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EXERGY-BASED METHOD FOR AN ENERGY-SERVICE-INVESTMENT-RETURN ASSESSMENT

Marcus Vinicius da Silva Neves

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Orientadores: Alexandre Salem Szklo
Roberto Schaeffer

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Orientadores: Alexandre Salem Szklo
Roberto Schaeffer

Aprovada por: Prof. Alexandre Salem Szklo
Prof. Roberto Schaeffer
Prof. David Alves Castelo Branco
Prof. Rafael Silva Capaz
Prof. Waldyr Luiz Ribeiro Gallo

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To my parents Jurandir and Sonia; my wife Daniele; and my children Carol and Marquinho.

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With sincere appreciation and modesty,
Marcus

Resumo da Tese apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Doutor em Ciências (D.Sc.)

MÉTODO BASEADO EM EXERGIA PARA AVALIAÇÃO DE RETORNO DE INVESTIMENTO DE SERVIÇOS ENERGÉTICOS

Marcus Vinicius da Silva Neves

Setembro/2024

Orientadores: Alexandre Salem Szklo
Roberto Schaeffer

Programa: Planejamento Energético

No contexto de uma significativa transição energética em curso, esta tese investiga como aprimorar as avaliações de sustentabilidade pela integração do conceito de retorno sobre investimento energético (EROI) com uma análise baseada em exergia. Apresenta o conceito de Retorno de Exergia sobre o Investimento Energético e do meio ambiente (ExROEEI), uma métrica inovadora que considera o ciclo de vida de projetos e empreendimentos, a qualidade da energia e os custos de exergia relacionados à mitigação de emissões de CO_2 e de outros esforços ambientais. Uma revisão bibliográfica detalhada faz parte do estudo, que também inclui o desenvolvimento do indicador ExROEEI. Este indicador avalia os gastos de capital e operacionais em exergia, o uso direto e indireto de exergia, e os impactos ambientais — incluindo os globais medidos pelas emissões de CO_2. O estudo demonstra a necessidade de avaliações personalizadas ao destacar as diferenças no ExROEEI e no Índice de Intensidade de Emissão de CO_2 (CEII) entre diferentes sistemas de energia, quando aplicado a cinco estudos de caso, incluindo usinas a carvão e a gás natural equipadas com tecnologia de captura de carbono, bem como usinas de biogás. Os resultados apoiam a expansão do escopo avaliações ambientais e de qualidade da energia em estruturas padrão de análise energética para fornecer representações mais profundas da sustentabilidade e eficiência dos sistemas energéticos. Em busca de um futuro sustentável de baixo carbono, esta pesquisa contribui para o debate acadêmico sobre transições energéticas ao propor um forte arcabouço para aplicações industriais e políticas no futuro.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

EXERGY-BASED METHOD FOR AN ENERGY-SERVICE-INVESTMENT-RETURN ASSESSMENT

Marcus Vinicius da Silva Neves

September/2024

Advisors: Alexandre Salem Szklo
Roberto Schaeffer

Department: Energy Planning

Amid a major energy transition underway, this thesis investigates how to improve sustainability assessments by integrating the concept of energy return on investment (EROI) with an exergy analysis. It presents the Exergy Return on Environment and Energy Investment (ExROEEI) concept, a novel metric that considers the lifecycle of projects and enterprises, energy quality, and the exergy costs related to CO2 mitigation and environmental efforts. A thorough literature analysis is part of it, which also incorporates the development of the ExROEEI indicator. This indicator evaluates capital and operating exergy expenditures, direct and indirect exergy usage, and environmental impacts—including global ones measured by CO2 emissions. The study demonstrates the necessity for customized assessments by highlighting differences in ExROEEI and CO2 Emission Intensity Index (CEII) across different power systems, when applied to five case studies including coal-based and natural gas equipped with carbon capture technology, as well as biogas power plants. Our results support expanding the scope of environmental and quality measures in standard energy analysis frameworks to provide more in-depth representations of the sustainability and efficiency of energy systems. In search of a sustainable low-carbon future, this research contributes to the academic debate on energy transitions by putting forward a strong framework for industrial and policy applications in the future.

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1 INTRODUCTION – EVOLUTION OF EROI AND THE IDEA OF EXERGY

To achieve climate stability, a structural shift to a low-carbon economy is essential (IPCC, 2022, RIAHI *et al.*, 2023). While using renewable energy is necessary to combat climate change, a low-carbon energy transition may have an impact on everyone's access to modern, dependable, and reasonably priced energy services because fossil fuels are typically more energy dense and even more affordable in certain developing countries and areas (CRONIN *et al.*, 2021, NERINI *et al.*, 2019). In fact, several studies show that fossil fuels have a higher Energy Return on Investment (EROI) than their renewable alternatives (HALL, 2017, HALL; CLEVELAND, 1981). However, other studies (FOUQUET; PEARSON, 2012, HALL *et al.*, 2014, LAMBERT *et al.*, 2014) highlight the net surplus of energy carriers that calls into question the complete transition to renewable sources. Accordingly, in a low-carbon energy system, the surplus energy (or the net available energy) may decline, necessitating improvements in energy efficiency and ultimately even degrowth (KLITGAARD; KRALL, 2012, LAMBERT *et al.*, 2014).

Nonetheless, consideration must also be given to the environmental effects of energy carriers when assessing and comparing them, in addition to their net energy services. They must specifically adhere to the goal of limiting the rise in the global surface temperature. This entails cutting greenhouse gas (GHG) emissions gradually and eventually reaching net zero CO_2 emissions (FANKHAUSER *et al.*, 2022, VAN SOEST *et al.*, 2021). Put differently, reducing the amount of fossil fuels used in the world's energy system, or what is sometimes referred to as the "decarbonization of the economy," is intimately associated with the energy transition that aims to achieve this goal (FOXON *et al.*, 2008, GRUBB *et al.*, 2008).

The urgent need for decarbonization and the pursuit of renewable energy sources are driving an extraordinary shift in the current global energy landscape. This transformation is marked by the difficult task of tackling the pressing issue of climate change while also satisfying the rising demand for modern energy services.

Considering this, the studies on energy efficiency and energy return on investment (EROI) are particularly relevant as frameworks for evaluating the practicality and sustainability of energy-related technology. In order to make the goals of this thesis clearer and place them within a larger energy discourse, this part will go deeper into the development of these concepts, their integration, and their importance within the framework of the current energy transition.

As explained by Hall *et al*. (2014), the concept of Energy Return on Investment (EROI) provides a way to assess the net energetic surplus of different fuels and energy sources. Nevertheless, its ability to evaluate energy systems completely is constrained by its historical emphasis on energy quantity rather than quality. The link between the energy a fuel supplies to society and the energy required to "capture" and "deliver" that energy in a form that is useful to humans is measured by EROI. The ratio, represented as X:Y, emphasizes that a value less than 1 denotes a loss, meaning that more energy was expended than was gained. According to Raugei (2019), this definition of net energy defines "profit" as net energy, which is calculated by weighing the energy generated by resource discovery as "revenue" against the "cost" of the energy spent in such activities.

The idea of "net energy production" was first presented by Cottrell (1955), who realized that part of energy output is used for the extraction and refining of energy resources, while the remaining portion promotes societal growth. This concept served as the foundation for the development of the EROI indicator. This second part is also referred to as "net energy production" or "surplus energy" (ODUM, 1973). EROI was first used by Charles Hall and associates in the 1970s to evaluate the energy efficiency of oil and gas production in the United States. Since then, it has been applied to a wide range of industrial processes and energy sources. Because they produce more energy than is needed for their production, operations with a high EROI are considered more efficient (HALL *et al*., 2009).

According to Cleveland *et al*. (1984), the use of EROI in the search for energy alternatives to oil to continue economic growth positioned the indicator as a crucial driver in addressing the global economy's dependency on finite fossil fuels, a significant societal challenge of the previous century (SMIL, 2004). Subsequent research has refined and expanded on EROI, highlighting its usefulness in assessing the energy sector's sustainability. Studies by Hu *et al*. (2013) and Guilford *et al*. (2011), for example, have shown that the energy efficiency of China's conventional fossil fuels varies, whereas the US oil and gas industry's energy efficiency is decreasing.

