus irmãos Henrique e Dime, que têm sido fontes constantes de apoio e inspiração nesta jornada. Sou imensamente grata por tê-los na minha vida. Guris, cada conquista minha sempre será por vocês.

À minha querida amiga Arlene, que se tornou mais do que uma amiga, mas uma verdadeira companheira de vida, meu mais sincero agradecimento. Sua presença, apoio constante e confiança inabalável foram os pilares que me sustentaram nos momentos de cansaço e desânimo. Sua amizade foi a força vital que me impulsionou a seguir em frente, mesmo quando tudo parecia difícil. Não sei como expressar o quanto sua parceria foi fundamental nesta jornada.

Aos grandes amigos que encontrei por Viçosa, agradeço profundamente pelos momentos únicos que passamos juntos. À Priscila, Junior e Flávia, meu muito obrigada pela parceria, pelos churrascos e conversas fiadas que ajudaram a levantar o ânimo e seguir na luta.

Aos colegas e alunos da Unioeste, que me acolheram de forma tão calorosa durante o período final de escrita desta tese, expresso minha mais profunda gratidão. Em um momento tão desafiador e de imersão intelectual, o apoio e a receptividade de vocês fizeram com que eu me sentisse verdadeiramente em casa, mesmo em meio às mudanças e a um ambiente novo. O aprendizado proporcionado pelos alunos foi uma experiência enriquecedora e inspiradora, muito além do que eu poderia imaginar. A sensação de pertencimento que vocês me ofereceram foi um alento que tornou essa etapa ainda mais significativa e especial em minha trajetória acadêmica e pessoal.

Também aos que, de maneira silenciosa e sem pretensão de reconhecimento, me apoiaram, seja com uma palavra de apoio, uma ajuda prática ou simplesmente com sua presença, meu profundo agradecimento.

Se cada pessoa mencionada aqui fez parte desta jornada, é porque as verdadeiras conquistas são construídas coletivamente. A todos, minha eterna gratidão. \ding{170}

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

"O correr da vida embrulha tudo, a vida é assim: esquenta e esfria, aperta e daí afrouxa, sossega e depois desinquieta. O que ela quer da gente é coragem." - Guimarães Rosa

ABSTRACT

PELLENZ, Jéssica de Lima da Vida, D.Sc., Universidade Federal de Viçosa, February, 2025. **Macroeconomics of Energy Transition: Two Essays on the Biophysical Approach to Economic Growth**. Adviser: Ian Michael Trotter.

This thesis explores the dynamics between energy expenditures, economic growth, and the biophysical constraints imposed by Energy Return on Investment (EROI) within the context of the ongoing energy transition. The main objective is to understand how these factors interact and influence each other, offering a comprehensive understanding of how energy efficiency and EROI impact the sustainability of economic growth. The analysis reveals that, to maintain positive economic growth, countries cannot spend more than 3.95% of their GDP on energy, which is associated with a minimum societal EROI of approximately 30:1. Moreover, Granger causality tests indicate a bidirectional relationship between energy expenditures and economic growth. The study suggests that economic policies focused on improving energy efficiency and transitioning to renewable energy sources with high EROI are crucial to ensuring sustainable economic growth in an environment marked by environmental challenges and energy price volatility.

Keywords: economic growth; ; biophysical economics; ; eroi.

RESUMO

PELLENZ, Jéssica de Lima da Vida, D.Sc., Universidade Federal de Viçosa, fevereiro de 2025. **A Macroeconomia da Transição Energética: uma Abordagem Biofísica do Crescimento Econômico**. Orientador: Ian Michael Trotter.

Esta tese investiga as dinâmicas entre os gastos com energia, o crescimento econômico e as limitações biofísicas impostas pelo Retorno sobre o Investimento de Energia (EROI) no contexto da transição energética em curso. O objetivo principal é entender como esses fatores interagem e influenciam mutuamente, oferecendo uma compreensão abrangente de como a eficiência energética e o EROI impactam a sustentabilidade do crescimento econômico. A análise revela que, para que o crescimento econômico se mantenha positivo, os países não podem gastar mais de 3,95% de seu PIB com energia, o que está associado a um EROI mínimo de aproximadamente 30:1. Além disso, os testes de causalidade de Granger indicam que uma relação bidirecional entre gastos com energia e crescimento econômico. O estudo sugere que políticas econômicas focadas na melhoria da eficiência energética e na transição para fontes renováveis de energia, com altos EROI, são essenciais para garantir o crescimento econômico sustentável em um cenário de desafios ambientais e de volatilidade nos preços da energia.

Palavras-chave: crescimento econômico; ; economia biofísica, ; eroi.

Lista de Figuras

1 Model of the Circular Flow of the Economy 25
2 EROI from different energy sources in the literature 47
3 Energy transition in the baseline scenario 64
4 The impact of different EROI for renewable and non renewable energy . . . 67

Lista de Tabelas

1 Descriptive Statistics 43
2 Cross-section dependence test 43
3 Homogeneous Slope test 43
4 Unit Root Test 44
5 Panel Cointegration 44
6 Results of panel regressions of economic growth on energy expenditure, capital formation, and unemployment rate between 1991 and 2021 45
7 Results of Granger Causality Test 48

Sumário

Lista de Figuras

Lista de Tabelas

1 General Introduction 14

1.1 Problem and Its Importance . . . 16

1.2 Objectives . . . 18

1.3 General Objective . . . 18

1.4 Specific Objectives . . . 19

1.5 Thesis Structure . . . 19

2 The Energy-Economics Paradigm: Reconciling Traditional and Biophysical Economic Perspectives 21

2.1 The Comeback of Biophysical Economic Theory and Its Convergence with Traditional Economics . . . 21

2.2 Considerations on the Biophysical and Thermodynamic Nature of Economics 24

2.3 The Role of EROI in Macroeconomic Analysis . . . 27

2.4 Policy Implications of EROI Assessments . . . 29

2.5 Challenges in Integrating Biophysical and Economic Models . . . 30

3 The role of Electricity Expenditure on Economic Growth and the Minimum Societal EROI 32

3.1 Introduction . . . 32

3.2 Methodology . . . 35

3.2.1 Model Development . . . 35

3.2.2 Cross-Sectional Dependence and Panel Unit Root Tests . . . 36

3.2.3 Panel Cointegration Test . . . 38

3.2.4 Long-run Estimators . . . 39

3.2.5 Maximum tolerable level of electricity expenditure . . . 40

3.2.6 Minumum EROI required for a positive growth rate . . . 41

3.2.7 Panel Long-run Granger Causality . . . 41

3.2.8 Data Sources and Descriptive Statistics . . . 42

3.3 Results and discussion . . . 42

3.4 Concluding Remarks . . . 48

4 **The Role of EROI and Finite Resources in Economic Growth: A Biophysical Economics Approach** **51**
4.1 Introduction 51
4.2 Theoretical Framework of EROI in Macroeconomic Models 53
4.3 EROI and Sustainable Economic Growth 55
4.4 Case Studies: EROI in Different Economic Contexts 57
4.5 Methodology 58
4.6 Model Structure 59
  4.6.1 Economic Identities and Transition Equations 60
  4.6.2 Intertemporal Optimization and Stationarity of the Value Function 61
  4.6.3 Parameters and Calibration 61
  4.6.4 Numerical Solution and Sensitivity Analysis 62
4.7 Results 63
4.8 A Baseline Scenario 63
4.9 Different EROI scenarios 65
  4.9.1 Discussion 69
4.10 Concluding remarks 71

5 **General Conclusions** **73**

1 General Introduction

The globalization of markets, the intensive pursuit of economic growth, and the improvement in living standards observed over the past two centuries can largely be attributed to the utilization of energy, particularly fossil fuels, which have served as the engine for production processes (SAUD; CHEN et al., 2018; KHAN et al., 2021). Technical progress, responsible for the increase in the productivity of inputs, has only been made possible through the refinement of strategies for the intensive exploitation of natural resources. The intensive use of fossil fuels in production processes has led to environmental pressure due to greenhouse gas emissions. Overall, in recent years, coal, oil, and natural gas have been considered the driving force behind economic growth and the primary contributors to pollutant gas emissions (ZAFAR et al., 2019; KHAN et al., 2021).

Concerns regarding environmental and energy issues gained prominence in the academic sphere, especially after the 1970s, when studies by Nordhaus (1974) and Nordhaus (1979) brought to light an important discussion about the availability of natural resources and the concern over the depletion of these resources in order to sustain long-term economic growth. This subject transcends academia and has also taken center stage in political debates due to (i) the perception of the initial effects of global warming, (ii) the emergence of serious instability in oil markets, and (iii) the growing need for financing fuel reserves (TROMBETTA, 2008).

Over the years, the transition to renewable energy sources has become imperative, as according to Panwar (2013), renewable energy sources may represent a viable alternative to alleviate pressure on fossil fuel stocks, in addition to meeting the necessary conditions to curb global warming by reducing greenhouse gas emissions. With the rise of renewable sources, a decrease in electricity generation from fossil sources has been observed. In 2020, a record growth in global photovoltaic and wind energy supply was witnessed (12% and 23%, respectively), while coal usage declined by 4.4%, marking the largest absolute decline on record, with the United States and the European Union being the main contributors to this decrease (IEA, 2021b). Moreover, the IEA (2021b) highlights the continuous annual decline in global electricity supply from oil since 2012, with a 4% reduction observed in 2020 alone. However, in absolute terms, due to the COVID-19 pandemic, the global energy supply experienced a decline during the lockdown period (IEA. International Energy Agency, 2021a).

Although gaining prominence in recent years, renewable energy sources still account for only 29% of the global electricity generation matrix[1]. In the United States, the share of renewables in the electricity generation mix is 20% (EIA 2021), a percentage that is still lower than the global average—similar to the situation in China, where it stands at 26% (IEA, 2020a). In the European Union, the proportion of renewables was 40.2% in 2020

---

[1] Data from 2020 presented in IEA 2021a

(IEA, 2020b). In Brazil, the electricity matrix is predominantly composed of renewable sources, which represent almost 85% of the total produced (EPE, 2021), with hydroelectric generation alone accounting for 65.2% of the total.

The utilization/generation of energy is one of the most discussed topics in major discussions regarding global policy implementations (Kyoto Protocol, Paris Agreement, Europe 2020 Strategy, among others) that focus on reducing the use of non-renewable energy sources in order to decrease pollutant gas emissions. The European Union, for example, has established a target of 27% of energy consumption from renewable sources by 2030 for its member states (European Commission, 2014). China has set a target to increase the use of non-fossil energy to 20% by 2030 (CHINA, 2015). The United States has proposed an even more ambitious target of achieving 100% carbon pollution-free electricity by 2035 (USA, 2021). Brazil, on the other hand, aims to maintain its status as the country with the most renewable energy matrix in the world, intending to triple the global supply of zero and/or low-carbon energy by 2050 (BRAZIL, 2016).

Recent studies have highlighted the effects of the energy transition and the assessment of the best ways to implement it. Argentiero et al. (2018) estimated a Bayesian DSGE model to evaluate the effectiveness of an environmental policy for renewable energy sources that includes carbon taxes and subsidy measures for the renewable sector. The results obtained allow for an assessment of which policy is best to implement to encourage the growth of the renewable energy sector. Zhang et al. (2021) developed a DSGE model to examine the macroeconomic effects of shocks from a coal usage reduction policy in China. Their results indicate that, regardless of the implemented policy, a reduction in coal usage will lead to a decline in social welfare.

In a study focused on Germany, Sievers et al. (2019) sought to identify the economic consequences of the energy transition, applying a regionalized economic impact assessment model that linked the economic activities resulting from energy consumption and supply to a macroeconomic model. The results inform that two regions of the country will benefit from the energy transition due to their attractive locations for investments in the renewable energy sector. Nieto et al. (2020) estimated a Post-Keynesian model to assess the macroeconomic impact of the targets established by the European Commission (2011) during the proposal known as "EU's Energy Roadmap 2050 (ER2050)."The results show that GDP growth and job creation may be interrupted due to energy scarcity if the ER2050 targets are met.

Despite the evident importance of energy issues for the development of societies and their undeniable relationship with economic science, there remain some gaps in the literature on energy and economic growth, particularly concerning the exhaustible nature of fossil fuels and the available flow of renewable energy. Thus, the role of energy must be adequately understood in order to incorporate this factor into economic analyses in a coherent and realistic manner.

1.1 Problem and Its Importance

In light of the problems associated with the indiscriminate use of fossil fuels, it is essential to present viable alternatives to substitute this production factor so that economic processes are not compromised. The relevance of energy to the economy is such that there exists a branch of researchers known as Biophysical Economics, who believe that energy utilization is a fundamental cause of economic growth and that overcoming the disparity in development levels among countries can only be achieved if these countries reach a satisfactory level of energy efficiency, gradually reducing their dependence on fossil fuels in a way that does not compromise productive performance. This branch is dedicated to developing a theory that allows for an adequate approach to energy, considering its physical limitations and its true importance to productive processes (COURT, 2016). Furthermore, Hall et al. (2014) state that the development of modern industrial economies heavily depends on the use of fossil fuels, suggesting that there may be a causal relationship between energy and economic growth.

One important consideration regarding fossil fuels is that, in addition to their environmental detrimental effects, their sources are depletable. Consequently, whether due to physical limitations or extraction constraints imposed by climate policies, a transition to clean energy sources is imperative. With the objective of reducing global CO_2 emissions by 50% from 2005 to 2050, certain energy policies are concentrating on the adoption of renewable energy sources in place of fossil fuels and on investing in technologies that enhance energy efficiency (IEA, 2015). Therefore, a more comprehensive investigation is required to determine how to implement the energy transition without jeopardizing long-term economic growth.

The issues surrounding the availability of energy resources, especially those concerning the choices made by nations to provide society with the necessary quantities for the maintenance and growth of production processes, have become the focus of major debates regarding the effectiveness of environmental policies aimed at mitigating the problems caused by climate change. A significant part of the response to climate changes lies in the implementation of policies that increase the share of renewable sources, a response that has been adopted by various countries (MATHIESEN; LUND; KARLSSON, 2011; ABOLHOSSEINI; HESHMATI, 2014; STANEK et al., 2018).

According to Stern (2006), fulfilling a global climate change mitigation agenda is not possible without the contribution of developing countries[2]. In this case, the best path toward sustainable and safer development is to seek less degrading productive means, such as the utilization of renewable energies. However, these countries will require financial assistance and technical support to implement their energy transition projects to avoid the

---

[2] Stern (2006) argues that greenhouse gas emissions are considered global negative externalities since the pollution generated by one country is not contained by any geographical boundary but spreads across the planet.

risk that the implementation of global mitigation laws could stifle economic growth in the face of potential forced reductions in fossil energy emissions/usage. In this context, the key point for lower-income countries is the efficient use of the production factor "energy,"aiming to avoid falling into a poverty trap (IEA. International Energy Agency, 2021c; FOLKE; CHAPIN; OLSSON, 2009; OVIEDO-TORAL; FRANÇOIS; POGANIETZ, 2021). To accelerate the energy transition, multilateral cooperation funds are being established[3] to finance a significant portion of renewable energy projects, particularly in low-income countries (KIM, 2019). However, although the issue of financing the transition in low-income countries is critical for achieving global emission targets, it will be addressed only tangentially in this research, delegating a more thorough analysis to future studies.

To understand the role of energy and the effects that a transition to an energy mix different from the current one will have on the performance of nations, it is essential that production processes are appropriately modeled. Court (2016) emphasizes that traditional economic growth models[4] are essentially closed systems in which energy is completely absent.

Stern (1999) argues that these models use the concepts of primary and intermediate production factors, with primary factors referring to inputs available at the start of production and not used directly in production, while intermediate factors are created during the production period and are entirely used in production. Therefore, capital and labor are primary factors, and inputs such as fuels are considered intermediate. This approach has led researchers to assign energy a secondary role in the production process. Stern and Cleveland (2004) suggest that this type of analysis implies that the amount of available energy would be exogenously determined, and thus does not consider the limiting nature of economic growth due to the finite nature of natural resources, as highlighted by Meadows (1972).

In recent decades, aiming to fill this gap, optimal control models that incorporate energy or natural resources into growth models have been implemented. However, few of these models have given importance to the biophysical nature of energy sources. Court, Jouvet, and Lantz (2018) classify this relationship between the economy and biophysical characteristics as "Biophysical Economics,"which has garnered more interest from energy sciences than from economics itself. Recently, an important variable has emerged in energy studies: EROI (the acronym for Energy Return on Investment), which represents a measure of the accessibility of a given resource.

Biophysical Economics posits that the laws of physics must constrain the available choices for economic agents and therefore utilizes basic ecological and thermodynamic principles to analyze the economic process. EROI is a measure of accessibility to a

---

[3] *Adaptation Fund*, *Green Climate Fund*, and *Special Climate Change Fund* are examples.

[4] Prominent examples include Solow's (1956), Lucas' (1988), Romer's (1990), Grossman and Helpman's (1991), among others.

particular resource, and the higher the EROI, the greater the amount of useful energy delivered to society (Hall et al., 2014). It is believed that the development of industrial economies depends heavily on fossil fuels and, in particular, on the high value of EROI, consequently on the capacity to provide large quantities of useful energy to society.

Court, Jouvet, and Lantz (2018) and Fagnart and Germain (2020) share objectives similar to those proposed by this project, presenting ways to integrate different literatures related to economic growth, EROI, and energy transition. Fagnart and Germain (2020) examine the possibility of a smooth transition from non-renewable to renewable energy and the impact of EROI on economic growth. In contrast, Court, Jouvet, and Lantz (2018) analyze an endogenous growth model subject to the physical limits of resources (i.e., the production costs of fossil and renewable energy have functional forms that respect their physical constraints). Moreover, the model reproduces the effects of an increasing dependence on fossil fuels from an initial fossil period and the complete transition to renewable energy. Structurally, the two previously mentioned models seek to unify the theories of endogenous growth and biophysical economics in order to explain the economic growth of nations through the utilization of net energy.

Fagnart and Germain (2020) and Court, Jouvet, and Lantz (2018) have demonstrated the importance of useful exergy[5] for the economy through the use of economic growth models incorporating the EROI variable as a factor of production. These contributions, although fundamental for addressing part of the methodological gap left by the previous literature, have not exhausted the topic. For instance, the effects of exogenous shocks on the variables, such as the impact of climate change on the availability of natural resources and, consequently, on the economic performance of nations, were not included in the analyses. Thus, this thesis, far from claiming to exhaust the subject, will seek to address the issues presented by the existing literature and advance the analysis of the impact of energy transition on economic growth. The outcome may be seen as an additional step towards a better understanding of an essential factor for the functioning of production processes, which has been constantly neglected by economic literature.

1.2 Objectives

1.3 General Objective

This thesis aims to explore the relationship between energy and economic growth, examining both short- and long-term dynamics and the implications of the energy transition for the economic growth of nations. To this end, the thesis consists of this general introduction, a comprehensive review chapter, and two essays, culminating in a general conclusion.

---

[5] The amount of primary energy extracted from the environment, transformed into goods and services, and dissipated by the economy.

1.4 Specific Objectives

To equip the research with the necessary tools to achieve this main objective, the specific aims are:

1. to conduct a scoping review on the main topics of biophysical economics with respect to the energy sector and its implications for economic processes;
2. to investigate the short and long-term relationships between energy expenditures and economic growth;
3. to identify the minimum EROI required to sustain positive economic growth;
4. to investigate the influence of renewable and non-renewable energy resource availability, along with the efficiency of their conversion into usable energy, on goods production
5. to examine macroeconomic dynamics given different EROI evolution scenarios.

1.5 Thesis Structure

Analyzing energy management entails understanding one of the most important strategic sectors of a nation, essential for comprehending the productive and political processes that directly impact economic development. A robust theoretical and practical framework is crucial for public policies to effectively support strategies aimed at transitioning to a cleaner and more renewable energy matrix without sacrificing economic growth.

The following chapter provides a comprehensive overview of the key concepts and discussions surrounding Biophysical Economics, as well as the efforts to integrate these ideas with traditional economic analyses. Additionally, it will highlight the challenges and opportunities presented by the integration of biophysical insights into mainstream economic frameworks, paving the way for more sustainable economic practices.

The first essay (chapter 3) sought to investigate the impact of electricity expenditures on economic growth for a sample of 19 countries during the period from 1991 to 2021 and to estimate the minimum required social Energy Return on Investment (EROI) needed for economic growth to remain positive.

The second essay (chapter 4) presents a theoretical model designed to analyze the dynamics between renewable and non-renewable energy production. This model includes production functions for both types of energy sources, integrating capital stocks, productivity factors, and unique EROI (Energy Return on Investment) functions. By applying numerical simulations, the model examines how these energy sources interact under various EROI progression scenarios.

The general conclusion provides a synthesis of the principal findings and reflections developed throughout this thesis. This section highlights the implications of the results for both theory and practice, outlines the limitations of the study, and offers suggestions for future research. It is essential to reiterate the significance of the themes addressed, emphasizing how investigations into EROI and economic growth contribute to a more comprehensive understanding of contemporary economic dynamics.

2 The Energy-Economics Paradigm: Reconciling Traditional and Biophysical Economic Perspectives

> *"Anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist."*
>
> Kenneth Boulding

The purpose of this chapter is to address the importance of incorporating the analysis of natural resources, especially energy, into economic models. The shortcomings of traditional economics are highlighted for neglecting key factors essential for economic growth. Subsequently, the fundamental laws of thermodynamics and essential concepts such as exergy and entropy are presented. This biophysical/thermodynamic approach is essential for a proper understanding of the crucial role of energy in the economic system and the hypothesis that the productive consumption of exergy can be considered the primary driver of economic growth.

2.1 The Comeback of Biophysical Economic Theory and Its Convergence with Traditional Economics

The analysis of energy resources is not a new phenomenon in economic literature. The impact of energy scarcity, for example, has been a research topic since Jevons (1862), who addressed the problem of the physical sustainability of production processes that strictly depended on fossil fuels at the time. A few years later, in the prelude to neoclassical theory, Hotelling (1931) also anticipated the problem concerning the optimal path for the use of natural resources and attempted to resolve it through variational calculus. However, the importance of energy was ultimately sidelined in the more prominent works of Neoclassical Economic Growth Theory (SOLOW, 1956; KOOPMANS et al., 1963; CASS, 1965), which, based on production functions, primarily focused on two productive inputs: capital and labor.

After the Oil Crisis of the 1970s, despite the notable ability of energy to influence economic processes, the prevailing narrative in economic literature was that technical progress was the main driver of economic growth. However, more than two centuries after the Industrial Revolution, there are sufficient reasons to believe that economic growth has been related not only to productivity increases and capital accumulation but also to a sustained increase in energy use, which typically occurred through a cyclical process involving technological progress that generates a growing demand for energy, which in turn provides the means to increase the production of goods (MACIAS; MATILLA-GARCIA, 2015).

Recognizing the recurring neglect of the importance of energy resources for economic growth from the perspective of mainstream economics, various scientists in the 1970s leveled harsh critiques against traditional economic methods, returning to an old economic paradigm—the scarcity of natural resources—which led to the emergence of two branches of economic science in the debate: Biophysical Theory and Ecological Economics. These branches have interlinked roots, although each has its own connections between the delivery of ecological services and the physical parameters of the natural system (YAN et al., 2019). According to Hall and Klitgaard (2011), the concept of Biophysical Theory depends on recognizing that the material well-being of individuals relies on nature, on what can be extracted from it, and on the difficulty or ease with which this extraction occurs. To elucidate, Hall and Klitgaard (2011) highlight that, during the time when humans did not produce specifically for sale and markets did not, therefore, establish prices, economies operated through exchanges and redistributions. In other words, the economy was based on its material foundation, which is understood as Biophysical Theory.

Ecological economics initially sought to explain the economy in terms of natural resources, focusing on thermodynamics, a concept that overlaps with Biophysical theory, as the founders of these two schools coincide, given their ability to navigate well through the characteristics of both. Yan et al. (2019) state that Biophysical theory and ecological economics served as an "umbrella"for the studies of Frederick Soddy, Fred Cottrell, M. King Hubbert, Nicholas Georgescu-Roegen, Howard T. Odum, Robert U. Ayres, and Charles A.S. Hall. However, recently, ecological economics has begun to distance itself from its roots and has effectively become, in essence, a branch of environmental economics, concerned primarily with assigning monetary values to ecosystem services and natural capital (RØPKE, 2004; HALL; KLITGAARD, 2006; HALL; KLITGAARD, 2018). Hall and Klitgaard (2006) criticize ecological economics, particularly and repeatedly, for excluding energy and energy quality as an independent variable in production functions. Krall and Klitgaard (2011) assess that ecological economics has divided its attention between focusing on the valuation of natural capital and modeling steady-state economies derived from the work of Daly (1996).

Odum (1971) recognized that there are differences in the quality of energy sources and that societies with access to higher-quality energy prevailed over others. Subsequently, following the same line of reasoning as Odum (1971), Georgescu-Roegen (1971), Odum and Odum (1976), Cleveland (1999), and Mayumi (2001) would also highlight that the economic growth provided by the Industrial Revolution was based on the intensive use of fossil fuel stocks and that a potential scarcity of these resources would elucidate the thermodynamic constraints characteristic of non-renewable energy sources.

Regarding the relationship between the economy and the biophysical nature of energy resources, Odum (1971) observed that for every monetary unit circulating in the economy, there is an amount of energy circulating in the opposite direction. However, while money flows in a closed circuit (with very little loss), energy exhibits a unidirectional flow (dissipating as it is used), highlighting the irreversible nature of energy dissipation as posited by the second law of thermodynamics. Court (2016) emphasizes that this flow begins with low-entropy energy (ordered system[6]) extracted from the environment, which is used in production processes and exits the economic system as degraded heat (dissipated energy) of high entropy (disordered system). Similarly, Daly (1985) and Georgescu-Roegen (1971) argue that the circular flow of money is maintained by a physical flow of matter (not just energy) that is not circular but rather linear and unidirectional, and that the economic process is an open system that converts high-quality raw materials (low entropy) into goods and services, dissipating and discarding large amounts of low-quality thermal energy (high entropy), in addition to material waste. Thus, they reaffirm the indispensable character of energy resources for the economy.

Some works have been developed to expand traditional economic models[7] aiming to include energy (or oil, specifically) to assess its importance for economic growth and understand the effect of shocks in oil prices on the economy. In response to Georgescu-Roegen (1971), Solow (1974), Solow (1997), Stiglitz (1974), and Stiglitz (1997), although they do not deny the biophysical constraints imposed on the economy through the use of energy, they minimize its importance. Stiglitz (1997), for instance, argues that although his model considers an infinite horizon and theoretically allows production to tend toward infinity, in practice, it considers a maximum horizon of 50 years. Therefore, as long as the physical limit imposed by the resource extends for a sufficient time, a model that does not consider it is perfectly capable of providing a satisfactory description of economic growth.

From the attempts of theorists linked to traditional economics to incorporate natural resources and sustainable development into their models, two strands emerged: Environmental Economics and Natural Resource Economics. Hall and Klitgaard (2018) state that, in summary, these strands do not overlap with the objectives of biophysical economics, as their goal is to integrate the environment with the economy through the pricing of environmental goods and services. However, they do not add to the analysis the biophysical characteristics of resources, especially when dealing with energy. While natural resource economics focuses on the efficient management of environmental resources and environmental impacts, environmental economics incorporates the analysis of the externalities of economic activity[8].

It is evident, therefore, that biophysical constraints have been repeatedly ignored by traditional economics and, as a result, are not considered limiting enough to compromise the performance of its models in depicting reality (SHERWOOD; CARBAJALES-DALE; HANEY, 2020). However, Hall and Klitgaard (2011, p. 106-107) argue that *"[...] wealth*

---

[6] For clarification regarding the ordering of open thermodynamic systems, see Prigogine and Nicolis (1967).

[7] Such as that of Solow (1956).

[8] Andrade (2008) presents interesting critiques of environmental economics and natural resource economics. However, these critiques fall outside the scope of this research.

that is distributed in markets must be produced in the natural world" and, as part of this "natural world,"production inevitably adheres to the laws of physics, chemistry, and biology.

The critiques of traditional economic models are synthesized into three arguments by Hall et al. (2001): (1) the structure of neoclassical models is unrealistic, as it does not rely on the biophysical world and the laws that govern it, especially thermodynamics; (2) the constraints of the analysis are inadequate, as they disregard the real processes of the biosphere that provide the inputs of raw materials and energy, the sinks for waste, and the medium necessary for the economic process to occur; and (3) the basic assumptions of the models do not translate into testable hypotheses but are treated as given data.

The second critique of traditional models refers to the fact that traditional economic models do not consider the limits that indicate the physical requirements or the effects of economic activities on the environment. Biophysical economics believes that an efficient representation of reality must consider factors that, at a minimum, include the resources necessary for production and the generation of waste by the economy. In other words, it is essential that the economic system operates within a larger system, the biosphere[9] (DALY, 1977; CLEVELAND et al., 1984; DASGUPTA; LEVIN; LUBCHENCO, 2000; HALL et al., 2001).

2.2 Considerations on the Biophysical and Thermodynamic Nature of Economics

Basic models of traditional economic theory describe abstract exchange relationships of goods, services, and money within an unrealistically limited world of firms and households. However, real economies also require materials and energy from the "natural world"to facilitate these exchanges and are constrained by the transformations of materials and energy. Figure 1 represents the circular flow of traditional economics (panel (a)). According to Hall et al. (2001), this view of the economy depicts a self-contained and self-regulating system, independent of the biophysical system and its laws (Figure 1, panel (b)). There are only two sectors, households and firms, with goods and services flowing from firms to households and productive inputs (land, capital, and labor) flowing from households to firms.

Hall and Klitgaard (2011) argue that models such as those depicted in Figure (1, a) pay minimal attention to the first law of thermodynamics and are entirely incompatible with the second law[10].

The first law of thermodynamics, which relates to the concept of energy, states that energy cannot be created or destroyed. Energy, in general, consists of a useful part (exergy) that can be converted into work and another part that is dissipated into the environment.

---

[9] As represented in the flow depicted in Figure (1-b)

[10] There are four laws of thermodynamics, but only the first and second relate to economic processes.

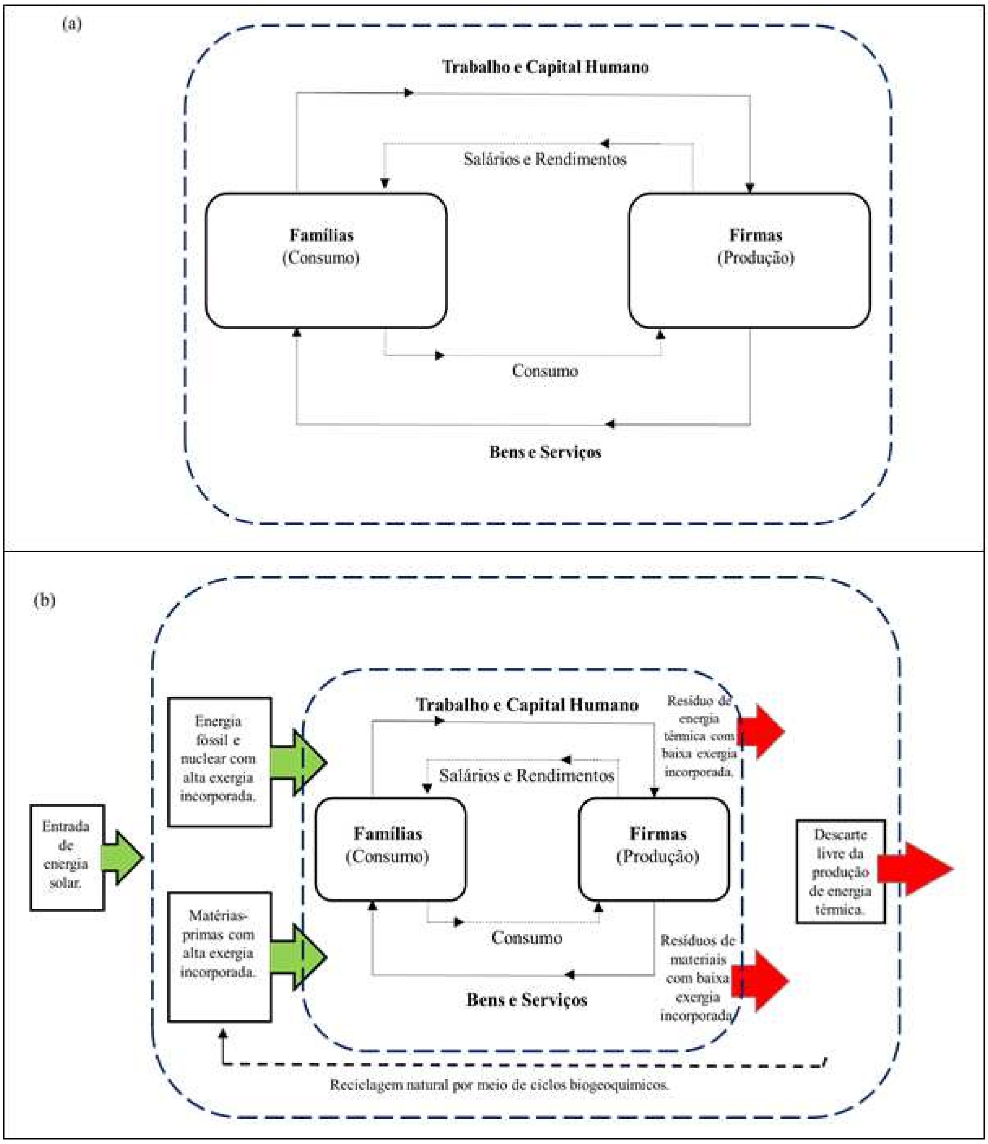


Figura 1: Model of the Circular Flow of the Economy

Note: Adapted from Hall et al. (2001, p.664). The colored arrows in (b) represent the biophysical pathways that are not captured in the conventional economic models of (a).

Kummel, Ayres, and Lindenberger (2010) emphasize that there is no industrial production without work on matter and that, therefore, energy (or, specifically, exergy) is the primary driver of growth in modern economies.

The second law of thermodynamics introduces a concept that will be fundamental for the development of this research, that of *entropy*, which is a physical measure of disorder and can be considered a measure of the quality of energy. Atkins (2010) points out that every process of energy conversion produces entropy. The lower the entropy, the higher the quality of an energy source, and the higher the entropy, the lower the quality.

The two laws of thermodynamics cited highlight that nothing occurs in the physical world without the utilization of exergy and the production of entropy. This demonstrates that any productive process requires the use of energy. The production of entropy implies the transformation of useful energy (exergy) into heat dissipation. During this process, matter can also be dissipated, resulting in pollution and, eventually, resource depletion (HALL et al., 2001).

Some works in the field of sustainability have utilized the concept of entropy applied to the economic system (COMMON; PERRINGS, 1992; SMULDERS, 1995; AYRES, 1999; KRYSIAK, 2006; GARRETT, 2014; GARRETT, 2015). However, these studies are strictly theoretical, as there is no practical indicator to measure entropy and guide discussions. Court (2016) explains that, since entropy is an abstract and difficult-to-understand concept, most empirical research related to the topic employs the concept of *Energy Return on Energy Invested* (EROI), which refers to the need to invest a certain amount of energy to operate the production mechanisms that extract primary energy from nature and transform it into useful energy (exergy).

Murphy and Hall (2010) define EROI as the ratio between the amount of energy produced and the amount of energy invested in the production process of that energy. EROI can also be characterized as an evaluation of energy surplus, energy balance, or net energy analysis. Mathematically, it can be defined as:

$$EROI = \frac{Net\ Energy\ Produced}{\sum Energetic\ Inputs} \tag{1}$$

Net energy can easily be expressed in terms of EROI through Equation (1):

$$\text{Net Energy} = \text{Gross Energy Produced} - \sum \text{Energy Inputs} \tag{2}$$

$$\text{Net Energy} = \text{Gross Energy Produced}\left(1 - \frac{1}{EROI}\right) \tag{3}$$

For the stock or flow of energy to be considered a resource, the amount of net energy extracted must be positive. In this case, the EROI[11] of the energy source will be greater than one. Conversely, cases with EROI less than one indicate that more energy has been invested than has been extracted. In this situation, it is said that the stock or flow is an energy sink.

It is evident, therefore, that the analysis of EROI represents a continuous conflict between the physical depletion of energy resources and technological advancements that can optimize the net benefits of that same energy source. Court (2016) asserts that understanding the future dynamics of net energy in societies is crucial for anticipating their evolution. Hall (2001) further complements this by stating that neoclassical theory, which does not recognize the proper importance of energy, does not efficiently explain the

---

[11] Gross energy extracted divided by energy invested.

phenomenon of economic growth.

2.3 The Role of EROI in Macroeconomic Analysis

The concept of EROI (*Energy Return on Energy Invested*) is frequently used in energy science to establish a relationship between energy resources and economic systems (FAGNART; GERMAIN; PEETERS, 2020). However, it is often overlooked in macroeconomic analyses, as discussed in the previous section. Murphy et al. (2011) highlight a series of benefits arising from the proper use of EROI, as listed below:

- EROI analysis provides a dimensionless value for energy sources, offering a measure that allows comparison with other similar resources. For instance, the EROI of gasoline, which ranges from 10:1 to 20:1, is comparatively higher than that of corn ethanol, which has an EROI below 2:1 (MURPHY; HALL; POWERS, 2011). From this information, one can infer that replacing gasoline with corn ethanol would imply an energy return that is (at least) five times lower;
- The value of EROI provides a useful measure of the quality of a resource[12]. Energy sources with high EROI are of higher quality than those with low EROI. Moreover, it is possible to analyze the evolution of the variable over time: if EROI declines, a larger portion of a nation's total economic activity will be allocated to obtain the energy that will be used in the production of the rest of the economy;
- The analysis of EROI, in conjunction with standard measures of magnitude, provides additional understanding of net energy gains. Murphy and Hall (2010) exemplify this benefit by arguing that Canada's oil sands, for instance, have a resource stock of about 170 billion barrels of crude oil, but the EROI of this resource is approximately 3:1, on average. This indicates that only three-quarters of the total barrels of oil will represent the net energy of this source;
- A temporal analysis of EROI for a specific resource allows for an understanding of how the quality of a resource base is changing over time. Additionally, it provides a means to examine the relative impacts of technology versus depletion. If EROI is decreasing, then depletion is more significant than technological change (MURPHY et al., 2011).

Murphy et al. (2011) assert the prevalent use of two methods for calculating EROI: (i) process analysis or (ii) input-output economic analysis. Process analysis, also known as *bottom-up* analysis (similar to life cycle analysis), accounts for the energy inputs and outputs in a process, aggregating them through sequential production stages. On the other

---

[12] According to Murphy et al. (2011), quality is defined as the capacity of a unit of heat to generate some economic product

hand, input-output analysis (*top-down*) converts economic input-output tables into energy units by multiplying them by sector-specific energy intensity values. These methods imply a static estimate of a resource at a specific point in time.

Dale, Krumdieck, and Bodger (2011a) proposed a dynamic function for annual EROI through a *top-down* structure to determine the EROI of an energy source throughout the entire production cycle of an energy resource. This function, associated with a purely physical allocation function of energy demand among different energy sources, allows for the forecasting of production costs (in energy terms) in the future. This methodology, referred to as GEMBA, also enables an energy supply forecast based solely on physical principles. Thus, the GEMBA method does not explicitly model the behavior of economic agents or market price formation.

On the other hand, Fagnart and Germain (2014) and Court, Jouvet, and Lantz (2018) operationalize the calculation of EROI by considering its definition as the ratio between the net energy delivered by an energy production process and the energy consumed in that process. Accordingly, they calculate EROI by defining the numerator in terms of net energy produced, while the denominator measures the energy content of the capital goods used in energy production. This methodology allows for the derivation of an explicit long-term EROI function at a macroeconomic level, linking EROI metrics to macroeconomic variables (such as the share of capital invested in energy production or the rate of economic growth).

In the approach proposed by Fizaine and Court (2016), the energy invested ($E_{in,i}$) in energy system i corresponds to the amount of money ($M_{in,i}$) invested in the energy sector, multiplied by the average energy intensity (EI_i) of the capital and services installed and utilized in energy sector i. Thus, they represent annual EROI as:

$$EROI_i = \frac{E_{out,i}}{E_{in,i}} = \frac{E_{out,i}}{M_{in,i}EI_i} \tag{4}$$

To estimate the amount of money invested in the sector ($M_{in,i}$), it is assumed that the unit price P_i of a particular type of energy divided by the monetary return on investment ($MROI_i$) of energy sector i serves as an indicator of the annual cost of that energy. Thus, it is possible to estimate the total amount of money invested ($M_{in,i}$) in a specific energy sector by multiplying the quantity of energy produced ($E_{out,i}$) by that sector by the approximate annual cost of that energy:

$$M_{in,i} = \frac{P_i}{MROI_i}E_{out,i} \tag{5}$$

Substituindo a Equação (5) em (4) encontra-se uma nova forma de estimar o EROI em função do retorno monetário do investimento em energia:

By substituting Equation (5) into (4), a new way to estimate the EROI as a function of the monetary return on investment in energy is obtained:

$$EROI_i = \frac{MROI_i}{P_i EI_i} \tag{6}$$

The methodology presented above can be implemented with consistent time series for the following variables: quantities of energy (EJ), energy prices, gross domestic product, and an estimate of the $MROI$ of the energy sector. This approach will be used in the next chapter, which estimates the minimum social EROI required for the economic growth rate to be positive.

2.4 Policy Implications of EROI Assessments

The findings from biophysical economics and EROI analyses have significant implications for policy formulation. Policymakers must consider the energy efficiency and sustainability of energy systems when designing economic policies. The integration of EROI into policy frameworks can guide investments towards energy sources that not only provide adequate returns but also align with sustainability goals (DUPONT et al., 2021).

For instance, policies that incentivize the development of renewable energy technologies with high EROI can facilitate a transition away from fossil fuels, thereby reducing greenhouse gas emissions and promoting environmental sustainability. Moreover, the recognition of EROI as a critical metric in economic assessments can facilitate more informed decision-making regarding energy transitions and climate mitigation strategies (ARNDT et al., 2019).

In addition to economic implications, the integration of EROI into policy frameworks can also enhance social equity. By prioritizing investments in renewable energy technologies that can maintain high EROI values, policymakers can ensure that energy resources are accessible and affordable for all segments of society. This approach can help mitigate energy poverty and promote social equity, particularly in marginalized communities.

Furthermore, the implications of EROI assessments extend to international energy policies. As countries strive to meet international climate commitments, understanding the EROI of different energy systems becomes increasingly important. Policymakers must prioritize investments in renewable energy technologies that can maintain high EROI values and support sustainable economic growth. This approach can facilitate a transition away from fossil fuels and promote the development of renewable energy technologies (CALVIN et al., 2020).

The integration of EROI into policy frameworks can also inform energy security strategies. Countries that prioritize investments in renewable energy technologies with high EROI values may achieve greater energy independence and resilience to external shocks. This is particularly important in the context of geopolitical tensions and fluctuating energy prices, which can threaten economic stability.

Moreover, the recognition of EROI as a critical metric in economic assessments can facilitate more informed decision-making regarding energy transitions and climate mitigation strategies. Policymakers can utilize EROI assessments to evaluate the potential impacts of different energy policies and identify strategies that promote sustainable economic growth while minimizing environmental impacts.

In addition to economic and environmental considerations, the integration of EROI into policy frameworks can also enhance public awareness and engagement. By communicating the importance of EROI in shaping energy policies, policymakers can foster greater public support for renewable energy initiatives and climate action. This increased engagement can create a positive feedback loop that encourages further investments in sustainable energy systems.

2.5 Challenges in Integrating Biophysical and Economic Models

Despite the potential benefits of integrating biophysical and economic models, several challenges persist. Differences in terminologies, methodologies, and disciplinary perspectives can hinder effective collaboration between biophysical scientists and economists (FENG; FENG, 2019). For instance, biophysical models may focus on energy flows and material balances, while economic models often emphasize monetary metrics and market dynamics.