The relationship between EROI and quality of life is further discussed by Lambert *et al*. (2014) and Hall (2017), who support EROI as a guiding concept in development, economics, and biology. The significance of efficient and sustainable energy systems for the well-being of society is emphasized by these studies. Furthermore, Brandt *et al*. (2013) emphasize how important it is to include environmental factors in the EROI framework. This more comprehensive, all-encompassing evaluation of energy choices that considers the environmental, economic, and technical aspects offers an essential connection to comprehending the dynamics of past energy transitions.

From the primary energy cycle perspective, energy transitions have been slow processes that have taken decades or even centuries to complete. One may argue that they were all motivated by opportunities, or that their main motivation was the need to find more economical, practical, and efficient energy sources (FOUQUET; PEARSON, 2012, SMIL, 2019). They did not, however, experience the same degree of environmental limitations or worldwide urgency that define the current change (SMIL, 2004). Actually, the understanding that fossil fuels are limited and that using them will negatively affect the climate of the earth is driving the current energy transition. Hence, this transition is problem driven rather than just an evolution towards more efficient energy sources, as it is motivated by the demand for sustainability and environmental preservation (DALE *et al.*, 2012, FOUQUET; PEARSON, 2012, SOVACOOL, 2009). However, the lower energy density of renewable sources further complicates this process, posing challenges to our ability to innovate in energy storage and distribution to meet global demand sustainably.

Given that the current transition is problem and not opportunity-driven, given that the problem is associated with the environmental problem, especially GHG emissions, particularly CO_2, because in this case the comparison between energy options (sources and converters) must include at its border the energy and energy service, the EROI indicator traditionally proposed and applied becomes insufficient. Figure 1 presents average EROI values for some sources, according to Hall *et al*. (2014). As seen in the figure, the average EROI of hydrogen was not presented due to the wide variety of routes for obtaining it, making its calculation unrepresentative Hall *et al*. (2014).

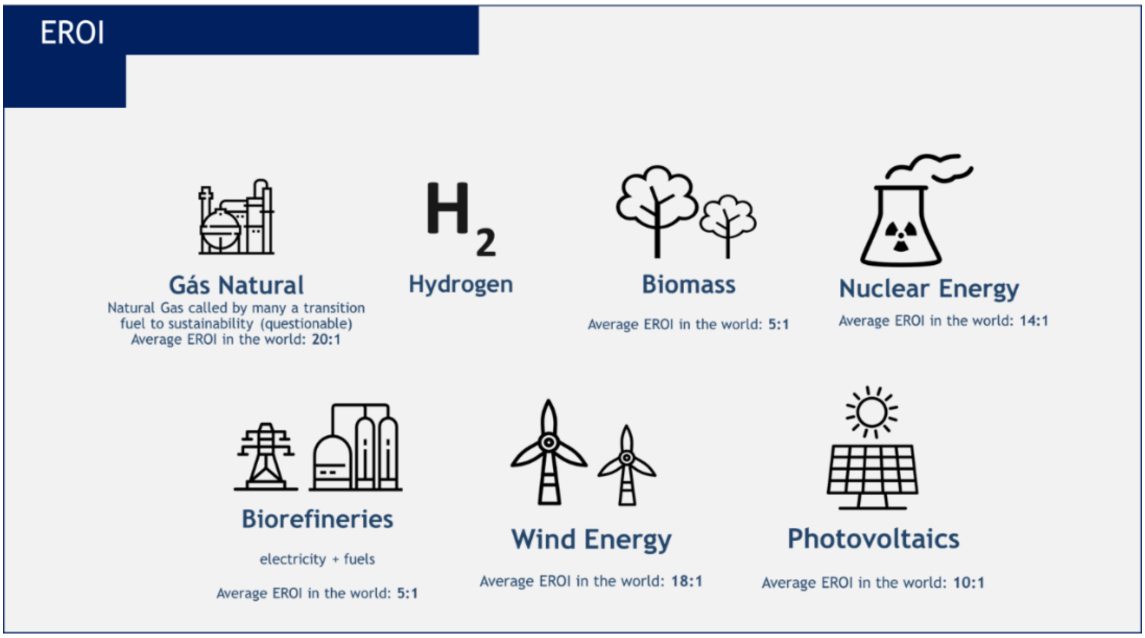

Figure 1 – EROI of different fuels

Source: Prepared by the author, adapted from Hall *et al*. (2014).

One viable approach to creating a more thorough framework for assessing energy systems that is in line with the overarching objectives of climate change mitigation and sustainable development is to incorporate exergy analysis into EROI. This integrated approach reflects the complex problems of making the transition to a sustainable and decarbonized energy future, while also improving the accuracy of energy assessments.

This thesis seeks to provide important insights into the evaluation of the sustainability and efficiency of energy systems, guiding international efforts towards a more sustainable energy landscape and influencing policy decisions by examining the in-depth evolution and integration of exergy and EROI within the framework of the current energy transition. As EROI analysis and other indicators face challenges in comprehensively evaluating the entire problem, this work is particularly relevant as it considers the broad control volume, energy quality, and environmental energy costs, especially those associated with CO_2 emissions.

1.1 OBJECTIVES

This thesis posits that in an era where the judicious use and enhancement of energy efficiency may determine the future habitability of our planet, the focused study of exergy and EROI within the energy transition narrative is not only relevant but imperative.

Therefore, the primary aim of this research is to enhance the domain of energy analysis by introducing and applying a novel framework that merges the principles of Exergy and Energy Return on Investment (EROI). This refined approach broadens the conventional EROI concept to encompass both chemical and physical exergies, and it extends the analysis boundary to include CO_2 emissions from fossil fuels and their capture. This extension is pivotal, as it incorporates the exergy required for CO_2 mitigation into a new, comprehensive indicator. The main objective is to deploy a methodology that integrates the First and Second Laws of Thermodynamics, while establishing the control volume and respective boundary assessments in their most inclusive forms to evaluate the whole lifecycle of the projects. This aims to capture the environmental goal of CO_2 emission control, enabling the evaluation of exergy surpluses from fossil fuel converters, with the dual requirement of providing useful energy and mitigating CO_2 emissions.

Thus, a significant innovative aspect of this methodology, presented by the author in Neves *et al.* (2023), is the development of an alternative to traditional EROI. This alternative method assesses the energy return of conversion processes by considering energy quality (or exergy), the lifecycle of energy processes including both direct and indirect uses of exergy, the exergy expended in the design and construction phases of energy conversion installations (related to the CAPEX – Capital Expenditure), operational and maintenance exergy usage (related to the OPEX – Expenditure), the environmental exergy cost due to generated effluents, and the exergy penalty associated with capturing emitted CO_2. This approach aims to advance the systematization of an appropriate analytical procedure for energy conversion processes, demonstrating the efficacy of this new approach in making meaningful comparisons between energy sources and conversion processes on a uniform basis, particularly considering CO_2 emissions.

To validate the utility of the proposed indicator, this study develops a universally applicable methodology and then applies it to 5 specific case studies: 1) a coal-based power plant equipped with carbon capture technology; 2) a natural gas Brayton or simple cycle power plant equipped with carbon capture technology; 3) a natural gas combined cycle power plant equipped with carbon capture technology; 4) a biogas Brayton or simple cycle power plant; and 5) a biogas combined cycle power plant. All cases are analyzed to provide 331 MW of net power to society. By doing so, the study seeks to illustrate how this innovative indicator can facilitate fair comparisons across diverse energy sources and conversion techniques within the context of an energy transition aimed at reducing CO_2 emissions.

The comprehensive objectives of this thesis are to contribute to the evolving field of energy analysis by integrating an exergy-EROI framework for assessing the sustainability and efficiency of various energy technologies. This encompasses critically reviewing existing Exergy Return on Investment methods, developing a novel solution for evaluating energy conversion processes, and applying this solution to 5 different case studies.

Main characteristics of the thesis project:

1. **Development of an Expanded Concept of EROI:** To propose an expanded EROI model that integrates the chemical and physical exergies and extends the system boundary to include CO_2 emissions and their mitigation as part of a new, comprehensive indicator, as well as the whole life cycle of the project.
2. **Incorporation of Environmental and Exergy Considerations:** To apply a method that includes both the direct and indirect uses of exergy, the exergy utilized in the design, construction (CAPEX), and operation (OPEX) of energy conversion installations, as well as the environmental exergy cost and the exergy penalty for CO_2 capture.
3. **Case Study Analysis:** To apply the developed methodology to 5 thermoelectric power plant cases, demonstrating how these facilities can be evaluated on the same basis, in order to demonstrate the relevance of the proposed indicator for every energy source.
4. **Comparative Assessment:** To determine the effectiveness of this new approach in making meaningful comparisons between different energy sources and conversion processes, considering the lifecycle of energy processes and the aim of CO_2 emission reduction.
5. **Contribution to Energy Transition Analysis:** To utilize the integrated exergy-EROI framework in a conceptual analysis of the energy transition from an exergy investment viewpoint. This involves identifying the strengths and weaknesses of current energy transition scenarios and exploring the opportunities and implications of scenarios based on an exergy analysis.