These differences can create barriers to interdisciplinary collaboration, limiting the effectiveness of research efforts aimed at understanding the complex interactions between energy systems and economic processes. To overcome these challenges, it is crucial to foster interdisciplinary collaborations that encourage dialogue and knowledge exchange between researchers from different fields. Such collaborations can lead to the development of innovative methodologies that integrate biophysical and economic assessments (KLING et al., 2017).

Moreover, the current academic merit system often rewards discipline-specific research, which can limit interdisciplinary efforts. Researchers may face challenges in securing funding for collaborative projects that bridge the gap between biophysical and economic research (FENG; FENG, 2019). Addressing these barriers is essential for advancing the field of biophysical economics and enhancing the robustness of macroeconomic models that incorporate energy dynamics.

In addition to disciplinary challenges, the integration of biophysical and economic models also raises methodological concerns. For instance, the selection of appropriate metrics for assessing EROI can vary significantly between disciplines, leading to inconsistencies in research findings. Establishing standardized methodologies for EROI assessments can enhance the comparability of research results and facilitate more effective policy formulation (CROMPTON, 2007).

Furthermore, the complexity of energy systems and their interactions with economic processes can make it challenging to develop comprehensive models that accurately capture these dynamics. Researchers must navigate a range of variables, including technological advancements, regulatory frameworks, and market dynamics, all of which can influence EROI values and economic outcomes. This complexity necessitates a robust modeling approach that can account for these interactions over time (WARD et al., 2018).

Moreover, the integration of biophysical and economic models can also be hindered by data limitations. Access to high-quality data on energy production, consumption, and EROI values can be challenging, particularly in developing countries. Researchers must work to improve data collection and sharing practices to enhance the robustness of EROI assessments and inform policy decisions.

As the field of biophysical economics continues to evolve, future research should focus on refining EROI assessments across diverse energy systems and economic contexts. There is a need for more comprehensive models that account for the qualitative aspects of energy, such as energy quality and its implications for economic productivity (CLEVELAND; O'CONNOR, 2011; HALL, 2004).

Moreover, interdisciplinary collaborations should be fostered to develop innovative methodologies that bridge the gap between ecological and economic research. Such efforts will be crucial for addressing the complex challenges posed by climate change and resource scarcity in the coming decades. By integrating insights from various disciplines, researchers can develop more holistic approaches to understanding the interactions between energy systems and economic processes.

Additionally, the use of advanced technologies and methodologies can facilitate improved data collection. Brown et al. (2016) highlights that agent-based modeling approaches can effectively incorporate biophysical, economic, and social processes, allowing for a more comprehensive understanding of system dynamics. Such methodologies can help bridge data gaps by simulating various scenarios and providing insights into the potential impacts of different policy decisions. In this sense, the following chapter explores the relationship between energy expenditure and economic growth, presenting a calculation of the minimum EROI required for nations to achieve positive economic growth.

3 The role of Electricity Expenditure on Economic Growth and the Minimum Societal EROI

Abstract

This paper investigates the impact of electricity expenditure on economic growth for a sample of 19 countries over the period 1991-2021 and estimate the minimum societal EROI. The paper employs heterogeneous panel cointegration techniques that take into consideration the impact of cross-section dependence. The analysis reveals some important findings. Firstly, that periods of high electricity expenditure relative to GDP are associated with low economic growth rates, and periods of low or falling expenditure expenditure are associated with high and rising economic growth rates. Secondly, statistically, in order to present positive growth, the economies cannot afford to spend more than 3.95% of its GDP on electricity. Thirdly, given the current electricity intensity of the countries, this translates in a minimum societal EROI of approximately 30:1. Besides, Granger tests consistently reveal a one way causality running from the level of electricity expenditure (as a fraction of GDP) to economic growth in the sample between 1991 and 2021. An effective economic policy should consider the improving net energy efficiency. This would contemplate a double goal: increased societal EROI (through decreased energy intensity of capital investment), and decreased sensitivity to energy price volatility.

Keywords: Economic Growth; Electricity Expenditure; Minimum EROI.

3.1 Introduction

Questions revolving economic growth and the problems caused to the environment, as well as the natural resources used in the production process, have been the subject of research among economists for decades. Especially after the oil crises in the 1970s, Energy Economics gained prominence in academic research due to the severe environmental and climate impacts caused, in large part, by the indiscriminate use of fossil fuels.

The transition to renewable energy sources has become imperative, since it can represent a viable alternative to alleviate the pressure on fossil fuel stocks, in addition to satisfying the necessary conditions to contain global warming by reducing greenhouse gases emissions (PANWAR et al., 2013). The rise of renewable sources allowed for a reduction in the generation of electricity from fossil sources. The year of 2020 showed a record in the world supply of photovoltaic and wind energy (increasing of 12% and 23%, respectively), while the use of coal was reduced by 4.4%, the biggest decline in absolute values of all time.

The United States and the European Union were the main responsible for this decrease (IEA, 2021b). In addition, IEA (2021b) highlights the uninterrupted annual drop in the global supply of electricity from oil since 2012, with a reduction of 4% observed in 2020 alone. In absolute terms, however, due to the new Coronavirus pandemic, the world's energy supply suffered a drop during the lockdown (IEA. International Energy Agency, 2021a).

Although the rising prominence in recent years, renewable energy sources still account for only 29% of the world's electricity generation matrix [13]. In the United States, for instance, the share of renewables in the mix of electricity generation is 20% (EIA 2021), an even lower percentage than the world's average - the same situation ocoured in China, with 26% (IEA, 2020a). In the European Union, the proportion of renewables was 40.2% in 2020 (IEA, 2020b). In Brazil, the electricity matrix is predominantly composed of renewable sources, representing almost 85% of the total produced (EPE, 2021), with hydraulic generation alone producing 65.2% of the total.

The use/generation of energy is one of the most discussed topics in the main discussions on the implementation of world policies (Kyoto Protocol, Paris Agreement, Europe 2020 Strategy, among others) that discuss the reduction in the use of non-renewable energies in order to reduce polluting emissions. The European Union, for example, has set a target of 27% of energy consumption from renewable sources by 2030 for its members (European Commission, 2014). China has adopted a target to increase non-fossil energy use to 20% by 2030 (CHINA, 2015). The United States has set itself an even more ambitious goal, of achieving 100% carbon-free electricity by 2035 (USA, 2021). Brazil, on the other hand, wants to maintain the position of the most renewable energy matrix in the world and, for that, intends to triple the global supply of zero and/or low carbon energy by 2050 (BRASIL, 2016).

In Germany, the energy transition is being carried out additionally with changes in the technological, economic and political structure (BOSCH; SCHMIDT, 2020). The introduction of the Renewable Energy Sources Law in 2000 stands as a forerunner in this process, forcing grid operators to purchase renewable electricity and guaranteeing renewable energy plant operators rates above market price for a period of twenty years (STRUNZ, 2014; KUNGL, 2015). This measure made Germany one of the most audacious countries in terms of energy transition, despite the economic effects it may cause in the short and long term (QUITZOW; ROEHRKASTEN; JÄNICKE, 2016; ANDOR; FRONDEL; SOMMER, 2018).

Energy expenditures also play a crucial role in a nation's economic growth, as the availability and cost of energy directly affect the productivity and efficiency of economic sectors. Murphy and Hall (2011) emphasize that in cases where countries experience an increase in energy expenditures, a compensatory movement by agents occurs, resulting

---

[13] 2020 data presented in IEA 2021a

in a reduction in the allocation of funds to other sectors that contribute to GDP. This reduction aims to cover the rise in energy expenses. Furthermore, they demonstrate that between 1970 and 2007, the economy of the United States of America (USA) encountered recessionary periods whenever expenditures on oil exceeded 5.5% of its GDP. Similarly, Lambert et al. (2014) suggest that in the US, once energy expenditure rises above 10% of GDP, recessions follow.

Applying a slightly different approach, Bashmakov (2007) identifies energy cost to GDP thresholds of 8–10% for the US and 9–11% for the OECD. Once these limits are surpassed, the economy enters periods of slowdown, and the demand for energy decreases until the energy cost in relation to GDP/consumer income falls back below its limits. Bashmakov (2007) states that until the share of energy expenditure reaches its upper critical limit, all other factors of production determine economic growth rates, and energy does not play a "limit to growth"role. "However, when energy costs relative to GDP exceed the threshold, it negates the impact of factors contributing to economic growth and slows it down, so that potential economic growth is not realized."

King, Maxwell, and Donavan (2015) calculated energy expenditures as a ratio of GDP for the period 1978-2010 for 44 countries, representing 93-95% of the Gross World Product (GWP) during that period. The authors found that the estimated energy cost as a ratio of GWP decreased from a peak of 10.3% in 1979 to 3.0% in 1998 before rising to 8.1% in 2008. Using the previous data, (2015), conducted a simple econometric regressions and concluded that energy expenditure expressed as a ratio of GDP is significantly correlated with lagged variables of GDP and total factor productivity, but not with contemporaneous variables.

Fizaine and Court (2016) share objectives similar to those proposed in the present paper. In their study, Fizaine and Court (2016) estimated energy expenditures as a fraction of GDP for the US, the world (1850–2012), and the UK (1300–2008). Their findings imply that the US economy cannot allocate more than 11% of its GDP to energy expenditures to maintain a positive growth rate. Furthermore, their research indicates that sustained US growth requires a primary energy system with a minimum EROI of approximately 11:1. Moreover, the application of Granger tests revealed a one-way causality running from the level of energy expenditure (as a fraction of GDP) to economic growth in the US between 1960 and 2010.

Furthermore, access to abundant and affordable energy sources is critical to boosting productivity, facilitating transportation, providing electricity for homes and industry, and fueling technological progress. Although, despite the importance and the topicality of the matter, few studies have given importance to the volume of expenditure in energy and to the biophysical nature of energy sources. This relationship between economics and biophysical characteristics is part of the so-called Biophysical Economics, which has aroused greater interest in the energy sciences than in economics itself (COURT; FIZAINE, 2017).

Biophysical economics is an interdisciplinary approach that combines concepts from both economics and physics to understand and analyze the interaction between the human economy and ecological systems. One of the key metrics used in the biophysical economy is the EROI (Energy Return on Investment), which measures the amount of energy obtained from a given source in relation to the amount of energy needed to get that source. The EROI is an important tool to assess the sustainability and energy efficiency of different economic activities. Studies in the area of biophysical economics have shown that the EROI of many energy resources, such as oil and natural gas, has decreased over time, which can have significant implications for economic growth, since the availability of cheap and abundant energy has historically been an engine for economic growth (CLEVELAND et al., 1984; HALL; BALOGH; MURPHY, 2009).

In order to shed more light on the subject and incorporate more ideas into the economic literature, this research aim to investigate the relationship between energy expenditure and economic growth. Once we estimate the statistics, it is possible to calculate the minimum EROI that must prevail in the economy for economic growth to be positive. To achieve these objectives, the energy-GDP ratio was analyzed using a heterogeneous panel cointegration method followed by a Granger causality test, which allowed for the identification of the causal relationship's direction between expenditure on electricity (both renewable and fossil) and GDP growth. The results are used to calculate the minimum EROI at which the economy presents positive growth rate.

An empirical strategy for the investigation of the relation between electricity expenditure and economic growth along with the approach to calculate the minimum EROI for the growth rate to be positive follows in the next section. In the third section, the results are shown and discussed. The fouth section outlines the main conclusions of this study in brief.

3.2 Methodology

3.2.1 Model Development

The economic growth approach from which the regression equation will be originated is an adaptation of Barro and Sala-iMartin (2004) and Acemoglu (2010), in which economic growth occurs only if the productive inputs also present growth. Thus, the economic growth rate can be decomposed as the growth rates of inputs weighted by the relative contributions of each of the factors on growth. The estimated equation will take the form as follows:

$$\frac{\dot{GDP}}{GDP}_{it} = \alpha_i + \delta_i t + \beta_1 \left(\frac{E_{tot}}{GDP}\right)_{it} + \beta_2 \left(\frac{F}{GDP}\right)_{it} + \beta_3 Unemp_{it} + \epsilon_{it} \quad (7)$$

where the subscripts i $(= 1, ..., N)$ e t $(= 1, ..., T)$ represent the countries and years of the sample, respectively, $\frac{\dot{GDP}}{GDP}$ is the economic growth rate, α_i represents country-specific fixed effects, $\delta_i t$ denotes the heterogeneous deterministic trend of countries, β_1 represents the sensitivity of economic growth to the level of energy expenditure (as a proportion of *GDP*). It is assumed that β_1 is negative, since the higher the expenditure on energy (E), the lower the amount allocated to consumption and investment that drives growth. β_2 represents the sensitivity of *GDP* growth to gross capital formation (F) and β_3 is the sensitivity of growth to changes in the unemployment rate.

3.2.2 Cross-Sectional Dependence and Panel Unit Root Tests

In order to investigate cointegration and/or causality relationships, especially when dealing with panel data, it is essential to consider the possibility of cross-sectional dependence before estimating any model. The dependence between cross-sections can be caused by various reasons, among them we can highlight commercial, financial, and geographic interactions between countries.

Once neglected the cross-dependency it is breaking a key assumption of first-generation unit root and cointegration tests[14], as they are characterized by the hypothesis of transversal independence. Such a condition does not seem to be realistic, since the economies studied have strong links between them and, therefore, it is likely that the independence hypothesis will be violated, for example, due to common shocks in oil prices, solar radiation and rainfall in geographically close countries.

To test the hypothesis of cross-sectional independence, it is common to use the Breusch and Pagan (1980) test, known as the "LM Test". However, Pesaran (2021) argue that the *LM* test is only feasible for panels with few cross-section units (N) and a relatively large period (T). To work around this limitation, Pesaran (2021) proposed a standardized LM test, which can be applied to panels with large N and T. The test statistic is given by the Equation 8.

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left(T \hat{\rho}_{ij}\right), \tag{8}$$

in which "$\hat{\rho}_{ij-1}$"indicates the correlation coefficient between residuals for pairs of observations from an OLS regression. The cross-sectional dependency test tests the null and alternative hypotheses as follows:

H_0: There is no cross-sectional dependency $(Cov(\mu_{it}, \mu_{jt} = 0) \; \forall \; t \; e \; i \neq j)$

H_1: There is cross-sectional dependency $(Cov(\mu_{it}, \mu_{jt} \; \neq \; 0) \; \forall \; t \; e \; i \neq j)$

---

[14] Ex.: Levin, Lin e Chu (2002), Im, Pesaran e Shin (2003)

Usually, common shocks between different countries are important sources of cross-sectional dependence because they generate a mistaken degree of correlation between economies (EBERHARDT; BOND, 2009; LIDDLE; LUNG, 2013; MAO; SHEN, 2019; CHENG; YAO, 2021). In the same way that heterogeneity affects correlation coefficients, it can also influence the impact of independent variables on the dependent variable across different countries. Thus, in the presence of cross-sectional dependence, when estimating homogeneous slope models, the results tend to be biased (SADORSKY, 2014; MA, 2015; LV; XU, 2018). To assess the existence of heterogeneous slope, the Pesaran and Yamagata (2008) test is applied, which is robust for cross-sectional dependence and for panels with large N and T (MUSAH et al., 2020; LI et al., 2021; MURSHED, 2021).

The Pesaran and Yamagata (2008) test involves estimating two estimates that are used to determine whether the slopes of the coefficients are homogeneously or heterogeneously distributed across the cross-sectional units. The Equations 9 and 10 present the test statistics.

$$\Delta = N^{\frac{1}{2}} (2k)^{\frac{-1}{2}} \left(\frac{1}{N} \tilde{S} - k \right) \tag{9}$$

$$\Delta^{adj} = N^{\frac{1}{2}} \left(\frac{2k(t-k-1)}{T+1} \right)^{\frac{1}{N}} \left(\frac{1}{N} \tilde{S} - 2k \right) \tag{10}$$

where Δ and Δ^{adj} are the test statistics. Homogeneous slopes are considered as the null hypothesis and tested against heterogeneous slopes, which is the alternative hypothesis.

Once the existence of cross-sectional dependence and heterogeneous slopes is proven, the first generation unit root tests[15] are not valid (CAVALCANTI; MOHADDES; RAISSI, 2011; DONG et al., 2018; USMAN et al., 2020). To address this shortcoming, Pesaran (2007) and Moon and Perron (2012) have proposed a new panel unit root test approach, known as second-generation test, which is robust to cross-dependency. However, it cannot handle panels containing structural breaks, producing inaccurate (CHEN et al., 2021) results. Thus, we chose to use the test proposed by Bai and Carrion-i-Silvestre (2009), which is robust for both cross-sectional dependence and structural breaks.

The Bai and Carrion-i-Silvestre (2009) unit root test was carried out through modifications in the procedure *PANIC* by Bai and Ng (2004), aiming to obtain a robust decomposition into common and idiosyncratic components in the presence of structural breaks. An iterative estimation procedure, suitable for dealing with heterogeneous breaks in deterministic components, was developed . When carrying out this procedure, they arrived at three statistics to analyze the existence (or not) of a unit root, Z^*, P_m and P.

---

[15] As examples, the tests of Levin, Lin and Chu (2002), Im, Pesaran, and Shin (2003), Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP).

The Equations 11, 12 and 13 present the test statistics.

$$Z = \sqrt{N}\frac{M\bar{SB}(\lambda) - \bar{\xi}}{\bar{\zeta}} \sim N(0,1) \tag{11}$$

$$P_m = \frac{-2\sum_{i=1}^{N} lnp_i - 2N}{\sqrt{4N}} \sim N(0,1) \tag{12}$$

$$P_m = -2\sum_{i=1}^{N} lnp_i \sim \chi^2_{2N} \tag{13}$$

The Z and P_m statistics follow the standard normal distribution, while the P statistic follows the Chi-square distribution. The term $MSB(\lambda)$ efers to the Modified Sargan Bhargava test statistic (*MSB*) [16] weighted, and $p_i$is the $p-value$. Bai and Carrion-i-Silvestre (2009) claim that the statistics P_m and P perform better with a finite sample compared to the test Z which suffers from problems of slight size distortion. The null hypothesis of a unit root is tested against the alternative hypothesis of no unit root.

3.2.3 Panel Cointegration Test

If, in a panel data, a non-stationary pattern is found, the analysis of the relationships between the variables through the estimation of Ordinary Least Squares (OLS) may be biased. Alternatively, cointegration analysis can be used to solve this problem. If the linear combination of integrated variables is stationary (no unit root present), then there must be a relationship between any two variables (cointegration) (JIN, 2022). Thus, running the cointegration test is the first step to analyzing relationships between variables in non-stationary panels. Based on the results of the cointegration test, the impact of energy expenditure on economic growth starts to be investigated. This analysis, therefore, will make it possible to verify whether energy expenditures and GDP share similar trajectories throughout the studied period of time, that is, to verify whether there is a long-term association between the variables.

In order to test panel cointegration accounting for cross-sectional dependency and structural breaks, the Westerlund and Edgerton (2008) and Banerjee and Carrion-i-Silvestre (2015) tests can be used. However, the second one is considered more restrictive than its predecessor (BANERJEE; SILVESTRE, 2015; YAO et al., 2019). Thus, to analyze the cointegration between the variables, the Westerlund and Edgerton test (2008) will be estimated, which is flexible enough to allow for the existence of heteroscedastic and serially correlated errors, country-specific trends, cross-sectional dependence and structural breaks in the intercept (level) or inclination (regime). Furthermore, Hamit-Haggar (2016) argue that the test distribution is normal and free of noise parameters under the null hypothesis.

---

[16] The statistic can be found in Stock (1999).

Westerlund and Edgerton's test is based on Lagrange Multiplier (LM) unit root testing approaches such as those developed by Schmidt and Phillips (1992), Ahn (1993) and Amsler and Lee (1995). This cointegration method samples via the LM approach with bootstrap and builds two statistics. By not rejecting the null hypothesis, the existence of long-term cointegration between the variables is implied. The test statistics reported by this test are provided by:

$$LM_{\phi} = \frac{1}{N}\sum_{i=1}^{N} T\tilde{\phi}_i \frac{\tilde{\omega}_i}{\tilde{\sigma}_i} \tag{14}$$

$$LM_{\phi} = \frac{1}{N}\sum_{i=1}^{N} \frac{\tilde{\phi}_i}{s.e.(\tilde{\phi}_i)} \tag{15}$$

These statistics can be estimated considering structural breaks in the form of level and regime changes.(SHAHZAD et al., 2021).

3.2.4 Long-run Estimators

After confirming the long-term equilibrium relationships between the variables through the cointegration test, long-term estimates will be carried out. The panel cointegration equation can be estimated using the Fully Modified OLS (FMOLS) estimator, proposed by Pedroni (2001), and Dynamic OLS (DOLS), presented in Mark and Sul (2003). However, the existence of cross-sectional dependence makes these estimators biased, even though they are capable of correcting serial correlation and endogeneity. Therefore, two Mean Group (MG) estimators will be used: the common correlated effects mean group estimator (CCEMG) and the augmented mean group estimator (AMG).

The CCEMG estimator, proposed by Pesaran (2006), has a common factor structure and follows a process as expressed in the Equation.

$$y_{it} = \alpha_i + \beta_i X_{it} + \delta_{1i}\bar{y}_{it} + \delta_{2i}\bar{X}_{it} + \xi_i F_t + \epsilon_{it} \tag{16}$$

$$\bar{y}_{it} = \frac{1}{N}\sum_{i=1}^{B} y_{it}$$

$$\bar{X}_{it} = \frac{1}{N}\sum_{i=1}^{B} X_{it}$$

where α_i, y and X denote the unobserved heterogeneity, the dependent variable (GDP growth rate) and a vector of independent variables, respectively. In the case of this research, vector X will be composed of the variables of growth rate of gross fixed capital formation and growth rate of energy expenditures (renewable and non-renewable). Linear combinations of common factors are approximated using the cross-means of y and X, which are added to Equation 18 as $\bar{y}_{it}$ and $\bar{X}_{it}$. F_t represents the common factor to all cross sections and ξ_i shows the factor loadings for each section. The coefficient β_i is estimated by Generalized Least Squares (GLS) applied to Equation 18. The CCEMG estimator will be:

$$\beta_{CCEMG} = \frac{1}{N}\sum_{i=1}^{N}\hat{B}_i \tag{17}$$

The second long-term estimator, augmented mean group (AMG), introduced by Eberhardt and Bond (2009), is also robust to cross-section dependence, heterogeneous slope, and structural breaks. While the CCEMG estimator addresses serial correlation and endogeneity with a process of cross-meaning, the AMG estimator uses a time variable *dummy* in a dynamic function estimated in two steps as follows:

$$\Delta y_{it} = \alpha_i + \beta_i \Delta x_{it} + \sum_{t=2}^{T}\delta_i D_t + \xi_i F_t + \epsilon_{it} \tag{18}$$

Δ and D_t represent the first-order difference operator and the *dummy* time variable, respectively. As in the CCEMG estimation, the AMG estimator can be obtained by averaging each coefficient of a cross section:

$$\beta_{AMG} = \frac{1}{N}\sum_{i=1}^{N}\hat{\beta}_i$$

Even though the two long-term estimators deal with serial correlation and cross-sectional dependence, the AMG estimator performs better than the CCEMG estimator when used on macroeconomic data (cross-country especially) (EBERHARDT, 2012; WANG; DONG, 2019; JIN, 2022). For this reason, the analysis preference is for the AMG estimators, even though the CCEMG estimators are estimated for comparison purposes.

3.2.5 Maximum tolerable level of electricity expenditure

Just like in Fizaine e Court (2016), we calculate the particular value of electricity expenditure (as a fraction of GDP) that leads to zero economic growth. In other words, from Equation 7, we define the maximum level of energy expenditure (as a fraction of GDP) above which positive economic growth is impossible. We also call β_{total} this maximum level of energy expenditure, with:

$$\beta_{total} = \frac{E_{tot}}{GDP} = \frac{-\alpha_i - \beta_2\left(\frac{F}{GDP}\right) - \beta_3 Unemp}{\beta 1} \tag{19}$$

3.2.6 Minumum EROI required for a positive growth rate

The EROI is the ratio between the amount of energy supplied by a given process and the amount of energy consumed in that same process. Thus, the EROI is a measure of the accessibility of a resource, which means that the higher the EROI, the greater the amount of net energy delivered to society to support economic growth (HALL; LAMBERT; BALOGH, 2014; FIZAINE; COURT, 2016). This definition is rather vague and that a clear distinction should be made between yearly power return ratios" (PRRs) of annual energy flow and "energy return rates" of full life cycle energy systems that which represent EROI more formally (KING; MAXWELL; DONOVAN, 2015).

King and Hall (2011) proposed an estimate of the yearly or "instantaneous" EROI of a given economy. It can be expressed as a function of the quantity-weighted average price of aggregated marketed energy, Paverage, the average monetary-return-on-investment (MROI) of the energy sector, the gross domestic product (GDP), and the total supply of marketed energy:

$$EROI = \frac{MROI}{P_{average\frac{E_{totalmarketed}}{GDP}}} \tag{20}$$

where $P_{average}$ can be calculated as

$$P_{average} = \frac{\beta_{total}}{\frac{Etotalmarketed}{GDP}}, \tag{21}$$

substituting Equation (21) in Equation (20), we have:

$$EROI = \frac{MROI}{\beta_{total}}. \tag{22}$$

3.2.7 Panel Long-run Granger Causality

Once a cointegration relationship between the variables is identified, then at least one direction of causality in the Granger sense must exist. The Granger Causality approach developed by Holtz-Eakin, Newey and Rosen (1988) and applied, among others, by Liddle and Lung (2013) and Nasreen, Mbarek and Atiq-ur-Rehman (2020) will be applied to verify the direction of long-term causality between energy expenditure and GDP variables.

The choice of this particular method is due to the fact that, notwithstanding the original Granger causality test, it allows for a high degree of heterogeneity in long-term relationships. In non-stationary and cointegrated panels, the test can be performed in the form of a two-step error correction model (ECM). In the first stage of the test, the cointegration equations are estimated and the regression residuals are recovered, which will be used in the second stage of the test.

Initially, the estimations of the cointegration are performed and the residuals

"(ϵ_{it}"and "η_{it})"are saved, which will serve as an error correction term (ECT):

$$y_{it} = \alpha_i + \beta_i X_{it} + \epsilon_{it} \tag{23}$$

$$X_{it} = \alpha_i + \beta_i y_{it} + \eta_{it} \tag{24}$$

The second step in building the Granger causality model with an error correction term is to incorporate the residuals from the first step into a VECM panel as follows:

$$\Delta y_{it} = \beta_0 i + \sum_p \beta_{1ip} \Delta y_{it-p} + \sum_p \beta_{2ip} \Delta X_{it-p} + \beta_3 \epsilon_{it-1} + u_{it}, \tag{25}$$

$$\Delta X_{it} = \beta_0 i + \sum_p \beta_{1ip} \Delta X_{it-p} + \sum_p \beta_{2ip} \Delta y_{it-p} + \beta_3 \eta_{it-1} + u_{it}, \tag{26}$$

Differentiated variables show short-term causality, while the values of ECTs (ϵ_{it-1} and η_{it-1}) show long-term causal relationship. The short-term causal association is calculated by the F statistic. However, the long-term causal association is calculated by the significance of the test t of the lagged ECT (LIDDLE; LUNG, 2013; NASREEN; MBAREK; REHMAN, 2020).

3.2.8 Data Sources and Descriptive Statistics

This study considered total electricity expenditure (EE), gross fixed capital formation (GFCF), unemployment and economic growth in terms of GDP. The data were collected through the World Bank, the Statistical Office of the European Union (Eurostat), the database of the Brazilian Institute of Applied Economic Research (IPEAData) and the U.S. Energy Information Administration (EIA). Table (1) presents the descriptive statistics of the variables and the respective data sources.

The sample consists of 19 countries and 31 years (1991-2021). The choice of countries was due to the availability of sufficient time series data for the price of electricity to carry out the estimates. The analyzed countries are: Belgium, Brazil, Denmark, Germany, Ireland, Greece, Spain, France, Italy, Luxembourg, Hungary, Malta, Netherlands, Portugal, Slovenia, Finland, Norway, United Kingdom and United States.

3.3 Results and discussion

Table 2 presents the results of the Pesaran test (2021), which indicate that the null hypothesis of cross-sectional independence in the panel data is rejected at a significance level of 1%. Liddle and Lung (2013) justify the the cross section dependence on variables such as GDP and energy due to macroeconomic links such as global crises, shared institutions (World Bank, IMF, WTO, etc.) and local indirect effects. Thus, when it is verified that the

Tabela 1: Descriptive Statistics

Variable	Mean	S.D.	Min	Max	Data Source
GDP	0.045091	0.09803	-0.3057	0.4644	World Bank. Eurostats;
EE	0.028815	0.01581	0.0102	0.2802	IPEAData; EIA.
$GFCF$	0.219197	0.03941	0.1189	0.5470	World Bank.
$Unemployment$	0.080487	0.04191	0.01480	0.2747	World Bank.

Source: Research data.

panel regression errors are transversally correlated, the estimatives produced by traditional models are inconsistent and would imply incorrect inferences (KAPETANIOS; PESARAN; YAMAGATA, 2011).

Tabela 2: Cross-section dependence test

Variable	Pesaran (2021) test	p-value	Abs. Correlation
GDP	$51,709^{***}$	$0,000$	$0,71$
EE	28.174^{***}	$0,000$	0.45
$GFCF$	12.732^{***}	$0,000$	0.35
$Unemployment$	13.251^{***}	$0,000$	0.40

Source: Research data.
Note: *, ** and *** significant at 10%, 5% e 1% respectively.

To check possible differences in the slopes of the estimated coefficients, the Pesaran and Yamagata test (2008) was applied. The results are displayed in the Table 3.

Tabela 3: Homogeneous Slope test

Variable	Pesaran and Yamagata (2008) Test	p-value
$\tilde{\Delta}$	2.574^{***}	0.001
$\tilde{\Delta}_{adj}$	2.810^{***}	0.005

Source: Research data.
Note: *, ** and *** significant at 10%, 5% e 1% respectively.

Table 3 suggests that both statistics ($\tilde{\Delta}$ and $\tilde{\Delta}_{abs}$) reject the null hypothesis of homogeneity of the coefficients at 1% of significance. Therefore, both the cross-sectional dependence and the homogeneous coefficients must be taken into account to avoid biased estimations.

To verify the existence of a unit root in the series, the test proposed by Bai and Carrion-i-Silvestre (2009) was performed. This approach take into account, in addition to the cross-sectional dependence and heterogeneity of the coefficients, the issues caused by structural breaks. Table 4 presents the results.

Tabela 4: Unit Root Test

	Variable							
	GDP	EE	$GFCF$	$Unemp$	$\Delta\ GDP$	$\Delta\ EE$	$\Delta\ GFCF$	$\Delta\ Unemp$
Z	-3.22^{***}	-0.46	1.00^{*}	12.43^{***}	-4.00^{***}	-3.59^{***}	-3.48^{***}	-3.39^{***}
P_m	6.98^{***}	-1.54^{**}	0.08	-1.11^{*}	21.04^{***}	14.80^{***}	16.45^{***}	14.22^{***}
P	98.81^{***}	24.62	38.68^{*}	28.30	214.50^{***}	161.54^{***}	175.61^{***}	156.67^{***}

Source: Research data.
Note: *, ** and *** significant at 10%, 5% e 1% respectively.

Considering a confidence level of 1%, the results of the Bai and Carrion-i-Silvestre (2009) test fail to reject the null hypothesis of a unit root in the level data for most of the variables. However, when performing the test on first-order differentiation, the result does not allow rejecting the alternative hypothesis of stationary or non unit root for all variables in the presence of cross-sectional dependence and structural break. Such results allow inferring that the variables are stationary in first difference or integrated of order I(1).

After the cross-sectional dependence and unit-root tests, the Westerlund and Edgerton (2008) test was performed to verify the existence of a long-term cointegration relationship between the variables, since the finding of cross-sectional dependence and structural breaks makes the estimates of the standard cointegration tests (such as Pedroni's (2004)) biased. The results are arranged in the Table **??**.

Tabela 5: Panel Cointegration

	$Z_\tau(N)$		$Z_\phi(N)$	
	test	p-value	test	p-value
No Break	-5.73^{***}	(0.00)	-8.79^{***}	(0.00)
Mean Shift	-3.95^{***}	(0.00)	-5.63^{***}	(0.00)
Regime Shift	-3.79^{***}	(0.00)	-5.33^{***}	(0.00)

Source: Research data.
Note: *, ** and *** significant at 10%, 5% e 1% respectively.

The cointegration test results of Table ?? imply the rejection of the null hypothesis of non-cointegration in all test specifications, especially in which there is a regime change. Thus, it is confirmed that the variables are cointegrated in the presence of cross-sectional dependence, heterogeneity of coefficients and structural breaks.

Long-term coefficients were conducted by the AMG[17] and CCEMG[18] approches and its results are are reported in Table 6. The CCEMG approach account for the presence of unobserved common factors and the heterogeneity of the factors is captured by country-specific parameters. On the other hand, the AMG estimator include a common factor variable, with which accounts for cross-dependence ((EBERHARDT; BOND, 2009)). This common factor is constructed through time dummy coefficients of a pooled regression transformed in first differences ((EBERHARDT; BOND, 2009)) to correct nonstationarity problems.

Tabela 6: Results of panel regressions of economic growth on energy expenditure, capital formation, and unemployment rate between 1991 and 2021

Variáveis	AMG		CCEMG	
	Coefficient	p-value	Coefficient	p-value
Constant	-0.150185^{**}	0.031	-0.97620	0.612
EE	-0.22099^{***}	0.000	-0.29092^{***}	0.000
GDCF	0.72098^{***}	0.000	0.65335^{***}	$0,000$
Unemployment	0.01103^{**}	0.023	0.00400	0.395
CDP	1.02022^{***}	0.000		
RMSE	0.0539		0.0456	
Wald test	518.96	0.000	227.97	0.000

Source: Research data.
Note: *, ** and *** significant at 10%, 5% e 1% respectively.

The results of Table (6) demonstrate that, considering the estimation by CCEMG, both electricity expenditure and the level of unemployment are not statistically significant. However, as discussed in section (3.2), the AMG model is preferred over the CCEMG, since the former performs better than the latter when used in macroeconomic variables.

From the estimates by AMG, we found a statistically significant (at 1% confidence level) decreasing relation between the economic growth and the level of electricity expenditure as a fraction of GDP between 1991 and 2021. Therefore, an increase of one percentage point electricity expenditure is statistically correlated to a 0.22 decline in economic growth.

Capital formation is also significant at 1% level. The coefficient estimated implies

---

[17] Introduced by Eberhardt and Bond (2009).

[18] Proposed by Pesaran (2006).

that at each point of increase in capital formation as a fraction of GDP economic growth rise by 0.79 percentage point. Similarly, unemployment rate is positively correlated with economic growth, which is surprising hence theory tell us otherwise. Such a result was also found by Fizaine e Court (2016) (PRECISA MELHORAR EXPLICAÇÃO!).

In order to calculate the maximum level of electricity expenditure as a fraction of GDP such that we keep a positive economic growth, we used the estimates presented in Table (6), according to the AMG method, applied to Equation (19). Replacing parameters α, θ_1, θ_2 and θ_3 by the estimated coefficients (-0.150185, 0.22, 0.72, and 0.011, respectively) and the mean values of gross capital formation (0.22), electricity expenditure (0.029), and unemployment (0.08), we were able to find the central value of the maximum level of total electricity expenditure for which economic growth is positive:

$$\beta_{elec} = \frac{0.150185 - 0.72098 \times 0.219197 - 0.01103 \times 0.080487}{-0.22099} = 0.0395467 \tag{27}$$

This result implies that, in the sample countries, if the fraction of electricity expenditure is superior than 3.95% of GDP, economic growth is statistically lower than or equal to zero. Fizaine e Court (2016) delimited a range from 9% to 13% for the aggregated energy expenditure for the USA.

The Appendix (3.4) shows the average of electricity expenditure by country. We noticed that some nations are close to the calculated limit. Among them, Brazil, Belgium, Germany, Portugal and Slovenia stand out. Two countries, however, already operate above the calculated limit, Finland and Norway.

Following the approach of Fizaine e Court (2016), the monetary-return-on-investment was calculated using the electricity production costs provided by the survey-923 published by EIA (2022) and the average electricity price verified in the sample countries. The average cost to produce one KWh of electricity, according to EIA data for the year 2021 was US$ 0.1476, while the average price verified in the sample countries was US$ 0.174. In this way, the calculated MROI is 1.1788, which means that on average the gross margin of the electricity sector has been about 17.9%. Using this average value of 1.1788 for the MROI, and the value of 0.0395 calculated for β, we estimate an $EROI_{min}$ of 30:1 in order to keep a positive rate of economic growth. Figure (2) presents values of EROI for some energy sources in the literature.

There are only a few researches that deal with the calculation of the minimum societal EROI (to use Hall et al. (2009) nomenclature). Hall et al. (2009) defend that the main energy sources would need to present an EROI of around 5:1 to maintain “everything we call civilization”, but this number is not the result of a calculation, but an assumption. Court and Fizaine e Court (2016) estimate the minimum EROI needed to maintain economic growth positive at a range from 8:1 to 13.5:1. In a more recent study, the estimated minimum EROI by Dupont, Germain and Jeanmart (2021) leads to a 9.4:1 value.

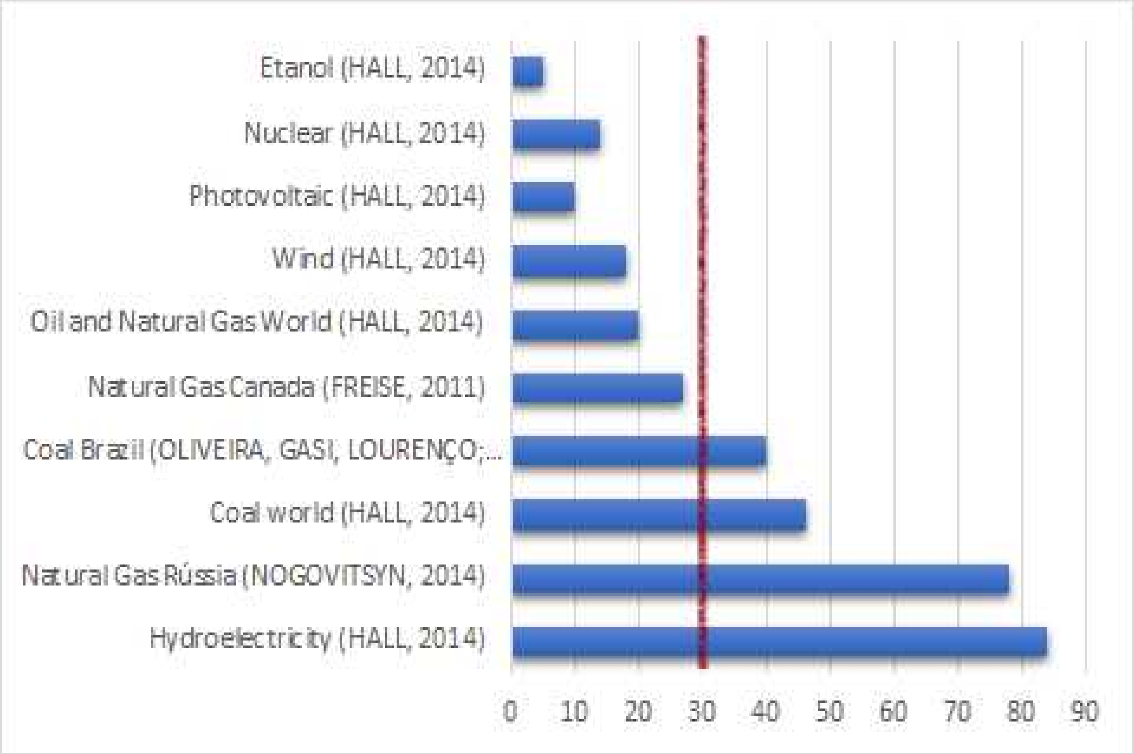


Figura 2: EROI from different energy sources in the literature

According to Ritchie, Roser and Rosado (2022), 36.7% of the world electricity production in 2019 came from coal, 23.5% came from natural gas and 15.8% from hydro power. As much as it may be tempting, comparison with the EROI values calculated in the literature must be performed with caution, since they are conducted using several different approaches that may, in some way, not be compatible with each other. Fizaine and Court (2016) evaluate in detail the implications resulting from the comparison between different studies, and conclude that it is convenient to make a comparison only between the order of magnitude of the ratios, but it is rather perilous to compare the precise values.

We can see that hydropower projects have high EROI ratios. Countries that have abundant water resources tend to benefit because it is possible to produce more electricity with less energy expenditure. On the other hand, countries that have an energy production mix with a large proportion of coal, even if they are able to produce energy at a lower energy cost (compared to other sources), may have complications in the future, as reduction targets are imposed on greenhouse gases emission.

Furthermore, the renewable sources towards which the energy transition is heading have relatively lower EROIs, with average values for wind energy, photovoltaic and etanol, respectively, around 19:1, 10:1 and 5:1. There is still concern about the intermittent nature of renewable energies, which seems to tell us that they may not be capable of handling the required minimum social EROI of 30:1 that we calculated.

From 1991 to 2021, during the years with uninterrupted year-to-year data availability, the Granger causality test was conducted. The aim was to determine the potential causal relationships among the sample countries' electricity spending as a fraction of GDP, gross fixed capital formation, unemployment rate, and GDP growth rate. Results are displayed in Table (7)

Tabela 7: Results of Granger Causality Test

Test Hypotheses (H_0)	Test	p-value
GDP does not Granger Cause EE	2.00015*	0.0933
EE does not Granger Cause GDP	6.74011***	0,0000
GDP does not Granger Cause GFCF	4.68071***	0.0010
GFCF does not Granger Cause GDP	3.95926***	0.0036
UNEMP does not Granger Cause GDP	1.02358	0.3945
GDP does not Granger Cause UNEMP	5.46320***	0.0003
GFCF does not Granger Cause EE	5.54113***	0.0002
EE does not Granger Cause GFCF	10.5737***	0.0000
UNEMP does not Granger Cause EE	0.82404	0.5102
EE does not Granger Cause UNEMP	0.59974	0.6630

Source: Research data.
Note: *, ** and *** significant at 10%, 5% e 1% respectively.

The results presented in the Table (7) show that we can reject at 5% level the hypothesis that the level of electricity expenditure as a fraction of GDP does not Granger cause economic growth. As for the reverse relation, the assumption that GDP growth does not Granger cause electricity expenditure cannot be rejected at 5% level. This finding implies a one way causality from electricity expenditure to economic growth. We can also say that there is a one way causality from GDP growth to unemployment. Besides, we find a bidirectional causality between GDP growth and capital formation as well as between capital formation and electricity expenditure.

3.4 Concluding Remarks

The results presented in this research provide valuable insights into the panel data analysis of the variables under investigation. The Pesaran test indicates that there is significant cross-sectional dependence in the panel data, suggesting the presence of macroeconomic links and local indirect effects. Consequently, the conventional panel regression models would produce inconsistent estimates and lead to incorrect inferences. Moreover, the Pesaran and Yamagata test rejects the null hypothesis of homogeneous coefficients, indicating the presence of differences in the slopes of the estimated coefficients. Therefore, both cross-sectional dependence and homogeneous coefficients must be considered to avoid biased estimations.

The unit root test based on the Bai and Carrion-i-Silvestre approach reveals that most of the variables exhibit a unit root in their level form. However, when considering the first-order differences, the test suggests stationarity or non-unit root for all variables, implying that they are integrated of order I(1). Lastly, the Westerlund and Edgerton test was conducted to examine the existence of a long-term cointegration relationship between the variables. The results indicate significant cointegration, further supporting the presence of a long-term equilibrium relationship.

The level of energy expenditure from 1991 to 2021 was calculated for a sample of 19 countries. Our results indicate that periods of high energy expenditure are associated with low rates of economic growth, and during periods of low electricity spending, economic growth rates are high. Granger causality tests consistently demonstrated a one-way temporal causality from the level of energy expenditure (as a fraction of GDP) to economic growth.