1.2 THESIS STRUCTURE

This thesis is organized into six main chapters, each dedicated to different aspects of the research, from foundational concepts to detailed case studies and discussions.

The first chapter, Introduction, sets the stage by introducing the research topic, outlining the objectives, and providing an overview of the thesis structure. It aims to contextualize the current energy transition and the need for integrating exergy analysis with EROI to address sustainability and efficiency in energy systems.

The second chapter, Theoretical Background, delves into the essential concepts underpinning the research. It begins with an explanation of the concept of exergy, its significance in energy analysis, and its role in evaluating energy systems. The discussion then shifts to the Energy Return on Investment (EROI) concept, detailing its application from energy extraction to end-use and examining its potential environmental implications. This chapter also explores the integration of exergy analysis with EROI, highlighting the benefits of a combined approach for a more comprehensive evaluation of energy systems. Additionally, it examines the unique characteristics of the current energy transition, emphasizing the need for new analytical frameworks that incorporate sustainability and decarbonization goals.

In the third chapter, Methodology, the thesis details the methodologies developed and employed in the research. It introduces the Exergy Return on Environment and Energy Investment (ExROEEI) indicator, explaining its components and the rationale behind its development. The chapter also describes the CO_2 Emission Intensity Index (CEII), its calculation, and its importance in assessing the environmental impact of different energy systems.

The fourth chapter, Case Studies, presents detailed analyses of five specific energy conversion systems. It outlines the key factors and premises used to ensure a fair and comprehensive comparison between the case studies. The case studies include a coal-based power plant with carbon capture technology, a Brayton-cycle natural gas power plant with carbon capture technology, a combined-cycle natural gas power plant with carbon capture technology, a Brayton-cycle biogas power plant, and a combined-cycle biogas power plant. Each case study is examined to elucidate the nuances and operational outcomes of each energy system.

Chapter five, Discussions and Comparison between Cases, compares the case studies, discussing sensitive aspects, technological challenges, and potential improvements in ExROEEI for each case. This chapter highlights the critical need for evaluating energy systems beyond traditional EROI, incorporating lifecycle and environmental impacts.

The final chapter, Conclusions, concludes the thesis by summarizing the findings and discussing the contributions of the proposed methodology and indicators. It also suggests directions for future research, emphasizing the necessity of context-specific evaluations to accurately gauge the sustainability and efficiency of energy systems. This chapter reinforces the importance of the ExROEEI indicator in guiding energy policies, development strategies, and comparisons between technological alternatives or energy sources.

2 THEORETICAL BACKGROUND

2.1 THE CONCEPT OF EXERGY

The thermodynamic laws, especially the Second Law, introduce a nuanced perspective by highlighting the qualitative differences in energy forms. While the First Law of Thermodynamics focuses on the conservation of energy, offering a quantitative analysis, the Second Law reveals the irreversibilities and entropy generation in energy processes, emphasizing the inevitable reduction in the capacity for energy conversion to perform useful work. The concept of exergy (both physical and chemical), which reflects the maximum potential work that can be extracted from a system, aligns with the Second Law, offering a framework for assessing the efficiency and environmental impact of energy systems more comprehensively.

In the mid-20th century, the term "exergy" was coined by Rant (1956), to describe the maximum useful work obtainable from a system in relationship to the thermodynamic properties of the environment on its surroundings, a concept rooted in the principles originally formulated by Gibbs (1873). This distinction between energy's available and unavailable parts, where the available part is termed exergy, underscores the maximum work a substance, energy, or system can perform as it reaches mechanical, thermal and chemical equilibrium with its environment through a completely reversible process. Exergy, derived from the Greek prefix ex- meaning "out" or "from" and ergon meaning "work," epitomizes the external force or work extractable from a system. This delineation posits exergy as a measure quantitatively gauging a system's deviation from the environmental state, underscoring its zero value when a system is in equilibrium with its surroundings.

This foundational understanding prompts the question: why prioritize a theoretical property like exergy, which seems unattainable in practical terms? The answer lies within the realm of entropy. The Second Law of Thermodynamics elucidates that while the conversion of work into thermal energy is wholly achievable, the reverse process is not, inherently due to entropy increase. Hence, exergy in a defined system state represents the maximum usable work potential, assuming no entropy generation. By measuring the entropy generated in a process, one can evaluate the extent of useful work capacity destroyed, highlighting the degree of irreversibility within the process.

The distinction between energy and exergy becomes clear when considering energy conservation and transferability against exergy's non-conservation and destruction through real-life energy conversion processes. Practical processes are inherently non-ideal, subject to various entropy generation mechanisms related to process irreversibilities such as friction, heat transfer across finite temperature differences, rapid fluid expansion or compression, combustion, and spontaneous gas mixing. Recognizing these mechanisms allows for exergy analysis to address process comparisons based on their irreversibility and entropy generation levels effectively.

Furthermore, exergy can be divided into physical and chemical exergy. Physical exergy represents the maximum potential work that can be extracted from a system due to differences between the system's state and the environmental state, such as temperature and pressure differences. Chemical exergy, on the other hand, refers to the potential work associated with the chemical energy of substances when brought to chemical equilibrium with the environment's standard chemical environment (BEJAN, 2016, SZARGUT, 1988).

According to Szargut (2005), physical exergy is quantified based on the deviation of the system's state from the environmental state in terms of temperature and pressure, while chemical exergy is determined by the difference in the chemical potential of the system's constituents compared to their equilibrium values in the environment. Bejan (2016) elaborates that the integration of both types of exergy allows for a more holistic evaluation of processes, addressing not only the conservation of energy but also the degradation and potential recovery of energy quality. This dual perspective is essential in identifying inefficiencies and optimizing energy use across different sectors, from industrial applications to environmental management.

Summarizing, while energy always conserves and can be stored or transferred, exergy can also be stored and transferred but is not conserved, highlighting its destruction in real-life energy conversion processes. This destruction underscores the clear distinction between energy conservation and exergy's role in assessing energy quality and system inefficiencies.

The distinction between energy and exergy is fundamental in evaluating the efficiency and sustainability of energy systems. Energy, as described by the First Law of thermodynamics, measures the quantity of work potential but does not account for the quality or usability of this potential. Exergy, grounded in the Second Law of thermodynamics, addresses this gap by assessing the quality or the useful work that can be extracted from a system, considering the ambient environment as a reference (BEJAN, 2016, GAGGIOLI, 1961).

The rationale behind favoring exergy over energy lies in its ability to identify inefficiencies and energy waste not apparent through energy analysis alone. These inefficiencies are crucial in the context of the current energy transition, where optimizing resource use and minimizing environmental impacts are paramount. Traditional energy assessments based on the First Law alone may overlook these inefficiencies, leading to less effective energy use and conservation strategies. Furthermore, exergy's capacity to combine physical and chemical exergy is particularly significant for assessing the exergy effort required to mitigate the environmental impacts of pollutants like CO_2. This combined approach highlights the total work potential needed not only to generate energy but also to manage and reduce CO_2 emissions, thus directly addressing the critical environmental challenges posed by GHG emissions. By incorporating both physical and chemical exergy, it becomes possible to quantify the effort necessary to mitigate the CO_2 emissions, thereby offering a more comprehensive and accurate assessment of an energy system's overall sustainability.

In this way, the First Law of Thermodynamics establishes the principle of energy conservation but lacks the distinction between energy qualities, presenting a purely quantitative analysis. In contrast, the Second Law of Thermodynamics introduces a qualitative dimension by highlighting the concept of entropy and its generation. This distinction allows for an assessment that goes beyond mere numbers to consider the quality of energy processes and the inevitable reduction in each energy conversion's capacity to generate useful work. Another reason for using exergy, however, is its ability to effectively address pollutants, particularly CO_2. Dealing with pollutants is inherently a problem of mixing (dilution) and chemical potential, making chemical exergy a crucial factor. Exergy analysis, by incorporating both physical and chemical exergy, provides also a comprehensive measure of the effort required to reduce the environmental impacts.