Furthermore, we were able to demonstrate that in order to achieve a positive growth rate statistically, the economies of the sampled countries cannot allocate more than 3.95% of their GDP to electricity expenditure. This implies that, considering their current energy intensity, the economies of the sampled countries need to have a minimum social EROI of approximately 30:1 to exhibit positive growth rates.

Such results suggest some important facts. First and foremost, electrical energy is crucial for economic growth, which tends to reinforce the theories of biophysical economics. Secondly, if we consider social EROI as an indicator of economic sustainability, it is necessary to take the necessary measures to prevent it from falling below its minimum threshold (estimated to be around 30:1 for the sampled countries).

Among the possible causes for the reduction in social EROI, two can be highlighted: (i) a drastic reduction in the level of electrical energy production; and (ii) increased investments in the electrical energy sector (resulting in consequent increases in energy prices) due to the decreased access to the energy resource. Thus, a coherent economic policy based on an efficient energy policy is imperative, aiming to achieve the dual objectives of increasing social EROI and reducing the economy's sensitivity to energy expenditures.

Future work should focus on developing more robust methodologies for calculating the minimum societal EROI that are less sensitive to parameter estimates. This could involve the adoption of non-parametric or semi-parametric models, which would reduce dependence on precise assumptions about the underlying parameter distributions.

Appendix 1 - Mean values of total electricity expenditure by country

Country	Electricity Expenditure
Belgium	0.033103
Brazil	0.035997
Denmark	0.025766
Finland	0.048633
France	0.024368
Germany	0.031146
Greece	0.022531
Hungary	0.028612
Ireland	0.016108
Italy	0.031627
Luxembourg	0.019830
Malta	0.019713
Netherlands	0.025105
Norway	0.048463
Portugal	0.032767
Slovenia	0.033411
Spain	0.028368
United Kingdom	0.017439
United States	0.024490

Source: Research data.

4 The Role of EROI and Finite Resources in Economic Growth: A Biophysical Economics Approach

Abstract

This study investigates the potential for economic growth constrained by biophysical limits, focusing on the impact of Energy Return on Investment (EROI) for fossil and renewable energy sources. The primary objective is to analyze how different EROI levels influence energy production, consumption, and overall economic performance. Three scenarios are examined: Scenario 1, which relies heavily on fossil fuels with limited renewable energy capacity; Scenario 2, characterized by a high EROI for renewable energy, supporting stable consumption and economic growth; and Scenario 3, where renewable energy partially compensates for the decline in fossil energy, resulting in intermediate outcomes. The findings emphasize that the transition to renewable energy, with a high EROI, is vital for sustaining economic growth in the face of bio-physical constraints. The study highlights the limitations of the model, such as the assumption of constant EROI and the exclusion of external factors like technological advancements and geopolitical influences. Future research could address these factors to provide a more comprehensive understanding of the energy transition's role in economic growth.

Keywords: Economic Growth; Biophysical Constraints; EROI.

4.1 Introduction

Biophysical economics is an interdisciplinary field that merges ecological principles with economic analysis to assess the sustainability of economic systems. This approach recognizes that economic activities are fundamentally dependent on the flow of energy and material resources, which are governed by the laws of thermodynamics. Traditional economic models often overlook the biophysical constraints imposed by energy resources, leading to an incomplete understanding of economic dynamics. By emphasizing the importance of energy flows, biophysical economics provides a framework for understanding the complex interactions between human activities and the environment (SHERWOOD; CARBAJALES-DALE; HANEY, 2020; LUZADIS et al., 2010).

Central to this discourse is the concept of Energy Return on Investment (EROI), which quantifies the ratio of energy output obtained from an energy-producing process to the energy input required to obtain that energy. This metric serves as a critical indicator of the viability and sustainability of energy systems. A high EROI indicates that a significant amount of energy is obtained relative to the energy expended, suggesting an efficient and sustainable energy production process. Conversely, a low EROI indicates that more energy is required to produce energy, raising concerns about the sustainability of such systems (HALL, 2004).

Research indicates that a minimum EROI threshold is necessary for sustaining economic growth. Some studies suggest that an EROI of at least 11 is required for continuous growth in developed economies, such as the United Kingdom (BRAND-CORREA et al., 2017). This threshold highlights the intricate relationship between energy quality and economic performance. As EROI values decline, economic outputs may diminish, leading to increased costs associated with energy transitions. Low EROI values can also exacerbate resource depletion and environmental degradation, raising concerns about the long-term sustainability of current economic practices (CLEVELAND; O'CONNOR, 2011; HABERL et al., 2019).

The implications of EROI extend beyond mere economic metrics; they encompass social, environmental, and political dimensions. For instance, energy systems with low EROI values can lead to increased reliance on fossil fuels, which not only threatens ecological balance but also poses significant risks to economic stability. Fluctuating energy prices and resource scarcity can lead to economic shocks, disproportionately affecting vulnerable populations (KLITGAARD, 2020). Therefore, understanding EROI is essential for evaluating the sustainability of energy systems and their implications for economic stability.

Moreover, the concept of EROI is not static; it evolves with technological advancements and changes in energy production methods. For example, the advent of renewable energy technologies has prompted discussions about the EROI of solar, wind, and bioenergy systems. While these technologies often have lower EROI values compared to fossil fuels, their environmental benefits and potential for long-term sustainability make them critical components of future energy systems (HALL, 2004). Thus, ongoing research is necessary to assess the EROI of emerging energy technologies and their implications for economic growth.

In addition to technological considerations, the geographical context plays a significant role in determining EROI values. Different regions possess varying energy resources, infrastructure, and regulatory frameworks, all of which influence the EROI of energy systems. For instance, countries with abundant renewable resources may achieve higher EROI values through efficient energy production methods, while others may struggle to transition away from fossil fuels (FENG; FENG, 2019). This geographical variability necessitates a nuanced understanding of EROI that considers local conditions and constraints.

Furthermore, the relationship between EROI and economic growth is complex and multifaceted. While a high EROI is generally associated with economic prosperity, the causality may not be straightforward. Economic growth can lead to increased energy consumption, which in turn may affect EROI values. Additionally, the distribution of energy resources and the socio-economic context can influence how EROI impacts different segments of society. Therefore, a comprehensive analysis of EROI must consider these interdependencies and their implications for policy and decision-making (HEUN, 2012).

The integration of EROI into economic models also presents challenges. Traditional economic models often overlook the biophysical constraints imposed by energy resources, leading to an incomplete understanding of economic dynamics. By incorporating EROI into growth models, researchers can better account for the role of energy in production functions and economic outputs. This integration allows for a clearer analysis of how energy quality impacts economic productivity and growth trajectories, revealing that GDP and productivity are emergent properties of the economic-biophysical system rather than mere exogenous parameters (KLING et al., 2017).

The main objective of this essay is to develop and simulate an economic growth model that incorporates the biophysical constraints of the energy sector as dictated by EROI. The model seeks to capture the interactions between energy production and economic output by integrating EROI into the economic growth framework.

4.2 Theoretical Framework of EROI in Macroeconomic Models

The theoretical framework of EROI in macroeconomic models provides a comprehensive understanding of the interplay between energy resources and economic growth. Traditional economic models, such as the neoclassical growth model, often overlook the biophysical constraints imposed by energy resources. By integrating EROI into growth models, researchers can better account for the role of energy in production functions and economic outputs (MACIAS; MATILLA-GARCíA, 2015). This integration is crucial for developing a more accurate representation of economic dynamics that reflects the realities of energy production and consumption.

In this context, EROI serves as a critical variable that influences the productivity of capital and labor. The relationship between energy inputs and economic outputs can be modeled to reflect how changes in EROI affect overall economic growth. For instance, a higher EROI indicates that less energy is required to produce a unit of economic output, thereby enhancing productivity and allowing for greater economic expansion. Conversely, a declining EROI suggests that more energy is needed for production, which can lead to increased costs and reduced economic growth (PALMER, 2017).

The incorporation of EROI into macroeconomic models also allows for the exploration of feedback loops between energy production and economic activity. As energy availability fluctuates, it can influence economic behavior, leading to shifts in consumption patterns and resource allocation. For example, during periods of high energy prices, businesses may invest in energy-efficient technologies or alternative energy sources, which can lead to reduced energy consumption and lower environmental impacts. This dynamic relationship underscores the importance of considering EROI in economic modeling (WARD et al., 2018).

Moreover, the theoretical framework of EROI can help elucidate the role of energy in shaping economic policies. Policymakers must consider the energy efficiency and sustainability of energy systems when designing economic policies. The integration of EROI into policy frameworks can guide investments towards energy sources that not only provide adequate returns but also align with sustainability goals (DUPONT et al., 2021). This approach can facilitate a transition away from fossil fuels and promote the development of renewable energy technologies.

The relationship between EROI and economic growth is not merely linear; it is influenced by various factors, including technological advancements, regulatory frameworks, and market dynamics. For instance, the advent of new technologies can enhance the EROI of renewable energy systems, making them more competitive with fossil fuels. Additionally, supportive regulatory frameworks can incentivize investments in energy-efficient technologies, further improving EROI and promoting sustainable economic growth (KLITGAARD, 2020).

Furthermore, the geographical context plays a significant role in determining EROI values and their implications for economic growth. Different regions possess varying energy resources, infrastructure, and regulatory frameworks, all of which influence the EROI of energy systems. For example, countries with abundant renewable resources may achieve higher EROI values through efficient energy production methods, while others may struggle to transition away from fossil fuels (FENG; FENG, 2019). This geographical variability necessitates a nuanced understanding of EROI that considers local conditions and constraints.

The integration of EROI into macroeconomic models also raises questions about the long-term sustainability of economic growth. As energy resources become scarcer or more expensive, the EROI of energy systems may decline, leading to potential economic stagnation. This scenario underscores the need for policymakers to prioritize investments in renewable energy technologies that can maintain high EROI values and support sustainable economic growth (HEUN, 2012).

In addition to economic implications, the theoretical framework of EROI also encompasses social and environmental dimensions. The distribution of energy resources and the socio-economic context can influence how EROI impacts different segments of society. For instance, marginalized communities may face greater challenges in accessing affordable energy, leading to increased inequality. Therefore, a comprehensive analysis of EROI must consider these interdependencies and their implications for policy and decision-making (KLING et al., 2017).

The general objective of this paper is to develop an economic growth model that incorporates the biophysical constraints of the energy sector, as dictated by the concept of Energy Return on Investment (EROI), in order to capture the interactions between energy production and economic output by integrating EROI into the economic growth framework. The specific objectives include: (i) developing an economic growth model that accounts for the limits imposed by EROI on energy production; (ii) analyzing the interactions between the three primary sectors of the economy: renewable energy, non-renewable energy, and final goods production, within the context of the proposed model; (iii) integrating EROI into the production functions of renewable and non-renewable energy sectors, reflecting its impact on economic growth; (iv) assessing the implications of energy production sustainability, considering resource depletion and declining EROI in non-renewable energy, and its effect on long-term economic growth; (v) formulating economic identities and transition equations governing the dynamics of consumption, investment, and capital accumulation in the model; and (vi) v) simulating three real-world scenarios: (a) declining fossil EROI with stable renewable EROI, (b) stable fossil EROI with growing renewable EROI, and (c) declining fossil EROI with growing renewable EROI. These scenarios reflect real-world energy trends and their implications for economic growth.

4.3 EROI and Sustainable Economic Growth

The relationship between EROI and sustainable economic growth is a focal point of biophysical economics. As energy systems transition towards renewable sources, the EROI of these systems must be carefully evaluated to ensure they can support economic growth without compromising environmental integrity (DUMAS et al., 2022). This relationship is particularly important in the context of global efforts to mitigate climate change and transition to a low-carbon economy.

Research has shown that energy systems with low EROI values can lead to increased reliance on fossil fuels, which exacerbates environmental degradation and climate change (CALVIN et al., 2020). This reliance not only threatens ecological balance but also poses significant risks to economic stability. Fluctuating energy prices and resource scarcity can lead to economic shocks, disproportionately affecting vulnerable populations. Therefore, understanding the EROI of various energy systems is essential for policymakers aiming to balance economic development with environmental sustainability.

Moreover, the implications of low EROI values extend beyond immediate economic concerns; they can also affect social equity and access to energy resources. As energy becomes more expensive to produce, marginalized communities may face greater challenges in accessing affordable energy, leading to increased inequality (KLITGAARD, 2020). This highlights the need for a comprehensive assessment of EROI that considers not only economic metrics but also social and environmental dimensions.

The transition to renewable energy sources presents both opportunities and challenges in terms of EROI. While renewable technologies such as solar and wind energy may have lower EROI values compared to fossil fuels, their long-term sustainability and lower environmental impacts make them critical components of future energy systems. Ongoing research is necessary to assess the EROI of emerging energy technologies and their implications for economic growth (HALL, 2004).

Furthermore, the relationship between EROI and economic growth is complex and multifaceted. While a high EROI is generally associated with economic prosperity, the causality may not be straightforward. Economic growth can lead to increased energy consumption, which in turn may affect EROI values. Additionally, the distribution of energy resources and the socio-economic context can influence how EROI impacts different segments of society. Therefore, a comprehensive analysis of EROI must consider these interdependencies and their implications for policy and decision-making (HEUN, 2012).

Additionally, A decline in EROI, which represents reduced energy returns for each unit of energy invested, has significant implications for economic growth. Court, Jouvet, and Lantz (2018) underscore the critical role of incorporating energy transitions into growth models, highlighting how societal EROI profoundly affects economic performance. They argue that traditional neoclassical models often overlook the intricate dynamics of energy, particularly the diminishing returns linked to declining EROI. This omission can lead to an incomplete understanding of the broader economic impacts of energy transitions.

To address this gap, Court, Jouvet, and Lantz (2018) introduce a dynamic EROI function into an endogenous growth model, showing that the implications of declining EROI extend to the sustainability of economic growth. As energy efficiency diminishes, simulation studied revealed that the transition may trigger adverse effects on economic growth, characterized by an initial peak followed by a phase of degrowth.

The integration of EROI into economic models also presents challenges. Traditional economic models often overlook the biophysical constraints imposed by energy resources, leading to an incomplete understanding of economic dynamics. By incorporating EROI into growth models, researchers can better account for the role of energy in production functions and economic outputs. This integration allows for a clearer analysis of how energy quality impacts economic productivity and growth trajectories, revealing that GDP and productivity are emergent properties of the economic-biophysical system rather than mere exogenous parameters (KLING et al., 2017).

Moreover, the implications of EROI for sustainable economic growth extend to the global context. As countries strive to meet international climate commitments, understanding the EROI of different energy systems becomes increasingly important. Policymakers must prioritize investments in renewable energy technologies that can maintain high EROI values and support sustainable economic growth. This approach can facilitate a transition away from fossil fuels and promote the development of renewable energy technologies (CALVIN et al., 2020).

In addition to economic implications, the relationship between EROI and sustainable growth also encompasses social and environmental dimensions. The distribution of energy resources and the socio-economic context can influence how EROI impacts different segments of society. For instance, marginalized communities may face greater challenges in accessing affordable energy, leading to increased inequality. Therefore, a comprehensive analysis of EROI must consider these interdependencies and their implications for policy and decision-making (KLITGAARD, 2020).

4.4 Case Studies: EROI in Different Economic Contexts

Empirical studies across various regions have illustrated the diverse implications of EROI on economic systems. For instance, the EROI of whole energy systems in Belgium has been analyzed to understand the interconnectedness of renewable energy sources and their economic viability (DUMAS et al., 2022). This case study bring attention to how different energy sources contribute to the overall EROI of a national energy system and the implications for energy policy and economic planning.

In Belgium, the transition towards renewable energy has been accompanied by a thorough assessment of EROI values across various energy sources. The findings indicate that while some renewable technologies may have lower EROI values compared to fossil fuels, their long-term sustainability and lower environmental impacts make them critical components of the energy transition. Policymakers in Belgium have utilized these insights to design strategies that promote the development of renewable energy technologies while ensuring economic viability (DUMAS et al., 2022).

Similarly, research on the economic integration of Tanzania emphasizes the biophysical impacts of energy systems on developing economies. The study reveals that energy access is a critical determinant of economic development in Tanzania, where low EROI values can hinder growth and exacerbate poverty (FRAME, 2015). This underscores the need for a comprehensive assessment that includes environmental indicators alongside economic metrics, as traditional economic analyses may overlook the biophysical constraints that shape economic outcomes.

In Tanzania, the reliance on traditional biomass and fossil fuels has resulted in low EROI values, limiting the country's ability to achieve sustainable economic growth. The findings suggest that investments in renewable energy technologies, such as solar and wind, could enhance EROI and promote economic development. Policymakers in Tanzania are increasingly recognizing the importance of transitioning to renewable energy sources to improve energy access and support economic growth (FRAME, 2015).

These case studies underscore the importance of context-specific analyses in understanding the broader implications of EROI on economic systems. By examining different regions and energy systems, researchers can identify best practices and strategies for enhancing EROI, thereby promoting sustainable economic growth. Furthermore, these case studies underline the need for interdisciplinary collaboration between researchers, policymakers, and industry stakeholders to develop effective energy policies.

In addition to Belgium and Tanzania, other regions have also explored the implications of EROI on economic systems. For example, studies in the United States have examined the EROI of shale gas production, revealing the trade-offs between energy production and environmental impacts. The findings indicate that while shale gas may provide a temporary boost to energy supplies, its long-term sustainability is questionable due to declining EROI values and environmental concerns (HEUN, 2012).

In the context of the United States, the EROI of shale gas production has been a topic of significant debate. Proponents argue that shale gas can provide a bridge to a cleaner energy future, while critics highlight the environmental risks associated with hydraulic fracturing and the declining EROI of shale gas production. This case illustrates the complexities of energy transitions and the need for comprehensive assessments that consider both economic and environmental dimensions (KLITGAARD, 2020).

Nakajima and Matsushima (2022) examine the relationship between energy quality and economic performance in Japan, revealing that a decrease in energy acquisition capacity, as reflected by declining EROI, correlates with stagnation in real GDP growth. Their analysis, which spans over five decades, underscores the importance of energy quality in sustaining economic vitality. As EROI diminishes, the capacity for economic expansion is compromised, suggesting that energy quality is a fundamental driver of economic productivity.

Conversely, countries with with a strong foundation in renewable energy tend to experience fewer economic disruptions during the transition to a more sustainable energy matrix. For instance, Brazil's reliance on hydroelectric power, with its high EROI, may provide a buffer against the costs associated with reducing dependence on fossil fuels. Brazil is recognized for its extensive reliance on hydropower, which accounts for approximately 70% of its electricity generation (MELLO et al., 2021; DRANKA; FERREIRA, 2018).

Moreover, international comparisons of EROI values can provide valuable analysis into the effectiveness of different energy policies. For instance, countries that have prioritized investments in renewable energy technologies may achieve higher EROI values and greater energy security compared to those that continue to rely on fossil fuels. These comparisons can inform policy decisions and guide investments in sustainable energy systems (CALVIN et al., 2020).

4.5 Methodology

This study employs an energy-economic model incorporating renewable and non-renewable energy production, where the Energy Return on Investment (EROI) plays a central role. The biophysical approach underscores that economic growth cannot be fully understood through monetary and technological variables alone; instead, it necessitates the inclusion of physical factors, such as energy efficiency and the finite availability of natural resources. Thus, this model is augmented with basis from Biophysical Economics to analyze the sustainability of resource use and its implications for economic growth.

4.6 Model Structure

The model structures the economy into three primary sectors: renewable energy, non-renewable energy, and final goods production. Each sector contributes uniquely to energy and economic dynamics.

1. **Renewable Energy Production:** Net renewable energy production, $ER(K_R)$, depends on the capital stock allocated to renewable energy production K_R, the EROI of renewable sources, and a fixed productivity factor a_R. The production function is given by:
$$ER(K_R) = a_R \frac{EROIR}{EROIR + 1} K_R^{\alpha_R}, \quad 0 < \alpha_R < 1 \tag{28}$$
Biophysical Economics highlights that the EROI of renewable energies is constrained by natural limits, such as the availability of land for solar and wind installations and the intermittency of these sources. In this context, the capacity of Renewable to sustain long-term economic growth depends on technological advances that maximize EROI and the necessary infrastructure to address variability and energy storage challenges.

2. **Non-Renewable Energy Production:** Gross production of non-renewable energy, $GN(K_N, S)$, depends on capital dedicated to non-renewable production K_N and the finite stock of resources S, in addition to a fixed productivity factor a_N.
$$GN(K_n, S) = a_N K_N^{\alpha_N}, \quad 0 < \alpha_N < 1 \tag{29}$$
The EROI for non-renewable energy declines as remaining resources become scarcer, represented by:
$$EROIN(S) = bS^{\gamma}, \quad 0 < \gamma < 1 \tag{30}$$
Net non-renewable production is thus:
$$EN(K_N, S) = \frac{EROIN(S)}{EROIN(S) + 1} GN \tag{31}$$
From a biophysical perspective, the use of non-renewable resources presents an unavoidable decline in EROI, reflecting the principle of diminishing returns, whereby resource extraction becomes more costly as high-quality reserves are depleted. This

factor imposes a physical limit on continued economic growth if the economy remains dependent on fossil resources.

3. **Final Goods Production:** Final goods production Y depends on the capital allocated to this sector K_F and the total energy available X, derived from the combined contributions of net renewable and non-renewable energy:

$$Y = a_F K_F^{\alpha_F} X^{1-\alpha}, \quad 0 < \alpha < 1 \tag{32}$$

Biophysical Economics views energy as an essential input, suggesting that the role of X in the production function is more crucial for economic growth than capital variation alone. The total energy production (X) is calculated by:

$$X = E_R(K_R) + E_N(K_N, S) \tag{33}$$

This perspective emphasizes that without access to a minimum level of energy (and sufficient levels of EROI), physical capital alone cannot sustainably drive production.

4.6.1 Economic Identities and Transition Equations

- **Income Identity:** Consumption (C) and investment (I) are components of the product:

$$Y = C + I \tag{34}$$

From a biophysical viewpoint, excessive consumption of energy and natural resources can reduce future capital availability for productive investments, limiting the economy's growth capacity.