For instance, comparing the availability of 10 MJ of electrical energy with 10 MJ of thermal energy highlights the superior "quality" of electricity due to its higher useful effect through existing conversion processes. Grubler *et al.* (2012) illustrate the distinction between energy and exergy through an example of a well-insulated room with a small container of kerosene surrounded by air. The combustion of kerosene results in a minor temperature increase within the room, signifying an unchanged total energy but altered energy quality. This transformation demonstrates the destruction of the fuel's initial potential, or its exergy, emphasizing the Second Law of Thermodynamics where energy conservation does not equate to exergy conservation.

Similarly, the operation of a combustion furnace illustrates the inefficiency arising from mismatched energy source quality and required energy service, further exemplified by the principle that achieving theoretical efficiency improvements is inherently limited by unavoidable frictions, resistances, and losses. The advantage of the Second-Law efficiency lies in its relation to real efficiencies against the theoretical maximum, identifying areas for significant efficiency improvement and emission mitigation potential. Furthermore, exergy efficiency's applicability to energy service provision marks its superiority over First-Law efficiency calculations, allowing for a nuanced comparison between real and ideal scenarios.

Incorporating these insights, this thesis aims to harmoniously blend historical perspectives on exergy with contemporary understandings, emphasizing its significance in evaluating energy systems' efficiency and sustainability.

The exploration of opportunities for process optimization and maximization of energy efficiency, as underscored by the work of Grubler *et al*. (2012) and Bejan (2016), highlights the critical importance of these themes in the current global context. With most global primary energy use not translating into useful energy services, the inefficiencies inherent in the current energy conversion and utilization paradigms present significant opportunities for improvement. Part of this advance can be done by the evaluation of the energy quality.

Exergy analysis provides a nuanced understanding of energy transformations and losses by highlighting the entropy generated during these processes. This analysis is pivotal in identifying novel ways to reduce energy consumption of natural resources and improve the sustainability of energy systems (GEORGESCU-ROEGEN, 1971, ODUM, 1973). As every real process, as the industrial ones, involves an overall increase of entropy, recognizing the limits of nature's capacity to absorb this entropy without harming ecosystems is crucial for sustainable development.

Incorporating exergy into energy system assessments enables the evaluation of the true environmental effects of energy processes, considering the physical and chemical characteristics of ecosystems and the energy waste discharged into the environment. This approach facilitates the development of more energy- and ecologically efficient methods for using energy in human activities, thereby minimizing environmental impacts and contributing to the sustainability of contemporary societies (LEAL FILHO *et al*., 2018).

Exergy analysis not only assesses the quality of energy resources but also provides insights into the global efficiency of transforming primary energy sources into usable forms. Despite the apparent high conversion efficiency reported by Grubler *et al*. (2012), nearly two-thirds of the primary energy used worldwide is wasted as waste heat rather than being utilized to deliver energy services. This inefficiency underscores the importance of exergy in evaluating energy systems, as it considers both the energy's quality and its conversion efficiency, offering a comprehensive view of the system's performance.

Grubler *et al*. (2012) highlight that the global efficiency of converting primary energy sources into end-use forms was about 67% in 2005, with the conversion efficiency to useful energy being even lower, averaging at 51%. This leads to an overall energy conversion efficiency of 34%, implying that approximately two-thirds of global primary energy use does not result in useful energy input but is dissipated as residual heat. This inefficiency underlines the vast potential for improvement across the energy chain, including shifts to more efficiently convertible fuels, adoption of more efficient conversion, distribution, and end-use technologies, and behavior changes at the end-use point to reduce wastage.

These newly incorporated elements emphasize the need for a holistic approach in evaluating and improving energy systems, considering both the quantitative conservation of energy and the qualitative degradation and transformation processes that influence the sustainability and efficiency of energy utilization.

The practical application of exergy analysis extends beyond theoretical considerations. By evaluating the degree of irreversibility and entropy generation in processes, exergy analysis effectively addresses the comparison of processes based on their energy quality. This analysis is instrumental in improving the utilization of energy resources, integrating processes to reuse energy waste, and accurately identifying environmental impacts (BEJAN, 2016).

Furthermore, exergy analysis underscores the necessity of using energy sources of minimal quality to provide the required energy services, thereby enhancing the overall efficiency of energy systems. This principle is essential in designing and implementing sustainable energy solutions that align with the goals of the energy transition and environmental protection.

In conclusion, the preference for exergy over energy in the assessment of energy systems lies in exergy's comprehensive approach to understanding energy quality, efficiency, and sustainability. An exergy analysis combines both the First Law of Thermodynamics (energy conservation) with the Second Law (considerations of non-idealities, irreversibilities, and entropy generation), to offer a more nuanced evaluation framework. This approach allows for a shift from a purely energy-centric view to one that incorporates exergy, providing a more detailed perspective on energy studies and integrated analysis models. Such a perspective facilitates improved utilization of energy resources, better integration between processes, and a more accurate identification of environmental impacts based on the disequilibrium between the properties of energy residues and the ecosystem.

This perspective is invaluable in guiding the global transition toward more sustainable and ecologically responsible energy systems, ensuring that humanity's energy practices are aligned with the imperative of environmental preservation and sustainable development. Crucially, expanding the analysis boundary to include pollutants such as CO_2 requires addressing the chemical potential and the entropy of mixing. This is where chemical exergy becomes essential. Incorporating chemical exergy allows for a comprehensive evaluation of the environmental costs and benefits of different energy systems, highlighting the importance of exergy analysis in understanding and optimizing the sustainability of energy enterprises. This approach not only provides a more complete assessment of energy systems but also underscores the necessity of considering both physical and chemical exergy in efforts to reduce the environmental impact and enhance the efficiency of energy conversion processes.

2.2 ENERGY RETURN ON INVESTMENT (EROI)

The concept of EROI has undergone significant evolution since its inception, initially serving as a metric to assess the efficiency of oil and gas production. The utility of EROI has expanded across various energy sources, offering a lens through which the diminishing returns of fossil fuels over time become evident (CLEVELAND *et al.*, 1984, HALL *et al.*, 2009). Despite its utility, traditional EROI analysis, with its focus squarely on energy quantity, has shown limitations in addressing energy quality—a gap becoming increasingly pertinent as the world undergoes a transformative energy transition.

To understand the concept of net energy, the total energy production from resource exploration activities is viewed as "revenue," while the energy consumed in the exploration process is considered "cost." Thus, net energy can be seen as "profit." In net energy research, EROI is often utilized to measure this net energy (GILLILAND, 1975, RAUGEI, 2019), hence, EROI represents the ratio between energy output and energy input in resource exploitation activities (CHEN *et al*., 2020).

These standard EROI analysis, which focus on calorific values to quantify direct inputs, indirect inputs, and energy outputs, estimate energy amounts but neglect energy qualities, even though an energy source's utility for society is determined by its quality (MURPHY *et al*., 2011). Moreover, the economic and physical systems' complexity requires taking labor, auxiliary services, direct and indirect energy inputs, and environmental inputs into account when calculating the EROI (HALL *et al*., 2014; MURPHY *et al*., 2011). At the end, the standard EROI analysis take into consideration a percentage of the total input components (MURPHY *et al*., 2011).[1]

Studies analyzing energy returns for different sources frequently reveal that (i) the EROI of fossil sources generally exceeds that of renewable sources (see Figure 1), and (ii) the The EROI of fossil sources has been declining over the years. Despite this, most renewable energy alternatives exhibit substantially lower EROI values. While the entry of high-quality renewable electricity in place of fossil sources has its advantages, significant challenges remain (HALL *et al*., 2014):

- Renewable electricity, from intermittent sources such as wind and photovoltaic. is less reliable and predictable than fossil fuels;
- Renewable sources are not energy dense enough and may suffer to be economically viable to displace fossil fuel investments through traditional market mechanisms;
- Electricity lacks the necessary infrastructure for transport, storage, and distribution to independently meet societal demands without fossil fuels; and
- From an EROI perspective, the current energy transition faces the challenge of intentionally replacing higher EROI sources with lower EROI ones, contrary to the trend of previous energy revolutions (SMIL, 2011).

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[1] Labor, supplementary services and environmental inputs are rarely considered in a comprehensive manner in the literature that currently exists on the combination of energy and EROI. However, the exergy accounting system has already taken into consideration a variety of material resources, socioeconomic factors including labor and capital, and environmental concerns, in addition to energy products (SCIUBBA, 2001 and 2011, WALL, 1977 and 1987).