- **Total Capital:** The total capital stock K comprises allocations to final goods, renewable energy, and non-renewable energy:

$$K = K_F + K_R + K_N \tag{35}$$

- **Capital Accumulation and Resource Depletion:**

$$K' = (1 - \delta)K + I, \quad 0 < \delta < 1 \tag{36}$$

$$S' = S - GN(K_N, S) \tag{37}$$

Biophysical Economics suggests that the depletion rate of S should be managed based on sustainability principles, aiming to extend resource availability and mitigate the impact of EROI constraints.

4.6.2 Intertemporal Optimization and Stationarity of the Value Function

The model is designed to maximize the intertemporal utility of the representative agent, whose preferences are represented by a utility function dependent on consumption C. The optimization problem is:

$$\max \sum_{t=0}^{\infty} \beta^t U(C), \quad 0 < \beta < 1 \tag{38}$$

where the instantaneous utility function is specified as $U(C) = \ln(C)$. The objective is to maximize the discounted sum of utility over time.

This problem is solved using dynamic programming, where the value function $V(K, S)$ is characterized by the Bellman equation:

$$V(K, S) = \max_{K_R, K_N, I} \ln(C) + \beta V(K', S') \tag{39}$$

The structure of the model ensures that it is stationary, meaning that the problem's decision rules and policy functions do not explicitly depend on time but only on the state variables (K, S). This stationarity implies that the optimization process can rely on fixed relationships between the state variables and control variables across periods.

Given this stationarity, the value function $V(K, S)$ can be numerically solved using the value function iteration method. This iterative process is feasible because the Blackwell conditions are satisfied. Specifically, these conditions confirm that the Bellman operator in this setting is a contraction mapping. The contraction mapping property guarantees the existence and uniqueness of a fixed point for $V(K, S)$, meaning that repeated applications of the Bellman operator will converge to the true value function. This approach allows for an efficient and stable solution to the optimization problem, as each iteration progressively refines the approximation of $V(K, S)$ until it meets a predetermined convergence criterion.

4.6.3 Parameters and Calibration

The model parameters were calibrated based on literature in energy economics and theoretical criteria to simulate the energy transition process. A Cobb-Douglas production function was employed, with the capital share in production (α) set at 0.36 as in Argentiero et al. (2018) and Kümmel, Henn and Lindenberger (2002).

The intertemporal discount rate (β) was fixed at 0.96, reflecting a moderate preference for present over future consumption, while the depreciation rate of capital (δ) was set at 10% annually, a typical value for long-term analyses in industrialized economies (ARGENTIERO et al., 2018).

For the energy sectos the elasticity of capital in energy production (α_{N} and α_{R}) were set equal to α, reflecting similarities in the dynamics of capital accumulation and energy production.

4.6.4 Numerical Solution and Sensitivity Analysis

The model is solved numerically through value function iterations. Sensitivity analyses are conducted across different EROI scenarios for renewable and fossil energy sources. Biophysical Economics emphasizes the importance of analyzing scenarios where non-renewable EROI declines substantially, limiting the economic viability of the sector. The analysis includes:

- **Low and High Initial EROI Scenarios for Non-Renewable (Fossil) Energy:** Scenarios explore low and high starting levels of $EROI_N$ (fossil energy) with a gradual decline over time, reflecting a range of initial energy efficiencies across countries. These simulations highlight how nations with different levels of fossil fuel efficiency might experience varying degrees of economic impact due to diminishing returns from non-renewable resources. This approach allows for an assessment of which economies may be more vulnerable in the transition away from fossil fuels.
- **Stable and Increasing EROI Scenarios for Renewable Energy:** Simulations assume either stable $EROI_R$ levels (e.g., holding constant at 10) or increasing values (e.g., rising to 20) due to technological improvements and expanded renewable capacity. These scenarios aim to assess the potential of renewable energy to support sustained economic growth under different efficiency levels.

The exploration of scenarios with low and high initial EROI for non-renewable energy reflects the variability in fossil fuel efficiencies observed across countries.

Fossil fuels, particularly oil and gas, have historically exhibited high EROI values, often exceeding 20:1 during their peak production phases. For instance, conventional oil extraction has been reported to have an EROI ranging between 10:1 and 20:1, depending on the geographical and technological context (MURPHY et al., 2011; KONG et al., 2017). In contrast, unconventional sources such as oil sands and shale gas typically present lower EROI values, often around 4:1 to 7:1, reflecting the increased energy costs associated with extraction processes (DUMAS et al., 2022; WANG et al., 2017). This decline in EROI for fossil fuels is attributed to resource depletion and the increasing difficulty of extraction as easily accessible reserves are exhausted (KREPS, 2020; MURPHY, 2014).

Renewable energy sources, such as solar and wind, present a different EROI profile. The EROI for solar photovoltaic (PV) systems typically ranges from 6:1 to 12:1, depending on factors such as location, technology, and system design (RAUGEI; FULLANA–I–PALMER; FTHENAKIS, 2012; RAUGEI et al., 2017). Wind energy has shown comparable EROI values, often falling within the same range (WEIBACH et al., 2013; RAUGEI; FULLANA–I–PALMER; FTHENAKIS, 2012). However, these values are generally lower than those of conventional fossil fuels during their peak production phases. The lower EROI for renewables can be attributed to the energy-intensive processes involved in manufacturing and installing renewable energy systems, as well as the intermittent nature of energy generation (BARNHART; BRANDT; BENSON, 2013).

By incorporating principles from Biophysical Economics, this model seeks to provide a more realistic analysis of the limits imposed by energy availability and the efficiency of natural capital. The sensitivity analysis explores the variability of EROIs to illustrate how the economy responds to the decline of fossil energies and the transition to renewable sources.

4.7 Results

4.8 A Baseline Scenario

In this section, we present the results obtained from simulating the economic model, which examines capital allocation across three sectors: fossil energy, renewable energy, and final goods. The model is initialized with parameters that reflect current realities, with particular focus on the Energy Return on Investment (EROI) rates for each energy source. The EROI for fossil energy begins at 20 and decreases over time, corresponding to the gradual depletion of non-renewable energy reserves, while the EROI for renewable energy remains constant at 10. This approach reflects the declining efficiency of fossil fuels as reserves diminish, contrasting with the stable but low efficiency of renewables (DALE; KRUMDIECK; BODGER, 2011b; BRAND-CORREA et al., 2017). Initial capital allocation was balanced between the fossil and renewable energy sectors, with a larger share directed to the final goods sector, aligning with its central role in global economic production. Figure (3) shows the baseline scenario.

At the outset, capital is distributed evenly between the fossil and renewable energy sectors, with a greater allocation in the final goods sector. However, as the simulation progresses, capital is gradually reallocated from the fossil and final goods sectors to the renewable energy sector. This shift is driven by the progressive depletion of fossil reserves, which reduces the economic feasibility of fossil energy investments due to declining effective EROI. Capital allocation plots indicate that during the initial periods, capital in both fossil and renewable energy remains relatively stable. However, around 30th period of the timeline, there is an accelerated shift toward renewable energy. This trend is consistent with real-world efforts to diversify energy sources for long-term sustainability, as highlighted by various international analyses and reports, such as those from the Intergovernmental Panel on Climate Change (IPCC).

Fossil energy production initially remains strong, driven by a high EROI of 20, providing substantial net energy output. However, as fossil resource reserves dwindle, fossil energy production steadily declines. This decline is evident in Figure (3-a), with

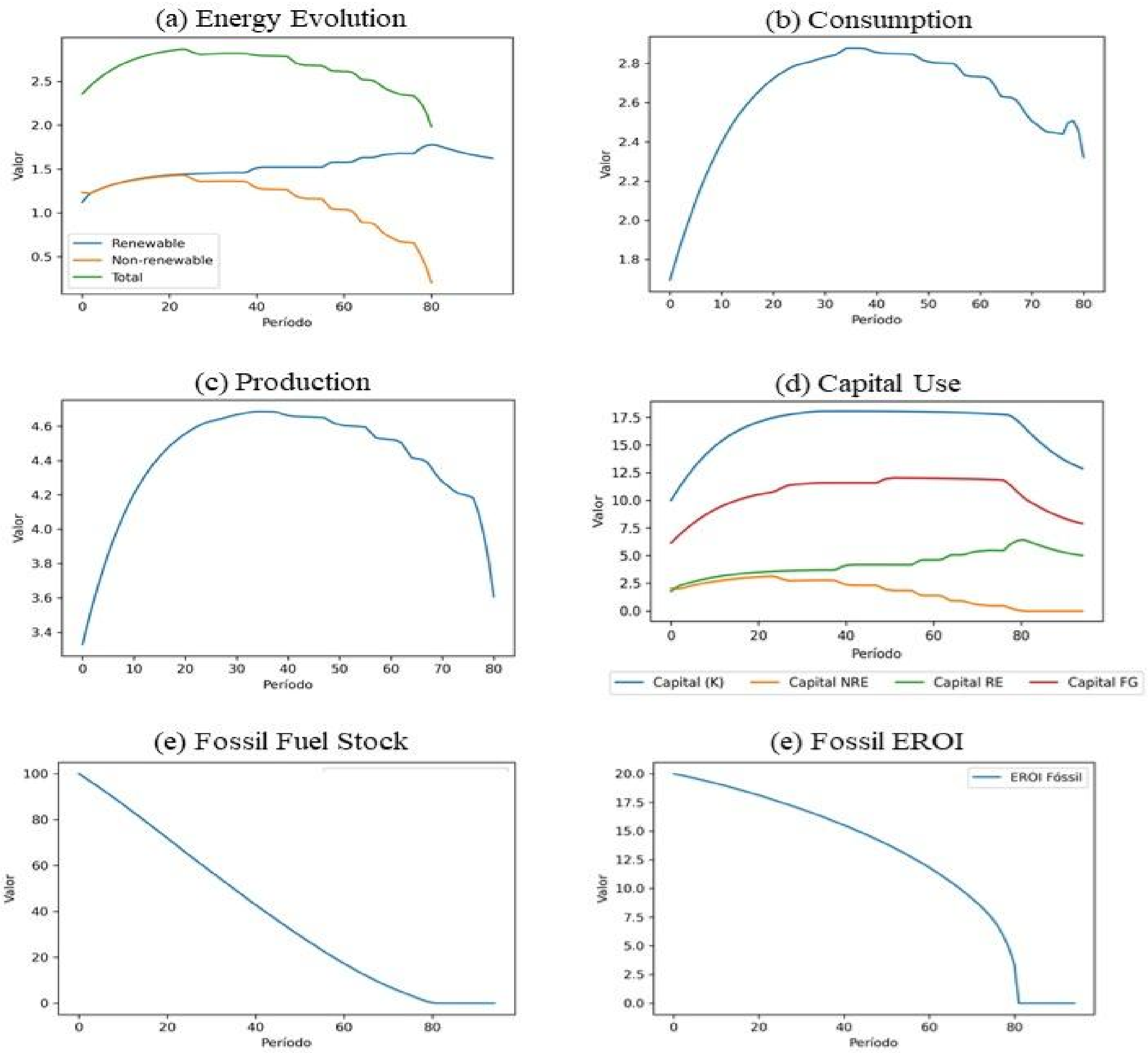


Figura 3: Energy transition in the baseline scenario

Note: The horizontal axis of each figure gives the simulation time period. The vertical axis gives the value of the displayed variable(s).

non-renewable production beginning to taper off after approximately 40 periods, in line with the depletion of fossil reserves and the declining EROI. Conversely, renewable energy production, with a constant EROI of 10, remains stable or shows moderate growth due to increased capital allocation in the renewable sector. This behavior reflects the growing installed capacity of renewable technologies, such as solar and wind, which, despite lower EROIs compared to fossil fuels, compensate through scalability and resource sustainability. Total energy production initially benefits from high fossil production, but as this declines, renewable production offsets the reduction, stabilizing the energy supply for several periods. However, this balance is not sustained in the long term, and around period 50, a progressive decline begins, with production levels falling to levels lower than those at the initial period.

The production of final goods is directly influenced by total energy availability. In the early stages of the simulation, high fossil energy production sustains robust final goods production, allowing for increasing consumption. However, as fossil reserves are depleted and fossil energy production wanes, capital reallocation becomes necessary to maintain final goods production. The results indicate that, while final goods production slightly decreases during the energy transition, renewable energy's production capacity ensures no abrupt downturn in total output. Consumption, calculated as the difference between final goods production and investment, initially rises due to increased efficiency but stabilizes in the long term as capital allocation adjusts to new energy realities. However, starting at period 60, final goods production begins to decrease more sharply, with a steep decline occurring by period 80, when fossil energy production reaches zero. This behavior aligns with economic theory, suggesting that diversifying and transitioning to sustainable energy sources are critical for long-term economic stability.

In the following section, different EROI scenarios will be evaluated to analyze their impacts on consumption and production, aiming to reduce the model's limitation of using a fixed EROI and exploring alternatives that consider the trend of decreasing fossil EROI and increasing renewable EROI over time.

4.9 Different EROI scenarios

The model simulation uses a fixed EROI for renewable energy and a declining EROI for fossil energy, linked to the depletion of fossil fuel stocks. This approach introduces a notable limitation, as real-world EROI values for fossil and renewable energy sources typically vary over time, influenced not only by resource availability but also by technological advancements, evolving extraction practices, and gains in production efficiency. In the model, fossil energy begins with an EROI of 20, which gradually decreases, while renewable energy is assigned a constant EROI of 10. Although this simplification provides a baseline for analysis, it does not fully capture the complexity of real-world dynamics: renewable EROI generally increases over time due to technological progress and efficiency improvements, while fossil EROI is influenced by a range of factors beyond resource depletion alone.

To address some of this limitation, different EROI scenarios were analyzed, adjusting the values to reflect current market trends and technological advancements. In the first scenario, the initial EROI for fossil fuels is set at a lower level and decreases over time while the EROI for renewable energy remains stable at 10. In the second scenario, the fossil fuel EROI starts higher, at 20, also declining over time, while the renewable EROI is also initially higher, set at 20, and remains stable. In the third scenario, the decreasing fossil EROI starts at 10, whereas the renewable EROI is set at a higher level of 20 and remains constant.

Scenario 1: In this scenario, the decreasing EROI of fossil energy is initially 10, while the EROI of renewable energy remains constant at 10. The effect of the decline in fossil EROI, paired with a stable renewable EROI, is assessed in terms of its impact on consumption and the production of final goods. As the efficiency of fossil energy decreases, production and consumption will probably be negatively impacted.

Scenario 2: Here, the decreasing EROI of fossil energy starts at the benchmark scenario, while the EROI of renewable energy increases to 20. This scenario explores the effects of a decreasing fossil EROI alongside an higher level initial renewable EROI. The rise in renewable energy efficiency will possibly help to stabilize consumption and reduce the negative effects on final goods production, allowing the economy to manage the energy transition more smoothly.

Scenario 3: In this case, the EROI of fossil energy starts at a lower level (10), while the EROI of renewable energy increases to 20. This scenario examines the combination of a reduced initial fossil EROI and an increased renewable EROI. The reduction in fossil energy production and the growth of renewable energy efficiency work together seeking to maintain moderate levels of consumption and production, underscoring the role of renewable energy efficiency in stabilizing the economy during an energy transition.

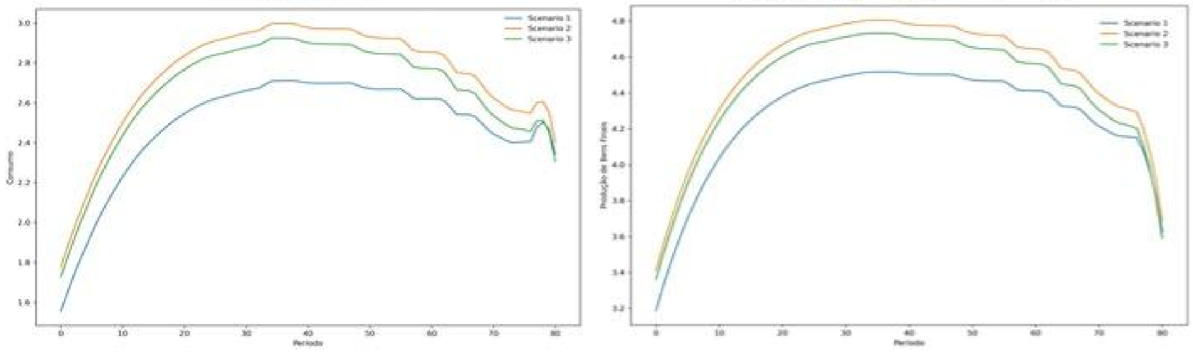
These scenarios underscore how critical EROI is in influencing macroeconomic outcomes, especially regarding the ability to sustain production and consumption levels during the transition toward renewable energy sources. The varying EROI values affect the economic viability of energy sources, impacting the stability and resilience of the economy as it adjusts to more sustainable energy options. Figure (4) presents the results for the different scenarios described.

In Scenario 1, energy production is initially high due to the reliance on fossil fuels, supported by a relatively high initial Energy Return on Investment (EROI) for fossil energy. However, as fossil reserves deplete, total energy production begins to decline rapidly, particularly after the 50th period. The low efficiency in converting fossil fuels into useful energy severely hampers the sustainability of production. Additionally, since the renewable energy EROI remains stable at 10 in this scenario, there is no compensatory effect from renewable sources to offset the decline in fossil energy. This emphasizes the vulnerabilities of over-relying on fossil energy, especially as its efficiency decreases over time and renewable energy cannot make up for the loss.

In Scenario 2, the higher initial EROI of renewable energy (set in 20) allows energy production to reach higher levels throughout the simulation compared to Scenario 1. With the renewable sector's greater efficiency, energy production maintains a constant and sustainable rate, ensuring that the system remains productive even as fossil fuel consumption decreases. However, similar to Scenario 1, total energy production begins to decline after the 50th period, with a more pronounced drop occurring near the 80th period. Despite the initial EROI of fossil energy set at 20, the transition to Renewable is smoother, with the increased efficiency of Renewable contributing to a higher overall

(a) Consumo

(b) Final goods production



(c) Renewable/ Non renewable production

(d) Total energy production

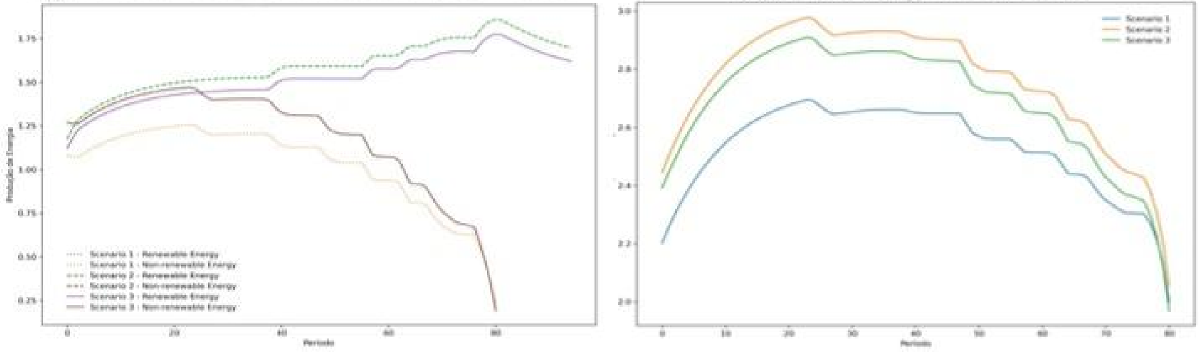


Figura 4: The impact of different EROI for renewable and non renewable energy

Note: The horizontal axis of each figure gives the simulation time period.

energy production level.

In Scenario 3, energy production starts high, driven by fossil fuel dependence, but the initial EROI of fossil energy now is set to 10 while the EROI of renewable energy increases to 20. As a result, part of the production decline due to fossil energy depletion is offset by the higher efficiency of renewable energy. However, the overall energy production pattern follows a similar trajectory to that of Scenario 1, with a gradual decline starting after the 50th period, followed by a more pronounced drop as the fossil energy reserves continue to deplete. This scenario achieves intermediate results between Scenarios 1 and 2, showing that while renewable energy can partially compensate for the loss of fossil fuel energy, the system still faces challenges in sustaining production over the long term without a more significant shift towards Renewable.

As for the final goods sector, in Scenario 1, production initially peaks at a moderate level, driven by the reliance on fossil fuels and the relatively high initial EROI of fossil energy. However, as fossil fuel reserves are depleted and the efficiency of fossil energy decreases, final goods production starts to decline rapidly. The limited efficiency of renewable energy, with its relatively low and stable EROI of 10, to compensate for the drop in fossil fuel energy results in a significant biophysical constraint. This constraint limits the economy's capacity to sustain production, highlighting the risks of an energy system overly dependent on fossil fuels and the need for a greater renewable energy capacity to mitigate the loss.

In Scenario 2, the production pattern is similar to that of Scenario 1, with production gradually increasing until it peaks around period 40. However, in this case, the levels reached are higher compared to Scenario 1. After the peak, production declines steadily until just before period 80, when it drops sharply, reaching levels similar to Scenario 1 but slightly above. This scenario demonstrates that while the overall production trend follows the same pattern as Scenario 1, the higher EROI of renewable energy results in higher production levels, albeit still subject to a significant decline as fossil fuel reserves diminish.

In Scenario 3, final goods production follows a similar pattern to the previous scenarios: it increases gradually, reaching a peak around period 40, then declines steadily until just before period 80, where it drops sharply to levels similar to Scenario 1, but slightly higher. The initial high production, driven by fossil energy, begins to decrease as the EROI of fossil fuels declines. Renewable energy, with a higher EROI of 20, partially compensates for this drop, but not enough to prevent a steep decline. This scenario reflects the risks of an inadequate transition to renewable energy, where the economy struggles to sustain production despite some compensation from renewable. It draws attention to the importance of a more effective but cautious shift toward renewable energy to maintain long-term economic stability.

Analyzing consumption, in scenario 1, it starts at low levels and gradually increases until it peaks shortly after period 30. Following the peak, consumption gradually declines until just before period 80, where it stabilizes at relatively high levels, demonstrating some fluctuations. Although consumption declines from its peak, it does not return to its initial low levels, remaining higher than in the early stages of the simulation. This scenario illustrates the impact of fossil resource depletion on consumption, with the economy struggling to sustain high consumption levels but still maintaining relatively elevated levels due to the existing fossil energy reserves, despite a lack of sufficient renewable energy support.

In Scenario 2, consumption follows a similar pattern to Scenario 1, but it reaches higher levels due to the greater efficiency and continuous availability of renewable energy. Consumption increases gradually, peaking after period 30, and then declines slowly, with some fluctuations. Although consumption decreases after its peak, it remains higher compared to Scenario 1, demonstrating the impact of a higher EROI for renewable energy. This scenario emphasizes the importance of renewable energy's efficiency and stability in supporting higher levels of consumption over time, resulting in more favorable economic and social well-being outcomes compared to the other scenarios.

In Scenario 3, consumption follows a pattern similar to Scenarios 1 and 2, gradually increasing until it peaks around period 40, then gradually declines. Prior to period 80, consumption presents some oscillation, reaching levels slightly higher than those observed in Scenario 1 but lower than Scenario 2. The reduction in consumption is explained by the insufficient renewable energy support. This scenario underscores the risks of failing to transition effectively to sustainable energy sources, as consumption face significant challenges due to the depletion of fossil reserves and the lack of an adequate transition to renewable energy.

Comparing the scenarios, it becomes clear that Scenario 2, with its focus on transitioning to highly efficient renewable energy sources, offers the best prospect for economic growth within bio-physical limits. This scenario demonstrates a higher, more sustainable level of consumption and production, driven by the continuous availability of renewable energy. Unlike Scenario 1, which is characterized by a high dependence on fossil fuels and a low EROI for renewable sources, Scenario 2 enables a gradual increase in energy production and consumption, reaching higher levels compared to the other scenarios, though without achieving stability.

4.9.1 Discussion

The literature indicates that the EROI for fossil fuels is indeed subject to decline as easily accessible reserves are depleted. For instance, Brand-Correa et al. (2017) argue that the depletion of easily recoverable fossil fuel reserves is outpacing technological advancements aimed at improving extraction efficiency, leading to a decrease in EROI values for fossil energy sources over time. This observation is echoed by Feng and Wang (2019), who highlight that the net energy yields from conventional fossil fuels have shown a marked decline, particularly in regions like China, where the EROI peaked in 2016 due to diminishing returns from extraction processes. Such findings underscore the notion that as fossil fuel reserves become increasingly difficult to extract, the energy return diminishes, aligning with the claim that EROI for fossil energy decreases over time.

In contrast, the EROI for renewable energy sources appears to maintain a more stable profile. Research by Raugei, Fullana–i–Palmer and Fthenakis (2012) suggests that EROI for renewables often stabilizes around a certain threshold, typically cited as approximately 10:1 for various renewable technologies. This stability can be attributed to the nature of renewable energy sources, which, unlike fossil fuels, are not subject to depletion in the same manner. The consistent availability of solar, wind, and hydro resources allows for a relatively stable energy return, as noted by Rana et al. (2020), who emphasize the importance of transitioning to renewable energy for sustainable socio-economic systems.

Moreover, the literature also discusses the implications of EROI on policy and investment decisions. For instance, the work of Shrimali (2021) highlights that the historical performance of renewable energy investments has shown more attractive characteristics, including higher returns and lower volatility compared to fossil fuel investments. This suggests that the perceived stability of EROI for renewables not only supports environmental sustainability but also presents a compelling case for financial investment, contrasting sharply with the declining EROI of fossil fuels which may deter future investments.

The economic implications of declining EROI for fossil fuels are further explored by Kreps (2020), who posits that the rising costs associated with fossil fuel extraction are indicative of a broader energy crisis that is unlikely to resolve without significant shifts in energy policy. This perspective aligns with the assertion that as fossil fuel reserves dwindle, the economic performance is negatively affected.

Furthermore, the role of policy in shaping the future of energy investments cannot be overlooked. Studies indicate that government interventions, such as carbon taxes and subsidies for renewable energy, can significantly influence the EROI landscape by making renewables more competitive against fossil fuels. This policy-driven approach is essential for facilitating a transition towards a more sustainable energy system, as it can help mitigate the economic risks associated with declining fossil fuel EROI while promoting the stability of renewable energy investments (RAUGEI, 2019).

In countries like the United States, the EROI for conventional oil has been steadily declining, with estimates indicating it may soon reach the critical threshold of 10:1 due to the increasing reliance on more energy-intensive extraction methods (MURPHY, 2014; POISSON; HALL, 2013). Scenario 1 demonstrates that such low fossil EROIs, as observed in the U.S., can significantly hinder production and consumption levels, particularly as non-renewable reserves near depletion, underscoring the vulnerabilities of economies heavily dependent on fossil fuels.

Conversely, countries with abundant conventional oil reserves, such as Saudi Arabia, maintain higher EROI values, often reported above 20:1, due to the relatively low energy input required for extraction (MURPHY et al., 2011; KONG et al., 2017). This underscores the role of resource quality and efficient extraction processes in ensuring economic sustainability. As illustrated in Scenario 2, a gradual transition toward renewable energy sources, accompanied by a high renewable EROI, can help mitigate economic disruptions. By sustaining production and consumption at higher levels, such transitions reduce dependency on finite fossil fuel reserves and highlight the importance of advancing renewable energy technologies for long-term economic resilience.

Countries at the forefront of renewable energy deployment, such as Germany and Denmark, have made substantial investments in technology and infrastructure, contributing to improvements in the EROI of their renewable systems. For example, Germany's ambitious solar energy policies have driven significant gains in efficiency and cost reductions, gradually increasing the EROI of its renewable energy sector (MURPHY et al., 2022; BRAND-CORREA et al., 2017). Achieving high renewable EROIs could lead to outcomes similar to those in Scenario 2, characterized by higher levels of economic growth and consumption, as well as a smoother and more efficient transition away from fossil fuels.

Another example of a country with strong renewable energy performance is Brazil, which relies heavily on hydropower. Studies indicate that hydropower generally exhibits a favorable EROI compared to fossil fuel sources, with some estimates suggesting EROI values ranging from 30:1 to 50:1 for conventional large-scale hydropower plants (WEIBACH et al., 2013).

This characteristics exemplifies the potential advantages for countries rich in renewable resources, as their energy systems can achieve significantly higher efficiencies. In contrast to Germany and Denmark, which focus on solar and wind energy, Brazil's dependence on hydropower provides a distinct path to high EROI renewables. These observations align with Scenario 2, where economies transitioning to renewable sources with high EROI values experience enhanced growth and consumption, along with a more efficient transition.

4.10 Concluding remarks

This study aimed to analyze the long-term sustainability of energy systems under different scenarios, focusing on the impact of varying initial Energy Return on Investment (EROI) levels for both fossil and renewable energy sources. The baseline scenario, representing a status quo with mixed energy sources and no substantial shift towards Renewable, provided a reference point for understanding the trajectories of energy production, consumption, and final goods production in the face of resource depletion. The objective of this research was to examine how different energy transition scenarios affect economic stability and social well-being, particularly under the constraints imposed by the finite nature of fossil fuels.

In Scenario 1, characterized by heavy reliance on fossil fuels and limited renewable energy capacity, the depletion of fossil resources led to a significant decline in energy production and consumption. This scenario points out the vulnerabilities of an energy system dependent on fossil fuels, underlining the importance of transitioning to more sustainable and efficient energy sources to mitigate the risk of economic contraction.

Scenario 2, with a higher EROI for renewable energy, shows a more optimistic future where energy production remains stable and consumption reaches its peak and remains elevated for a longer period. This scenario demonstrates the benefits of transitioning to renewable energy, emphasizing how a high EROI can support economic activity, maintain consumption, and ensure long-term social and economic well-being.

Scenario 3 offers a middle ground, where renewable energy partially compensates for the decline in fossil energy. While this scenario leads to higher levels of production and consumption compared to Scenario 1, it still reflects the risks of an incomplete transition to renewable energy. The scenario underscores the necessity of a balanced approach to energy policy, with a more effective and comprehensive shift towards Renewable to avoid economic disruptions.

The results from the baseline scenario and alternative scenarios emphasize the critical role of EROI in shaping the energy-economic system. The findings suggest that, without a well-coordinated transition, reliance on fossil energy can lead to rapid economic and social instability as resources deplete.

However, this model has limitations. First, it assumes a constant EROI for renewable energy sources, whereas technological advancements and innovations in energy efficiency could lead to increases in EROI over time. Second, the model does not account for geopolitical factors, technological disruptions, or market dynamics that may affect the energy transition. Furthermore, the interactions between energy policy, societal adaptation, and consumption behavior were simplified, which could be explored in more detail in future research.

Future research could delve into enhancing the model by integrating technological advancements in renewable energy, exploring the role of policy interventions, and examining scenarios with varying rates of energy transition and adaptation. Developing a dynamic framework that incorporates feedback mechanisms between energy production, consumption, and economic output would allow for a more comprehensive understanding of the complexities and temporal dynamics involved in energy transitions.

Additionally, future research endeavors could also benefit significantly from focusing on the estimation of parameters derived directly from primary data rather than relying solely on values adopted from previous studies. While leveraging parameters from existing literature facilitates initial modeling and enables comparisons across studies, this approach may introduce biases that do not fully capture the specific dynamics of the case under examination. Tailoring parameter estimates to the unique characteristics of the research context would enhance the reliability and validity of results, ensuring that models more accurately reflect the realities they aim to represent.

5 General Conclusions

This thesis has explored how energy expenditures, economic growth, and energy return on investment (EROI) interact, particularly in the context of the ongoing transition to low-carbon energy systems. The main objective was to understand how these factors influence each other, contributing to the broader discourse on sustainable economic growth in light of environmental challenges.

One major finding is that when a country's energy expenditure exceeds approximately 3.95% of GDP, economic growth tends to slow down. On the other hand, when energy expenditure is lower, economic growth rates tend to be higher. This relationship highlights the critical role of energy costs and efficiency in shaping economic performance. Based on this, the minimum EROI required to sustain positive growth is estimated to be about 30:1. This suggests that economies with higher EROI are more likely to achieve sustainable growth.

Additionally, the thesis emphasizes the importance of managing energy expenditures to maintain a balance that supports growth. The Granger causality tests reveal a bidirectional relationship between energy expenditure and economic growth, emphasizing the mutual influence of these factors in shaping long-term economic stability.

Regarding the energy transition, the findings underscore the necessity of improving energy production efficiency, particularly in renewable sectors, to sustain economic output as non-renewable resources deplete. As such, transitioning to more efficient, renewable energy sources is not only essential for environmental sustainability but also crucial for maintaining high economic growth.

Overall, the research shows that policies aiming to reduce energy intensity and improve energy efficiency will be key to ensuring economic resilience. By fostering a transition to renewable energy with a high EROI, economies can mitigate the risks of energy volatility and continue to grow sustainably.

Future research could expand on this by incorporating more dynamic variables such as technological innovation and resource availability, providing a more detailed understanding of the relationship between energy systems and economic growth. This would further help guide policies aimed at promoting a sustainable and resilient energy future.

Referências

ABOLHOSSEINI, S.; HESHMATI, A. The main support mechanisms to finance renewable energy development. **Renewable and Sustainable Energy Reviews**, Elsevier, v. 40, p. 876–885, 2014. 16

ACEMOGLU, D. Introduction to modern economic growth. **Privredna kretanja i ekonomska politika**, v. 123, p. 89, 2010. 35

AHN, S. K. Some tests for unit roots in autoregressive-integrated-moving average models with deterministic trends. **Biometrika**, Oxford University Press, v. 80, n. 4, p. 855–868, 1993. 39

AMSLER, C.; LEE, J. An lm test for a unit root in the presence of a structural change. **Econometric Theory**, Cambridge University Press, v. 11, n. 2, p. 359–368, 1995. 39

ANDOR, M. A.; FRONDEL, M.; SOMMER, S. Equity and the willingness to pay for green electricity in germany. **Nature Energy**, Nature Publishing Group, v. 3, n. 10, p. 876–881, 2018. 33

ARGENTIERO, A. et al. Renewable energy sources policies in a bayesian dsge model. **Renewable Energy**, Elsevier, v. 120, p. 60–68, 2018. 15, 61

ARNDT, C. et al. Climate change and developing country growth: the cases of malawi, mozambique, and zambia. **Climatic Change**, Springer, v. 154, n. 1, p. 1–16, 2019. 29

ATKINS, P. **The laws of thermodynamics: A very short introduction**. [S.l.]: OUP Oxford, 2010. 25

AYRES, R. U. The second law, the fourth law, recycling and limits to growth. **Ecological economics**, Elsevier, v. 29, n. 3, p. 473–483, 1999. 26

BAI, J.; CARRION-I-SILVESTRE, J. L. Structural changes, common stochastic trends, and unit roots in panel data. **The Review of Economic Studies**, Wiley-Blackwell, v. 76, n. 2, p. 471–501, 2009. 37, 38, 44

BAI, J.; NG, S. A panic attack on unit roots and cointegration. **Econometrica**, Wiley Online Library, v. 72, n. 4, p. 1127–1177, 2004. 37

BANERJEE, A.; SILVESTRE, J. L. Carrion-i. Cointegration in panel data with structural breaks and cross-section dependence. **Journal of Applied Econometrics**, Wiley Online Library, v. 30, n. 1, p. 1–23, 2015. 38

BARNHART, C. J.; BRANDT, A. R.; BENSON, S. M. The energetic implications of curtailing versus storing solar- and wind-generated electricity. **Energy & Environmental Science**, 2013. 63

BARRO, R.; MARTIN, X. Sala-i. **Economic growth second edition**. [S.l.]: Cambridge MA.: The MIT Press, 2004. 35

BASHMAKOV, I. Three laws of energy transitions. **Energy Policy**, Elsevier, v. 35, n. 7, p. 3583–3594, 2007. 34

BOSCH, S.; SCHMIDT, M. Wonderland of technology? how energy landscapes reveal inequalities and injustices of the german energiewende. **Energy Research & Social Science**, Elsevier, v. 70, p. 101733, 2020. 33

BRAND-CORREA, L. I. et al. Developing an input-output based method to estimate a national-level energy return on investment (eroi). **Energies**, MDPI, v. 10, n. 4, p. 534, 2017. 52, 63, 69, 70

BRASIL. República Federativa do Brasil. **Intended Nationally Determined Contributions.** Brasília, 2016. 15, 33

BREUSCH, T. S.; PAGAN, A. R. The lagrange multiplier test and its applications to model specification in econometrics. **The review of economic studies**, JSTOR, v. 47, n. 1, p. 239–253, 1980. 36

BROWN, C. et al. An agent-based modelling approach to evaluate factors influencing bioenergy crop adoption in north-east scotland. **Gcb Bioenergy**, Wiley Online Library, v. 8, n. 1, p. 226–244, 2016. 31

CALVIN, K. et al. Global market and economic welfare implications of changes in agricultural yields due to climate change. **Climate Change Economics**, World Scientific, v. 11, n. 1, 2020. 29, 55, 56, 58

CASS, D. Optimum growth in an aggregative model of capital accumulation. **The Review of economic studies**, JSTOR, v. 32, n. 3, p. 233–240, 1965. 21

CAVALCANTI, T. V. d. V.; MOHADDES, K.; RAISSI, M. Growth, development and natural resources: New evidence using a heterogeneous panel analysis. **The Quarterly Review of Economics and Finance**, Elsevier, v. 51, n. 4, p. 305–318, 2011. 37

CHEN, J. et al. The sustainable potential of efficient air-transportation industry and green innovation in realising environmental sustainability in g7 countries. **Economic Research-Ekonomska Istraživanja**, Taylor & Francis, p. 1–22, 2021. 37

CHENG, Y.; YAO, X. Carbon intensity reduction assessment of renewable energy technology innovation in china: A panel data model with cross-section dependence and slope heterogeneity. **Renewable and Sustainable Energy Reviews**, Elsevier, v. 135, p. 110157, 2021. 37

CHINA. República da China - Comissão de Desenvolvimento e Reforma. **Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions**. Pequim, 2015. 15, 33

CLEVELAND, C. J. **Biophysical economics: from physiocracy to ecological economics and industrial ecology**. [S.l.]: Edward Elgar Publishing, Cheltenham, England, 1999. 22

CLEVELAND, C. J. et al. Energy and the us economy: a biophysical perspective. **Science**, American Association for the Advancement of Science, v. 225, n. 4665, p. 890–897, 1984. 24, 35

CLEVELAND, C. J.; O'CONNOR, P. Energy return on investment (eroi) of oil shale. **Sustainability**, MDPI, v. 3, n. 11, p. 2307–2321, 2011. 31, 52

COMMON, M.; PERRINGS, C. Towards an ecological economics of sustainability. **Ecological economics**, Elsevier, v. 6, n. 1, p. 7–34, 1992. 26

COURT, V. **Energy, EROI, and Economic Growth in a Long-Term Perspective**. Tese (Doutorado), 11 2016. 16, 17, 23, 26

COURT, V.; FIZAINE, F. Long-term estimates of the energy-return-on-investment (eroi) of coal, oil, and gas global productions. **Ecological Economics**, Elsevier, v. 138, p. 145–159, 2017. 35

COURT, V.; JOUVET, P.-A.; LANTZ, F. Long-term endogenous economic growth and energy transitions. **The Energy Journal**, v. 39, n. 1, 2018. 17, 18, 28, 56

CROMPTON, J. Proceedings of the thirty-ninth meeting of the agricultural research modellers' group. **The Journal of Agricultural Science**, v. 145, n. 1, p. 1–10, 2007. 30

DALE, M.; KRUMDIECK, S.; BODGER, P. A dynamic function for energy return on investment. **Sustainability**, Molecular Diversity Preservation International, v. 3, n. 10, p. 1972–1985, 2011. 28

DALE, M.; KRUMDIECK, S.; BODGER, P. Net energy yield from production of conventional oil. **Energy policy**, Elsevier, v. 39, n. 11, p. 7095–7102, 2011. 63

DALY, H. E. **The steady-state economy**. [S.l.]: na, 1977. 24

DALY**, H. E. The circular flow of exchange value and the linear throughput of matter-energy: a case of misplaced concreteness. **Review of Social Economy**, Taylor & Francis, v. 43, n. 3, p. 279–297, 1985. 23

DALY, H. E. **Beyond growth: the economics of sustainable development**. [S.l.]: Beacon Press, 1996. 22

DASGUPTA, P.; LEVIN, S.; LUBCHENCO, J. Economic pathways to ecological sustainability. **BioScience**, BioOne, v. 50, n. 4, p. 339–345, 2000. 24

DONG, K. et al. Co2 emissions, economic and population growth, and renewable energy: empirical evidence across regions. **Energy Economics**, Elsevier, v. 75, p. 180–192, 2018. 37

DRANKA, G. G.; FERREIRA, P. V. Planning for a renewable future in the brazilian power system. **Energy**, 2018. 58

DUMAS, P. et al. The energy return on investment of whole energy systems: application to belgium. **Biophysical Economics and Sustainability**, Springer, v. 7, n. 1, p. 1–20, 2022. 55, 57, 62

DUPONT, A. et al. Feasibility and economic impacts of the energy transition. **Sustainability**, MDPI, v. 13, n. 10, p. 5345, 2021. 29, 54

DUPONT, E.; GERMAIN, M.; JEANMART, H. Estimate of the societal energy return on investment (eroi). **Biophysical Economics and Sustainability**, Springer, v. 6, n. 1, p. 1–14, 2021. 47

EBERHARDT, M. Estimating panel time-series models with heterogeneous slopes. **The Stata Journal**, SAGE Publications Sage CA: Los Angeles, CA, v. 12, n. 1, p. 61–71, 2012. 40

EBERHARDT, M.; BOND, S. Cross-section dependence in nonstationary panel models: A novel estimator (mpra paper no. 17692). **Germany: University Library of Munich**, 2009. 37, 40, 45

EIA. Energy Information Administration. **Eletric Power Monthly.** United States of America, 2021. 14, 33

EPE. Empresa de Pesquisa Energética. **Balanço Energético Nacional: Relatório Síntese Ano Base 2020.** Brasil, 2021. 15, 33

EUA.Estados Unidos da América. **The United States' Nationally Determined Contribution Reducing Greenhouse Gases in the United States: A 2030 Emissions Target**. [S.l.], 2021. 15, 33

Europian Commission. **Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions. : A policy framework for climate and energy in the period from 2020 to 2030**. Brussels, 2014. 15, 33

FAGNART, J.-F.; GERMAIN, M. et al. Can the energy transition be smooth? In: **CEREC Discussion Paper 2014–11 and FAERE Working Paper 215.04**. [S.l.: s.n.], 2014. 28

FAGNART, J.-F.; GERMAIN, M.; PEETERS, B. Can the energy transition be smooth? a general equilibrium approach to the eroei. **Sustainability**, Multidisciplinary Digital Publishing Institute, v. 12, n. 3, p. 1176, 2020. 18, 27

FENG, Y.; FENG, J. Literature review about mainstream economics and biophysical economics. **Destech Transactions on Economics Business and Management**, v. 2019, p. 1–10, 2019. 30, 52, 54, 69

FIZAINE, F.; COURT, V. Energy expenditure, economic growth, and the minimum eroi of society. **Energy Policy**, Elsevier, v. 95, p. 172–186, 2016. 28, 34, 40, 41, 46, 47

FOLKE, C.; CHAPIN, F. S.; OLSSON, P. Transformations in ecosystem stewardship. In: **Principles of ecosystem stewardship**. [S.l.]: Springer, 2009. p. 103–125. 17

FRAME, T. Economic integration in tanzania (1970–2011): A biophysical assessment. **Journal of Industrial Ecology**, Wiley, v. 19, n. 2, p. 263–275, 2015. 57

GARRETT, T. J. Long-run evolution of the global economy: 1. physical basis. **Earth's Future**, Wiley Online Library, v. 2, n. 3, p. 127–151, 2014. 26

GARRETT, T. J. Long-run evolution of the global economy–part 2: Hindcasts of innovation and growth. **Earth System Dynamics**, Copernicus GmbH, v. 6, n. 2, p. 673–688, 2015. 26

GEORGESCU-ROEGEN, N. **The Entropy Law and the Economic Process**. [S.l.]: Harvard University Press, 1971. 22, 23