Table 1 provides a more complete review than Figure 1, including additional data, sources, and considerations about the Energy Return on Investment (EROI) of various energy sources:

Table 1 – EROI of different energy sources

Energy Source / Technology	Avarage EROI	Commentary
Oil and Natural Gas	**20:1** (HALL *et al*., 2014) | **18:1** (GAGNON *et al*., 2009) | **10:1** *Only in USA (GUILFORD *et al*., 2011) | **20:1** - Oil and - NG **40:1** (PAHUD; DE TEMMERMAN, 2022) | **40:1** *Only in Norway (GRANDELL *et al*., 2011) | **10-20:1** (MURPHY *et al*., 2011)	Oil and natural gas have relatively high EROI values due to their high energy density and mature extraction technologies. However, the EROI has been declining over time as easily accessible reserves are being depleted, requiring more energy for exploration and production. It is difficult to establish EROI values for natural gas alone as data on natural gas are usually aggregated in oil and gas statistics.
Biomass	**5:1** (HALL *et al*., 2014) | **2:1** (MURPHY *et al*., 2011) | **2-5:1** (LAMBERT *et al*., 2013)	Biomass has a relatively low EROI due to the low energy density and the energy required for cultivation, harvesting, processing, and transportation. Advances in processing technologies can improve efficiency, but it remains lower compared to other energy sources.
Biorefineries	**5:1** (HALL *et al*., 2014)	Biorefineries that convert biomass into biofuels exhibit similar EROI values to biomass due to the energy-intensive processes required for conversion.
Wind Energy	**18:1** (KUBISZEWSKI *et al*., 2010) | **20:1** (LAMBERT *et al*., 2013)	Wind energy has a high EROI, attributed to the low operational and maintenance energy requirements after the initial installation. The EROI can vary depending on location and wind availability. The value in practice may be less, than presented here, due to the need for backup facilities.
Photovoltaics	**10:1** (HALL *et al*., 2014) | **6-12:1** (WEIßBACH *et al*., 2013) | **2-3:1** (PALMER, 2013, WEIßBACH *et al*., 2013)	Photovoltaic energy has a moderate EROI, influenced by the low energy density, requiring the installation of many solar panels for a minimum amount of delivered energy. This value can improve with technological advances. The value in practice may be less, than presented here, due to the need for backup facilities.
Nuclear Energy	**14:1** (HALL *et al*., 2014) | **5-15:1** (MURPHY *et al*., 2011)	Nuclear energy shows a high EROI due to the high energy density of nuclear fuel and the long operational life of nuclear plants. However, high construction, decommissioning, and waste management costs are significant factors.
Hydroelectric	**84:1** (HALL *et al*., 2014)	Hydroelectric power has one of the highest EROI values due to the low operational costs once the dam infrastructure is in place. The value can vary significantly depending on the site's geography and the scale of the project.
Coal	**46:1** (HALL *et al*., 2014) | **20:1** (WEIßBACH *et al*., 2013) | **95:1** (PAHUD; DE TEMMERMAN, 2022)	Coal has a high EROI but comes with significant environmental drawbacks, including high CO_2 emissions. Technological advances in carbon capture and storage (CCS) can mitigate some of these impacts, but they also require additional energy input, as this thesis will further detail.

Source: Prepared by the author (2024).

Further remarks on the data presented in Table 1 should also be highlighted:

- **Control volume sensitivity:** The Energy Return on Investment (EROI) results can exhibit substantial variations depending on the specification of the control volume of the analysis. For instance, considering factors such as the requirement for energy storage or backup for intermittent sources like wind and solar can considerably reduce the Energy Return on Investment (EROI).
- **Comparison of Sources:** Although fossil fuels like coal and natural gas have traditionally exhibited high Energy Return on Investment (EROI), renewable sources, such as wind and photovoltaics, are increasingly becoming competitive due to technological breakthroughs and cost reductions. Nevertheless, challenges such as intermittency and the requirement for energy storage for renewable sources persist.
- **Implications for Energy Transition:** The transition towards a more sustainable energy mix has to consider not only the Energy Return on Investment (EROI), but also the environmental, social, and economic consequences. An integrated analysis, which encompasses CO_2 capture methods, offers a more holistic perspective and aids in informing policy and strategic choices.

Therefore, when the limitations of traditional EROI are questioned in the contemporary context, the answer lies in its intrinsic design, which overlooks the qualitative aspects of energy. This oversight restricts its utility in providing a comprehensive assessment of energy systems, particularly renewable sources and integrated systems, which are crucial in the energy transition. The transition necessitates a broader, more nuanced analysis that considers not just the energy returned but the quality and environmental impact of that energy (CHEN *et al.*, 2020, MURPHY *et al.*, 2011).

To transcend the quantitative confines of traditional EROI, methodologies such as Life Cycle Analysis (LCA), Cost-Benefit Analysis (CBA), carbon footprinting, and energy efficiency metrics have emerged, each contributing valuable insights into the environmental, economic, and efficiency facets of energy options (BARACSKAY, 1998, IPCC, 2019, ISO, 2006). These methodologies highlight the multifaceted nature of energy analysis, where considerations extend beyond the simple calculus of energy returned on energy invested.

EROI, when integrated with life cycle analysis and carbon footprint metrics, for instance, can offer a more holistic view of the sustainability of renewable energy sources. This integrated approach can account for the environmental and socioeconomic impacts of energy options, from raw material extraction to end-of-life disposal, offering a comprehensive evaluation framework (ARVIDSSON, 2021, FTHENAKIS; KIM, 2010).

The evolution of the EROI methodology can potentially address its current limitations by incorporating externalities related to environmental and social impacts and by adopting a more integrated systems perspective. Utilizing accurate and reliable data, potentially sourced from advanced monitoring technologies, can enhance the precision of EROI calculations (GUPTA; HALL, 2011). Moreover, applying EROI to broader sectors and utilizing it to inform public policy could further underscore its relevance in guiding the transition to sustainable energy systems (HALL, 2017).

Nevertheless, the integration of exergy analysis with EROI represents an untapped frontier in energy analysis, particularly relevant in the crafting of Integrated Assessment Models (IAMs) and the development of energy transition scenarios. By combining the quantitative rigor of EROI with the qualitative insights of exergy analysis, this integrated approach can offer a more complete picture of energy system performance, encompassing efficiency, sustainability, and environmental impacts.

Whatever the case, there have been lately several EROI-related studies looking at the depletion of fossil fuels, evaluating the quality of renewable energy sources, and examining the effects on energy transition and sustainability research (BROCKWAY *et al.*, 2019, DALE *et al.*, 2012, HALL *et al.*, 2014, KING; VAN DEN BERGH, 2018, LAMBERT *et al.*, 2014, RAUGEI, 2019, SERS; VICTOR, 2018). For instance, to quantify the conversion coefficients of various types of components, materials, and energy, the idea of Cumulative Exergy Consumption (CEx_C) has been proposed by integrating the exergy and life cycle views. If exergy is regarded as a flow, then CEx_C might represent the cost of exergy for a good or service (ROCCO *et al.*, 2014). Consequently, CEx_C enables the analysis of the primary natural resource consumption of goods or services that are evaluated throughout their life cycle and are required for the conversion process (SZARGUT, 2005).

Nevertheless, not all types of material resources have CEx_C conversion coefficients, even though conversion coefficients are comparable to calorific value coefficients. This means that getting access to data is still a huge problem (CHEN *et al.*, 2020). Furthermore, the use of exergy analysis also should have allowed assessing the pollution of processes by their exergy cost. This could have been done by quantifying the energy effort to control the chemical pollution, which will depend on processes that are non-spontaneous and hence consume chemical and physical exergy. In the end, despite all attempts to incorporate issues relating to energy quality, life cycle, and indirect energy uses in energy return on investment analysis, current methodologies can be improved to better define the system boundaries and control volume, to allow better comparisons between fossil and non-fossil fuel sources, particularly addressing the decarbonization ambition.

In summary, while the traditional EROI indicator provides a foundational understanding of energy system efficiency, its limitations in the face of the current energy transition challenges highlight the need for a more comprehensive analytical framework. By integrating EROI with exergy analysis and considering broader environmental and social impacts, it is possible to develop a nuanced understanding of energy systems that aligns with the goals of sustainability and decarbonization. This expanded approach not only addresses the qualitative aspects of energy but also supports informed decision-making in the pursuit of a sustainable energy future.

The traditional EROI's focus on quantifying energy alone falls short in the current context of energy transition due to its inability to address qualitative aspects and environmental impacts of energy production. This limitation underscores the urgency of integrating exergy analysis into EROI, allowing for a more holistic assessment that considers both the efficiency and sustainability of energy systems. Importantly, this expanded focus is crucial for navigating the challenges of transitioning to renewable and low-carbon energy sources, highlighting the necessity of moving beyond conventional metrics to fully understand contemporary energy dynamics. Moreover, the need to evaluate EROI across the entire lifecycle of energy processes further emphasizes the requirement for a comprehensive approach that encapsulates all aspects of energy production, from resource extraction to end-use and potential environmental ramifications.

2.3 THE INTEGRATION OF EXERGY ANALYSIS AND EROI

The necessity of integrating exergy with EROI stems from a fundamental understanding that the value of an energy source is not solely determined by the amount of energy it can produce but also by the quality of that energy in performing useful work. Traditional EROI analysis, focusing primarily on energy quantities, fails to capture this nuanced perspective, especially critical in evaluating renewable energy technologies and carbon mitigation strategies. Incorporating exergy, which evaluates energy quality against the backdrop of environmental and technical constraints, enriches the EROI framework, making it a more comprehensive tool for assessing energy systems (LOZANO *et al*., 1994, VALERO *et al*., 2018).

For the quality of the energy, examining the utilization of energy resources accurately from a physical standpoint was one of the initial objectives of Odum (1973) at the very beginning of the idea of EROI. This has evolved to studies that were based on emergy and exergy analysis (MULDER; HAGENS, 2008, MURPHY *et al*., 2011), Return on Exergy-Related Investment (ExROI) (LIOR, 2016), Return of Exergy on Investment in Exergy (HASSAN *et al*., 2019), and discussions on minimal exergy return rates (ExRR) required by society (COURT, 2019). In addition, the energy return method based on extended exergy analysis on investment in EROI (Extended-exergy based energy return on investment method (ExEROI)) developed by Chen *et al*. (2020) was based on the framework for extended exergy accounting (Extended Exergy Accounting – EEA) proposed by Sciubba (2001)[2] and aimed to effectively incorporate exergy in the EROI with a life cycle view. The basic formulations for these methods are presented in the following equations:

$$ExROI = \frac{Ex_o}{Ex_d} \qquad \text{(Equation 1)}$$

Where:

ExROI – Exergy Return On Investment;

Ex_O: Output Exergy;

Ex_d: Direct Exergy.

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[2] Sciubba (2001) proposed extending exergy analysis by including effort, capital, and environmental impact in exergy accounting systems, even those indirectly required for the examined activities.

$$ExRR = \frac{P}{\mathrm{U}} = \frac{1}{\varepsilon} \qquad \text{(Equation 2)}$$

Where:
ExRR – Exergy Return Rate,
P – Extract Primary Exergy,
U – Produced Useful Exergy, and
ε – Exergy Efficiency

$$ExEROI = \frac{Ex_o}{Ex_d + CEx_{id} + Ex_L + Ex_A + Ex_{env}} \qquad \text{(Equation 3)}$$

Where:
ExEROI -Exergy Based Energy Return On Investment,
Ex_O: Output Exergy,
Ex_d: Direct Exergy,
CEx_{id}: Indirect Exergy (from indirect energies and general material resources),
Ex_L: Labor Exergy Equivalent,
Ex_A: Capital Exergy Equivalent, and
Ex_{Env}: Exergy Equivalent of Environmental Impacts

As seen previously, the preference for exergy over energy in integrated analysis highlights a paradigm change in the assessment of energy. It is acknowledged by energy analysis that not all joules are created equal; energy's capacity to carry out work differs greatly depending on its quality (or order degree). In the context of renewable energy and carbon mitigation, when energy system sustainability and efficiency are critical, this distinction becomes even more important. Exergy gives a clearer view of the underlying performance of energy systems by revealing losses and inefficiencies that are hidden by traditional energy analysis. This helps to steer the energy transition towards more sustainable and effective solutions.

Energy analysis is in line with the larger goals of sustainable development and climate change mitigation when it incorporates energy and EROI with life cycle and environmental factors, especially CO_2 emissions. By considering the environmental effects across the whole life cycle of energy production and consumption, in addition to energy and energy efficiency, this method makes it possible to evaluate energy systems in a more comprehensive manner. Considering their contributions to CO_2 emissions and potential for mitigating the effects of climate change, the extended notion of EROI, which incorporates these components, offers a more realistic comparison between various energy sources and conversion processes (CHEN *et al.*, 2020).

However, traditional analyses often treat CO_2 as a system output without considering the removal processes within the system boundaries. In contrast, the approach established in this work incorporates the CO_2 removal process into the control volume, significantly increasing the input exergy required to reduce CO_2 emissions. By including the exergy associated with CO_2 capture and sequestration within the system boundaries, a more comprehensive evaluation of the true environmental and energetic costs is provided. This expanded boundary highlights the additional exergy inputs necessary for environmental mitigation, allowing for a more realistic comparison between various energy sources and conversion processes.

The integration of exergy analysis with EROI presents several hurdles despite the potential benefits, such as complexity, challenges in gathering data, a lack of standardization, and the requirement for a more thorough examination of social and environmental aspects. It will take coordinated efforts in research, data collection, and methodological development to address these issues and improve and standardize the integrated approach (CHEN *et al.*, 2020).

An example of this integrated approach is the Extended-Exergy Based Energy Return on Investment Method put out by Chen *et al.* (2020). This method provides a comprehensive perspective of energy system efficiency by integrating exergy factors into traditional EROI analysis; it is especially useful in complicated scenarios such as China's shale gas extraction. This approach represents a significant step forward in addressing the shortcomings of conventional EROI evaluations by emphasizing the significance of evaluating energy inputs and outputs' quality as well as quantity through the lens of exergy (CHEN *et al.*, 2017 and 2020).

The approach described above, as previously indicated, was based on the extended exergy accounting framework (also known as extended exergy accounting, or EEA), which is a thorough process for figuring out the total amount of primary exergy needed to generate a good or service. This method measures the "embodied exergy" of commodities, taking into consideration externalities like labor, capital, and environmental costs in addition to the direct exergy utilized. One of the most important parts of EEA is calculating the two econometric coefficients, "α" and "β," which are used to calculate the labor and capital extended exergy equivalents, respectively. These coefficients are determined using precise energy and monetary balances unique to a civilization, as opposed to the estimated values that were previously assigned based on global systemic factors (PTASINSKI *et al.*, 2006, SCIUBBA *et al.*, 1999, 2001 and 2004).

Two basic postulates form the foundation of the EEA technique (SCIUBBA, 2011):

1st postulate: The primary purpose of the worldwide inflow of energy resources (E_{in}) in any society is to support the labor-generating workers. The part of the incoming exergy flow that "feeds" Labour (E_L) is expressed in terms of exergy as follows:

$$E_L = \alpha E_{in}[\frac{J}{year}] \qquad \text{(Equation 4)}$$

2nd postulate: The labor exergy determines the exergy flux required to produce the monetary circulation M2 in a society:

$$E_K = \beta E_L[\frac{J}{year}] \qquad \text{(Equation 5)}$$

Where α and β are numerical factors, or time- and space-dependent model constants, that depend on the kind of societal organization, the historical period, the technological level, the pro-capita resource consumption, and the geographic location of the Society. Their value must be determined using econometric data because it is not assigned by the theory. And E_K is the part of the incoming exergy that "feeds" Capital.

The EEA is dependent on both time and location, and the coefficients α and β are crucial since they represent the labor statistics and the flow of money inside a given nation. As demonstrated by Equation (6), the extended exergy of labor (ee_L) is calculated by dividing the total exergy flux required to support labor by the total number of workhours (Nwh) in a given time period. Similarly, by dividing the entire exergy flux into capital by the monetary circulation (M2) over the same period, one can compute the extended exergy of capital (ee_k), as shown in Equation (7) below. These coefficients offer a sophisticated perspective on the ways in which a nation's resource consumption patterns are influenced by socioeconomic standards, consumption habits, and technical advancements (ERTESVÅG, 2001 and 2005).

$$ee_L = \frac{\alpha \mathrm{E}_{in}}{N_{wh}} \left[\frac{J}{workhour}\right] \qquad \text{(Equation 6)}$$

$$ee_k = \frac{\alpha\beta \mathrm{E}_{in}}{M2} \left[\frac{J}{€}\right] \qquad \text{(Equation 7)}$$

Therefore, the EEA technique highlights the socio-economic factors impacting these prices in addition to improving our understanding of the resource costs related to producing commodities. To better inform sustainability assessments, this method provides an insightful viewpoint on the relationship between a society's economic activities and patterns of resource consumption. It does this by requiring the upkeep of an updated database of societal exergy flows and econometric factors (GASPARATOS *et al.*, 2009, SCIUBBA, 2004).