GROSSMAN, G. M.; HELPMAN, E. **Innovation and growth in the global economy**. [S.l.]: MIT press, 1991. 17

HABERL, H. et al. Contributions of sociometabolic research to sustainability science. **Nature Sustainability**, Nature Publishing Group, v. 2, n. 1, p. 1–11, 2019. 52

HALL, C.; KLITGAARD, K. The need for a new, biophysical-based paradigm in economics for the second half of the age of oil. **International Journal of Transdisciplinary Research**, v. 1, n. 1, p. 4–22, 2006. 22

HALL, C. et al. The Need to Reintegrate the Natural Sciences with Economics: Neoclassical economics, the dominant form of economics today, has at least three fundamental flaws from the perspective of the natural sciences, but it is possible to develop a different, biophysical basis for economics that can serve as a supplement to, or a replacement for, neoclassical economics. **BioScience**, v. 51, n. 8, p. 663–673, 08 2001. ISSN 0006-3568. Disponível em: <https://doi.org/10.1641/0006-3568(2001)051[0663:TNTRTN]2.0.CO;2>. 24, 25, 26

HALL, C. A.; BALOGH, S.; MURPHY, D. J. What is the minimum eroi that a sustainable society must have? **Energies**, Molecular Diversity Preservation International, v. 2, n. 1, p. 25–47, 2009. 35, 46

HALL, C. A.; KLITGAARD, K. **Energy and the wealth of nations: An introduction to biophysical economics**. [S.l.]: Springer, 2018. 22, 23

HALL, C. A.; KLITGAARD, K. A. **Energy and the wealth of nations: understanding the biophysical economy**. [S.l.]: Springer Science & Business Media, 2011. 22, 23, 24

HALL, C. A.; LAMBERT, J. G.; BALOGH, S. B. Eroi of different fuels and the implications for society. **Energy policy**, Elsevier, v. 64, p. 141–152, 2014. 16, 41

HALL, C. A. S. Ecological economics: principles and applications. **Choice Reviews Online**, v. 41, n. 5, 2004. 31, 52, 56

HAMIT-HAGGAR, M. Clean energy-growth nexus in sub-saharan africa: Evidence from cross-sectionally dependent heterogeneous panel with structural breaks. **Renewable and Sustainable Energy Reviews**, Elsevier, v. 57, p. 1237–1244, 2016. 38

HEUN, M. Energy return on (energy) invested (eroi), oil prices, and energy transitions. **Energy Policy**, v. 45, p. 1–10, 2012. 53, 54, 56, 58

HOLTZ-EAKIN, D.; NEWEY, W.; ROSEN, H. S. Estimating vector autoregressions with panel data. **Econometrica: Journal of the econometric society**, JSTOR, p. 1371–1395, 1988. 41

HOTELLING, H. The economics of exhaustible resources. **Journal of political Economy**, The University of Chicago Press, v. 39, n. 2, p. 137–175, 1931. DOI: 10.1086/254195. 21

IEA. International Energy Agency. **Electricity mix in China.** Paris, 2020. 14, 33

IEA. International Energy Agency. **Electricity mix in the European Union.** Paris, 2020. 15, 33

IEA. International Energy Agency. **Global electricity generation mix, 2010-2020.** Paris, France, 2021. 14, 33

IEA. International Energy Agency. **Global Energy Review 2021.** Paris, France, 2021. 14, 33

IEA. International Energy Agency. **Theme Report on Energy Transition: Towards the Achievement of SDG 7 and Net-Zero Emissions**. Paris, 2021. 17

IM, K. S.; PESARAN, M. H.; SHIN, Y. Testing for unit roots in heterogeneous panels. **Journal of econometrics**, Elsevier, v. 115, n. 1, p. 53–74, 2003. 36, 37

JEVONS, W. S. The coal question. **An Inquiry Concerning the Prog**, 1862. 21

JIN, T. Impact of heat and electricity consumption on energy intensity: A panel data analysis. **Energy**, Elsevier, v. 239, p. 121903, 2022. 38, 40

JR, R. E. L. On the mechanics of economic development. **Journal of monetary economics**, Elsevier, v. 22, n. 1, p. 3–42, 1988. 17

KAPETANIOS, G.; PESARAN, M. H.; YAMAGATA, T. Panels with non-stationary multifactor error structures. **Journal of econometrics**, Elsevier, v. 160, n. 2, p. 326–348, 2011. 43

KHAN, I. et al. The dynamic links among energy transitions, energy consumption, and sustainable economic growth: A novel framework for iea countries. **Energy**, Elsevier, v. 222, p. 119935, 2021. 14

KIM, J. E. Sustainable energy transition in developing countries: the role of energy aid donors. **Climate Policy**, Taylor & Francis, v. 19, n. 1, p. 1–16, 2019. 17

KING, C. W. Comparing world economic and net energy metrics, part 3: Macroeconomic historical and future perspectives. **Energies**, MDPI, v. 8, n. 11, p. 12997–13020, 2015. 34

KING, C. W.; HALL, C. A. Relating financial and energy return on investment. **Sustainability**, Molecular Diversity Preservation International (MDPI), v. 3, n. 10, p. 1810–1832, 2011. 41

KING, C. W.; MAXWELL, J. P.; DONOVAN, A. Comparing world economic and net energy metrics, part 2: total economy expenditure perspective. **Energies**, Multidisciplinary Digital Publishing Institute, v. 8, n. 11, p. 12975–12996, 2015. 34, 41

KLING, C. et al. Integrated assessment models of the food, energy, and water nexus: A review and an outline of research needs. **Annual Review of Resource Economics**, v. 9, p. 1–20, 2017. 30, 53, 54, 56

KLITGAARD, R. Sustainability as an economic issue: A biophysical economic perspective. **Sustainability**, MDPI, v. 12, n. 1, p. 364, 2020. 52, 54, 55, 57, 58

KONG, Z. et al. Energy return on investment, energy payback time, and greenhouse gas emissions of coal seam gas (csg) production in china: A case of the fanzhuang csg project. **Petroleum Science**, 2017. 62, 70

KOOPMANS, T. C. et al. **On the concept of optimal economic growth**. [S.l.], 1963. 21

KRALL, L.; KLITGAARD, K. Ecological economics and institutional change. **Annals of the New York Academy of Sciences**, Wiley Online Library, v. 1219, n. 1, p. 185–196, 2011. 22

KREPS, B. H. The rising costs of fossil-fuel extraction: An energy crisis that will not go away. **American Journal of Economics and Sociology**, 2020. 62, 70

KRYSIAK, F. C. Entropy, limits to growth, and the prospects for weak sustainability. **Ecological Economics**, Elsevier, v. 58, n. 1, p. 182–191, 2006. 26

KÜMMEL, R.; AYRES, R. U.; LINDENBERGER, D. Thermodynamic laws, economic methods and the productive power of energy. Walter de Gruyter GmbH & Co. KG, 2010. 25

KÜMMEL, R.; HENN, J.; LINDENBERGER, D. Capital, labor, energy and creativity: modeling innovation diffusion. **Structural Change and Economic Dynamics**, Elsevier, v. 13, n. 4, p. 415–433, 2002. 61

KUNGL, G. Stewards or sticklers for change? incumbent energy providers and the politics of the german energy transition. **Energy Research & Social Science**, Elsevier, v. 8, p. 13–23, 2015. 33

LAMBERT, J. G. et al. Energy, eroi and quality of life. **Energy Policy**, Elsevier, v. 64, p. 153–167, 2014. 34

LEVIN, A.; LIN, C.-F.; CHU, C.-S. J. Unit root tests in panel data: asymptotic and finite-sample properties. **Journal of econometrics**, Elsevier, v. 108, n. 1, p. 1–24, 2002. 36, 37

LI, Z.-Z. et al. Determinants of carbon emission in china: how good is green investment? **Sustainable Production and Consumption**, Elsevier, v. 27, p. 392–401, 2021. 37

LIDDLE, B.; LUNG, S. The long-run causal relationship between transport energy consumption and gdp: Evidence from heterogeneous panel methods robust to cross-sectional dependence. **Economics Letters**, Elsevier, v. 121, n. 3, p. 524–527, 2013. 37, 41, 42

LUZADIS, V. A. et al. The science of ecological economics: a content analysis of ecological economics, 1989–2004. **Annals of the New York Academy of Sciences**, Wiley Online Library, v. 1185, n. 1, p. 1–10, 2010. 51

LV, Z.; XU, T. Is economic globalization good or bad for the environmental quality? new evidence from dynamic heterogeneous panel models. **Technological Forecasting and Social Change**, Elsevier, v. 137, p. 340–343, 2018. 37

MA, B. Does urbanization affect energy intensities across provinces in china? long-run elasticities estimation using dynamic panels with heterogeneous slopes. **Energy Economics**, Elsevier, v. 49, p. 390–401, 2015. 37

MACIAS, A.; MATILLA-GARCIA, M. Net energy analysis in a ramsey–hotelling growth model. **Energy Policy**, Elsevier, v. 86, p. 562–573, 2015. 21

MACIAS, A.; MATILLA-GARCíA, M. Net energy analysis in a ramsey–hotelling growth model. **Energy Policy**, Elsevier, v. 77, p. 1–10, 2015. 53

MAO, G.; SHEN, Y. Bubbles or fundamentals? modeling provincial house prices in china allowing for cross-sectional dependence. **China Economic Review**, Elsevier, v. 53, p. 53–64, 2019. 37

MARK, N. C.; SUL, D. Cointegration vector estimation by panel dols and long-run money demand. **Oxford Bulletin of Economics and statistics**, Wiley Online Library, v. 65, n. 5, p. 655–680, 2003. 39

MATHIESEN, B. V.; LUND, H.; KARLSSON, K. 100% renewable energy systems, climate mitigation and economic growth. **Applied energy**, Elsevier, v. 88, n. 2, p. 488–501, 2011. 16

MAYUMI, K. **The origins of ecological economics: the bioeconomics of Georgescu-Roegen**. [S.l.]: Routledge, 2001. v. 1. 22

MELLO, C. R. de et al. Climate change impacts on water resources of the largest hydropower plant reservoir in southeast brazil. **Water**, 2021. 58

MOON, H. R.; PERRON, B. Beyond panel unit root tests: Using multiple testing to determine the nonstationarity properties of individual series in a panel. **Journal of Econometrics**, Elsevier, v. 169, n. 1, p. 29–33, 2012. 37

MURPHY, D. J. The implications of the declining energy return on investment of oil production. **Philosophical Transactions of the Royal Society a Mathematical Physical and Engineering Sciences**, 2014. 62, 70

MURPHY, D. J.; HALL, C. A. Year in review—eroi or energy return on (energy) invested. **Annals of the New York Academy of Sciences**, Blackwell Publishing Inc Malden, USA, v. 1185, n. 1, p. 102–118, 2010. 26, 27

MURPHY, D. J.; HALL, C. A. Energy return on investment, peak oil, and the end of economic growth. **Annals of the New York Academy of Sciences**, Wiley Online Library, v. 1219, n. 1, p. 52–72, 2011. 33

MURPHY, D. J. et al. Order from chaos: a preliminary protocol for determining the eroi of fuels. **Sustainability**, Molecular Diversity Preservation International, v. 3, n. 10, p. 1888–1907, 2011. 27, 62, 70

MURPHY, D. J.; HALL, C. A.; POWERS, B. New perspectives on the energy return on (energy) investment (eroi) of corn ethanol. **Environment, development and sustainability**, Springer, v. 13, n. 1, p. 179–202, 2011. 27

MURPHY, D. J. et al. Energy return on investment of major energy carriers: Review and harmonization. **Sustainability**, 2022. 70

MURSHED, M. Can regional trade integration facilitate renewable energy transition to ensure energy sustainability in south asia? **Energy Reports**, Elsevier, v. 7, p. 808–821, 2021. 37

MUSAH, M. et al. The link between carbon emissions, renewable energy consumption, and economic growth: a heterogeneous panel evidence from west africa. **Environmental Science and Pollution Research**, Springer, v. 27, n. 23, p. 28867–28889, 2020. 37

NAKAJIMA, Y.; MATSUSHIMA, J. Japan's low-growth economy from the viewpoint of energy quality. **International Journal of Energy Economics and Policy**, v. 12, n. 1, p. 460–468, 2022. 58

NASREEN, S.; MBAREK, M. B.; REHMAN, M. Atiq-ur. Long-run causal relationship between economic growth, transport energy consumption and environmental quality in asian countries: Evidence from heterogeneous panel methods. **Energy**, Elsevier, v. 192, p. 116628, 2020. 41, 42

NIETO, J. et al. An ecological macroeconomics model: The energy transition in the eu. **Energy Policy**, Elsevier, v. 145, p. 111726, 2020. 15

NORDHAUS, W. D. Resources as a constraint on growth. **The American Economic Review**, JSTOR, v. 64, n. 2, p. 22–26, 1974. 14

NORDHAUS, W. D. Efficient use of energy resources. Yale University Press, New Haven, CT, 1979. 14

ODUM, H. **Environment, Power, and Society**. [S.l.]: New York, USA: John Wiley Sons Inc, 1971. 22

ODUM, H. T.; ODUM, E. C. Energy basis for man and nature. McGraw-Hill Book Company, New York, 1976. 22

OVIEDO-TORAL, L.-P.; FRANÇOIS, D. E.; POGANIETZ, W.-R. Challenges for energy transition in poverty-ridden regions—the case of rural mixteca, mexico. **Energies**, Multidisciplinary Digital Publishing Institute, v. 14, n. 9, p. 2596, 2021. 17

PALMER, C. A biophysical perspective of ipcc integrated energy modelling. **Energies**, MDPI, v. 11, n. 4, p. 839, 2017. 53

PANWAR, N. et al. Sustainable development with renewable energy resources: a review. **World Review of Science, Technology and Sustainable Development**, Inderscience Publishers Ltd, v. 10, n. 4, p. 163–184, 2013. 14, 32

PEDRONI, P. Fully modified ols for heterogeneous cointegrated panels. In: **Nonstationary panels, panel cointegration, and dynamic panels**. [S.l.]: Emerald Group Publishing Limited, 2001. 39

PEDRONI, P. Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the ppp hypothesis. **Econometric theory**, Cambridge University Press, v. 20, n. 3, p. 597–625, 2004. 44

PESARAN, M. H. Estimation and inference in large heterogeneous panels with a multifactor error structure. **Econometrica**, Wiley Online Library, v. 74, n. 4, p. 967–1012, 2006. 39, 45

PESARAN, M. H. A simple panel unit root test in the presence of cross-section dependence. **Journal of applied econometrics**, Wiley Online Library, v. 22, n. 2, p. 265–312, 2007. 37

PESARAN, M. H. General diagnostic tests for cross-sectional dependence in panels. **Empirical Economics**, Springer, v. 60, p. 13–50, 2021. 36, 42, 43

PESARAN, M. H.; YAMAGATA, T. Testing slope homogeneity in large panels. **Journal of econometrics**, Elsevier, v. 142, n. 1, p. 50–93, 2008. 37, 43

POISSON, A.; HALL, C. A. S. Time series eroi for canadian oil and gas. **Energies**, 2013. 70

PRIGOGINE, I.; NICOLIS, G. On symmetry-breaking instabilities in dissipative systems. **The Journal of Chemical Physics**, American Institute of Physics, v. 46, n. 9, p. 3542–3550, 1967. 23

QUITZOW, R.; ROEHRKASTEN, S.; JÄNICKE, M. The german energy transition in international perspective. **IASS Studies Available online: https://www. iasspotsdam. de/, accessed on**, v. 10, p. 2018, 2016. 33

RANA, R. L. et al. Trends in scientific literature on energy return ratio of renewable energy sources for supporting policymakers. **Administrative Sciences**, 2020. 69

RAUGEI, M. Energy return on investment: Setting the record straight. **Joule**, 2019. 70

RAUGEI, M.; FULLANA–I–PALMER, P.; FTHENAKIS, V. The energy return on energy investment (eroi) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. **Energy Policy**, 2012. 62, 69

RAUGEI, M. et al. Energy return on energy invested (eroei) for photovoltaic solar systems in regions of moderate insolation: A comprehensive response. **Energy Policy**, Elsevier, v. 102, p. 377–384, 2017. 62

RITCHIE, H.; ROSER, M.; ROSADO, P. Energy. **Our World in Data**, 2022. Https://ourworldindata.org/energy. 47

ROMER, P. M. Endogenous technological change. **Journal of political Economy**, The University of Chicago Press, v. 98, n. 5, Part 2, p. S71–S102, 1990. 17

RØPKE, I. The early modern history of ecological economics. **Ecological Economics**, v. 50, p. 293–314, 2004. 22

SADORSKY, P. The effect of urbanization on co2 emissions in emerging economies. **Energy economics**, Elsevier, v. 41, p. 147–153, 2014. 37

SAUD, S.; CHEN, S. et al. An empirical analysis of financial development and energy demand: establishing the role of globalization. **Environmental Science and Pollution Research**, Springer, v. 25, n. 24, p. 24326–24337, 2018. 14

SCHMIDT, P.; PHILLIPS, P. C. et al. Lm tests for a unit root in the presence of deterministic trends. **Oxford bulletin of economics and statistics**, v. 54, n. 3, p. 257–287, 1992. 39

SHAHZAD, U. et al. Does export product diversification help to reduce energy demand: Exploring the contextual evidences from the newly industrialized countries. **Energy**, Elsevier, v. 214, p. 118881, 2021. 39

SHERWOOD, J.; CARBAJALES-DALE, M.; HANEY, B. R. Putting the biophysical (back) in economics: A taxonomic review of modeling the earth-bound economy. **Biophysical Economics and Sustainability**, Springer, v. 5, p. 1–20, 2020. 23, 51

SHRIMALI, G. Financial performance of renewable and fossil power sources in india. **Sustainability**, 2021. 69

SIEVERS, L. et al. Macroeconomic impact of the german energy transition and its distribution by sectors and regions. **Ecological Economics**, Elsevier, v. 160, p. 191–204, 2019. 15

SMULDERS, S. Entropy, environment, and endogenous economic growth. **International Tax and public finance**, Springer, v. 2, n. 2, p. 319–340, 1995. 26

SOLOW, R. M. A contribution to the theory of economic growth. **The quarterly journal of economics**, MIT Press, v. 70, n. 1, p. 65–94, 1956. 17, 21, 23

SOLOW, R. M. Intergenerational equity and exhaustible resources. **The review of economic studies**, JSTOR, v. 41, p. 29–45, 1974. 23

SOLOW, R. M. Georgescu-roegen versus solow-stiglitz. **Ecological Economics**, v. 22, n. 3, p. 267–268, 1997. ISSN 0921-8009. Disponível em: <https://www.sciencedirect.com/science/article/pii/S0921800997000815>. 23

STANEK, W. et al. Thermo-ecological cost of electricity from renewable energy sources. **Renewable Energy**, Elsevier, v. 115, p. 87–96, 2018. 16

STERN, D. I. Is energy cost an accurate indicator of natural resource quality? **Ecological Economics**, Elsevier, v. 31, n. 3, p. 381–394, 1999. 17

STERN, D. I.; CLEVELAND, C. **Energy and economic growth. Rensselaer Polytechnic Institute**. [S.l.], 2004. 17

STERN, N. **Stern Review: The economics of climate change**. [S.l.]: HM Treasury, London., 2006. 16

STIGLITZ, J. Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths12. **The Review of Economic Studies**, v. 41, n. 5, p. 123–137, 12 1974. ISSN 0034-6527. Disponível em: <https://doi.org/10.2307/2296377>. 23

STIGLITZ, J. E. Georgescu-roegen versus solow/stiglitz. 1997. 23

STOCK, J. H. A class of tests for integration and cointegration. **Cointegration, Causality and Forecasting. A Festschrift in Honour of Clive WJ Granger**, Oxford University Press Oxford, p. 137–167, 1999. 38

STRUNZ, S. The german energy transition as a regime shift. **Ecological Economics**, Elsevier, v. 100, p. 150–158, 2014. 33

TROMBETTA, M. J. Environmental security and climate change: analysing the discourse. **Cambridge Review of International Affairs**, Taylor & Francis, v. 21, n. 4, p. 585–602, 2008. 14

USMAN, M. et al. An empirical nexus between economic growth, energy utilization, trade policy, and ecological footprint: a continent-wise comparison in upper-middle-income countries. **Environmental Science and Pollution Research**, Springer, v. 27, n. 31, p. 38995–39018, 2020. 37

WANG, J.; DONG, K. What drives environmental degradation? evidence from 14 sub-saharan african countries. **Science of the Total Environment**, Elsevier, v. 656, p. 165–173, 2019. 40

WANG, K. et al. Energy return on investment of canadian oil sands extraction from 2009 to 2015. **Energies**, Multidisciplinary Digital Publishing Institute, v. 10, n. 5, p. 614, 2017. 62

WARD, A. et al. Integrating fast and slow processes is essential for simulating human–freshwater interactions. **Ambio**, v. 47, n. 3, p. 1–10, 2018. 31, 54

WEIBACH, D. et al. Energy intensities, erois (energy returned on invested), and energy payback times of electricity generating power plants. **Energy**, 2013. 62, 71

WESTERLUND, J.; EDGERTON, D. L. A simple test for cointegration in dependent panels with structural breaks. **Oxford Bulletin of Economics and Statistics**, Wiley Online Library, v. 70, n. 5, p. 665–704, 2008. 38, 44

YAN, J. et al. Biophysical economics as a new economic paradigm. **International Journal of Public Administration**, Taylor & Francis, v. 42, n. 15-16, p. 1395–1407, 2019. 22

YAO, Y. et al. Human capital and energy consumption: Evidence from oecd countries. **Energy Economics**, Elsevier, v. 84, p. 104534, 2019. 38

ZAFAR, M. W. et al. From nonrenewable to renewable energy and its impact on economic growth: the role of research & development expenditures in asia-pacific economic cooperation countries. **Journal of cleaner production**, Elsevier, v. 212, p. 1166–1178, 2019. 14

ZHANG, Y. et al. Macroeconomic effect of energy transition to carbon neutrality: Evidence from china's coal capacity cut policy. **Energy Policy**, Elsevier, v. 155, p. 112374, 2021. 15