Furthermore, incorporating exergy addresses the "quality" dimension of energy, revealing the diminishing returns of fossil fuels over time and highlighting the potential of renewable sources under more rigorous scrutiny. This addresses a fundamental shift towards evaluating energy not merely by its availability but by its capacity to do work efficiently and sustainably (HALL *et al.*, 2014; MULDER; HAGENS, 2008).

Integrating exergy analysis with EROI transcends traditional energy assessment methods by incorporating not only the quantity and quality of energy but also the environmental impacts throughout an energy system's life cycle. This method’s approach uniquely includes the CO_2 control system within the control volume, which increases the exergy input required for mitigating emissions and thereby reduces the overall exergy output. This expanded boundary provides a more accurate reflection of the true environmental and energetic costs, highlighting the additional work needed for CO_2 capture and sequestration. By embedding these control mechanisms within the system, the methodology enhances the complete assessment's comprehensiveness, making it possible to evaluate energy systems more effectively and aligned with sustainability goals. This holistic approach is imperative for advancing sustainable development and effectively addressing climate change challenges. It ensures that energy systems are not only evaluated for their immediate energy returns but also for their long-term sustainability and environmental compatibility. Such integration is essential in the era of energy transition, where the focus shifts towards renewable sources and carbon mitigation strategies, demanding a nuanced understanding of energy's role in both human advancement and ecological balance. This necessitates collaborative research and methodological innovation to overcome existing challenges and fully realize the potential of combined exergy and EROI analyses in shaping a sustainable energy future.

In sum, recognizing the limitations of traditional EROI in evaluating the quality and environmental impacts of energy production, the proposed integration of exergy analysis aims to provide a more nuanced understanding of energy systems' sustainability and efficiency. This methodological advancement is crucial for assessing energy transitions in the context of contemporary environmental and societal needs (DALE *et al.*, 2012, SOVACOOL, 2009).

2.4 THE CURRENT ENERGY TRANSITION: A DIFFERENT PARADIGM

The ongoing energy transition is marked by a fundamental shift from high-density fossil fuels to lower-density renewable sources, as shown in Figure 1, necessitating a reevaluation of energy assessment methodologies. As mentioned before, the traditional EROI, while useful, does not fully account for the energy quality or the environmental impacts of energy production.

This transition, moving from high-density fossil fuels to lower-density renewable sources, necessitates a profound reevaluation of how energy systems are assessed and understanded. Unlike past transitions, the contemporary shift is driven not only by the quest for more efficient or accessible energy sources but also by the urgent need to mitigate climate change and reduce carbon emissions. Here, it is necessary to delve into why this energy transition is fundamentally different, using insights from history and current research.

The proposed integration of exergy analysis into EROI aims to address these limitations, providing a more nuanced understanding of the sustainability and efficiency of energy systems in the context of the energy transition (DALE *et al.*, 2012, SOVACOOL, 2009).

As previously mentioned, historically, energy transitions have been slow processes, often taking decades, if not centuries, to unfold. And mainly, they were opportunity driven (FOUQUET; PEARSON, 2012; SMIL, 2019). The current energy transition is propelled by a recognition of the finite nature of fossil fuels and the detrimental impact of their consumption on the planet's climate.

However, the introduction of renewable alternative energy sources for mitigating CO_2 emissions is a recent major challenge that drives the energy transition (FOUQUET;

PEARSON, 2012, SOVACOOL, 2015). This transition also requires the comparison between energy sources in terms of their energy return on investment.

Numerous studies examine the energy return (BHANDARI *et al*., 2015, GUPTA, 2018, GUPTA; HALL, 2011, HALL *et al*., 2014, WANG *et al*., 2021). A common finding is that most renewable energy options have significantly lower EROI values, despite the declining EROI of fossil fuels (HALL *et al*., 2014).

So, it is important to highlight why this energy transition is different:

1. **Environmental Imperatives:** Unlike past transitions motivated by economic or efficiency gains (opportunity driven), the current shift is significantly driven by the need to address climate change and reduce global carbon emissions (problem driven). This adds a layer of urgency and a global scale of cooperation previously unseen in energy transitions (FOUQUET; PEARSON, 2012, SOVACOOL, 2015).
2. **Technological Innovation and Adoption Rates:** The pace of technological innovation, particularly in renewable energy technologies, has accelerated, offering the potential for a quicker transition than those seen historically. However, the adoption rates of these technologies face numerous barriers, including infrastructural, regulatory, and social challenges (SMIL, 2019).
3. **Societal and Economic Transformations:** The current transition is also characterized by its potential to drive significant societal and economic transformations. The shift towards renewable energy sources is not just about changing the types of energy that are used but about rethinking how energy is produced, distributed, and consumed, highlighting the need for a more decentralized and democratized energy system (FOUQUET; PEARSON, 2012).

In conclusion, the current energy transition is distinct in its urgency, driven the problem of environmental imperatives and the global consensus on the need to combat climate change. It requires a reevaluation of traditional energy assessment methodologies, as incorporating considerations of energy quality and environmental impact through the integration of exergy analysis with EROI. As this transition is navigated, understanding its unique characteristics and challenges is essential for developing strategies that ensure a sustainable and equitable energy future.

3 METHODOLOGY

This thesis delves into the evolution and application of the Energy Return on Investment (EROI) concept, focusing on its energy-based and exergy-based versions. The methodology begins with a comprehensive literature review, critically examining significant academic contributions to the field of EROI, highlighting their strengths and identifying their shortcomings. This foundational step sets the stage for the development of an alternative method based on exergy. This new approach aims to overcome the limitations found in the literature by proposing a broad indicator that encompasses the lifecycle of energy conversion processes and establishing suitable boundaries to ensure analyses are adequately comprehensive.

3.1 EXERGY RETURN ON ENVIRONMENT AND ENERGY INVESTMENT

The core of this methodology put forth here is based on the proposition and application of the ExROEEI (Exergy Return on Environment and Energy Investment) indicator, which considers the quality of energy, and the mitigation of CO_2 emissions in the assessment of energy conversion chains.

The equation below establishes the proposed indicator:

$$ExROEEI = \frac{Ex_O}{Ex_d + Ex_{id} + Ex_K + Ex_{OP} + Ex_{Env} + Ex_{CO2}} \qquad \text{(Equation 8)}$$

Where:

(1) Ex_O: Output Exergy. Corresponds to exergy that leaves a process and is assessed as the portion referring to the society's ultimate use. The model uses it as input data. It relates to the electricity provided for societal usage in the case of an electrical energy producing process;

(2) Ex_d: Direct Exergy. Corresponds to the amount of energy used directly to produce the energy resource utilized in the evaluated process. The general definition of this term is represented by the equation shown below:

$$\dot{Ex}_d = \sum_i \dot{m}f_{d_i} . ex_{ch.i} + \sum_j \dot{Ex}_{d_j} \qquad \text{(Equation 9)}$$

Where:

$\dot{m}f_{d_i}$ – Mass flow rate of each fuel (i) used directly to produce the process's main source of energy,

$ex_{ch.i}$ – Specific chemical exergy of each fuel in kJ/kg (i) used directly to produce the primary energy source for the process under analysis (KAUSHIK; SINGH, 2014), and

$\dot{Ex}_{d_j}$ – Each source of exergy (j - normally electrical energy) used directly to produce the primary energy source for the process under analysis.

(3) Ex_{id}: Indirect Exergy. Part of the exergy used in supporting processes connected to the in-question technology, such as transportation and production of inputs required for the primary energy resource's production or for use in the energy conversion process. The equation below corresponds to the general formulation for this term:

$$\dot{Ex}_{id} = \sum_i \dot{m}f_{id_i} . ex_{ch.i} + \sum_j \dot{Ex}_{id_j} \qquad \text{(Equation 10)}$$

Where:

$\dot{m}f_{id_i}$ – Mass flow of each fuel (i) used indirectly as support for the process under analysis,

$ex_{ch.i}$ – Specific chemical exergy of each fuel in kJ/kg (i) used indirectly to produce the primary energy source for the process under analysis (KAUSHIK; SINGH, 2014), and

$\dot{Ex}_{id_j}$ – Each source of exergy (j - usually electrical energy) used indirectly as support for the process under analysis.

(4) Ex_K: Capital Exergy. Part referring to the exergy used during the design, construction, and installation phases of the energy-related enterprise under analysis. Based on the project's CAPEX and a conversion of capital (US$) to energy (MJ) that was presented in Sciubba (2011). The general definition of this term is represented by the equation shown below:

$$Ex_K = CAPEX . W_O . \mathrm{ee_K} \qquad \text{(Equation 11)}$$

Where:

CAPEX – Specific investment costs based on the enterprise's size (US$/MW),

W_O – Output Net Power that leaves a process and is assessed as the portion referring to the society's ultimate use (MW), and

$\mathrm{ee_K}$ – Equivalent primary exergy resource embodied in one monetary unit (MJ/US$). See subsection 4.1

(5) Ex_{OP}: Operational Exergy. The amount of exergy used throughout the operational phase of an enterprise. Based on the operational expenses in the installation and the same conversion of Sciubba (2011) capital (US$) to energy (MJ). Although some authors, such as Chen *et al.* (2020), use the exergy associated with human labor, the use of exergy during operational phases goes far beyond human labor. Indeed, the equipment installed in the facility requires ongoing maintenance that, for instance, consumes spare parts, or they need to be replaced due to failure or obsolescence. The equation below corresponds to the general formulation for this term:

$$Ex_{OP} = OPEX.Ex_O.\mathrm{ee_K} \qquad \text{(Equation 12)}$$

Where:

OPEX – Specific operational costs based on the size and complexity of the energy conversion facility (US$/MWh),

Ex_O – Output exergy that leaves a process and is assessed as the portion referring to the society's ultimate use (MWh), and

$\mathrm{ee_K}$ – Equivalent primary exergy resource embodied in one monetary unit (MJ/US$). See subsection 3.1

(6) Ex_{Env}: Exergy Equivalent of Environmental Impacts.

In a broader sense, environmental impacts are directly associated with the solid, liquid, and gaseous effluents released into the environment. The Exergy Equivalent of Environmental Impacts refers to the exergy of these effluents, which accounts for their physical exergy (the difference in temperature and pressure relative to the environment) and chemical exergy (the difference in concentration or composition relative to the reference environment). Thus, the Exergy Equivalent of Environmental Impacts can be subdivided as:

$$Ex_{\mathbf{Env}} = Ex_{\mathbf{Env,s}} + Ex_{\mathbf{Env,l}} + Ex_{\mathbf{Env,g}} \qquad \text{(Equation 13)}$$

Expanding this concept further, one could also consider environmental impacts related to water usage, land use, and biodiversity loss, among other factors. However, these aspects are challenging to correlate with the energy cost required to restore the environment. All these aspects can be evaluated in future studies.

In this context, since the primary energy effluent related to the thermal power plants studied in this thesis is associated with the thermal energy of exhaust gases released into the atmosphere, and based on Sciubba's (2001, p. 70) approach, the exergy associated with environmental impacts can be expressed as follows: “If an effluent stream of a generic process is required to have a zero impact on the environment, the stream must be brought to a state of thermodynamic equilibrium with the reference state before being discharged into the environment. The minimum amount of energy that must be used to perform this task by means of ideal transformations is proportional to the physical exergy of the stream: therefore, the physical exergy of effluents is a correct measure of their potential environmental impact”.

Thus, in the case studies of this work, Ex_{Env} will be calculated according to the following equation:

$$Ex_{\mathbf{Env}} = EQ_{Lb} \qquad \text{(Equation 14)}$$

Where:

$Ex_{\mathbf{Env,s}}$ – Exergy Equivalent of Environmental Impacts of energetic solid effluents,
$Ex_{\mathbf{Env,l}}$ – Exergy Equivalent of Environmental Impacts of energetic liquid effluents,
$Ex_{\mathbf{Env,g}}$ – Exergy Equivalent of Environmental Impacts of energetic gaseous effluents,
EQ_{Lb} – Thermal Exergy from energy effluents (See Ex_{env} Calculation in subsections 4.2.2, 4.3.2, 4.4.2, 4.5.2, and 4.6.2).

(7) Ex_{CO_2}: Requested exergy to Carbon Capture and Sequestration (CCS). Represents the exergy cost associated with managing CO_2 emissions, encompassing the chemical effort required by the environment to remove or

neutralize CO_2, rather than solely referring to Carbon Capture and Sequestration (CCS) technologies. This term accounts for the exergy penalty imposed by CO_2 emissions, highlighting the environmental burden and reduction of available net exergy, regardless of whether CCS is applied in practice. The concept aligns with Odum's idea of emergy, where the available energy is diminished by the ecological effort required to mitigate the environmental impacts (Odum, 1973). Therefore, while Ex_{CO_2} is calculated to indicate the environmental exergy cost, it does not imply the implementation of CCS, but rather reflects the impact of this environmental stressor. In this analysis, CO_2 offsets (or compensation) to achieve net-zero emissions in fuel combustion facilities are not considered. See Ex_{CO_2} Calculation in subsections 4.2.2, 4.3.2 and 4.4.2.

This formulation goes beyond a simple assessment of energy quality, extending the analytical framework to include a comprehensive life cycle evaluation of energy conversion technologies and their environmental impacts. By integrating the exergy penalties associated with environmental effluents—solid, liquid, and gaseous—this methodology provides a more nuanced understanding of the broader environmental consequences of energy systems. The inclusion of CO_2 emissions within the ExROEEI framework, whether Carbon Capture and Sequestration (CCS) is implemented, introduces an essential element: the exergy cost of mitigating environmental damage. This is not merely a technical add-on but a critical expansion that reflects the broader environmental and ecological effort needed to address CO_2 emissions. This aligns with Odum’s concept of emergy, highlighting how environmental burdens diminish the net available exergy, ultimately linking energy system performance to real-world sustainability challenges.

The theoretical contribution of this methodology lies in its ability to expand the traditional boundaries of energy system analysis to include the exergy costs of environmental degradation and mitigation, thus providing a more realistic and holistic framework for assessing the sustainability of energy systems. This is particularly relevant in the context of the current energy transition, where decarbonization is a central challenge, and where simplistic assessments based only on energy quantity, such as traditional EROI or even ExROI (Exergy Return on Investment), fall short. The ExROEEI indicator, as developed here, not only offers a tool for comparing energy sources but also integrates lifecycle environmental impacts, making it an invaluable resource for other researchers in energy studies. The ability to account for both the energy services provided and the environmental exergy cost creates a more equitable and accurate method for evaluating the trade-offs inherent in transitioning to alternative energy systems. This expanded boundary of analysis, which includes environmental and CO_2 exergy, serves as a robust foundation for future research and policy development aimed at advancing the global energy transition towards sustainability and decarbonization.

The EROI and ExROI are calculated as follows – as shown in the equations bellow (CHEN *et al.*, 2020, HALL *et al.*, 2014):

$$EROI = \frac{\text{Energy return to society}}{\text{Energy required do get the energy}} \qquad \text{(Equation 15)}$$

It is important to highlight that in this work, the EROI will be calculated using the traditional method applied during the production phase of the energy source, with the *Energy return to society* representing the amount of energy generated by this source during that phase.

$$ExROI = \frac{Ex_o}{Ex_d} \qquad \text{(Equation 16)}$$

3.2 THE CO_2 EMISSION INTENSITY INDEX

In academic research, the CO_2 intensity index is frequently used to compare the environmental impact of traditional fossil fuels with that of renewable energy sources. Research frequently shows that green energy sources, including solar and wind power, have far lower CO_2 intensities than fossil fuels like coal and oil, underscoring their potential to cut greenhouse gas emissions. By offering a quantifiable framework for evaluating increases in energy efficiency and decreases in carbon intensity, this index also helps monitor the advancement of global climate targets, such those set forth in the Paris Agreement (IEA, 2023, IPCC, 2022).

The CO_2 Emission Intensity Index, or CEII as it is referred to here, is especially useful when considering international efforts to mitigate climate change. The index assists in determining which energy sources are more carbon intensive and which are cleaner by comparing CO_2 emissions to energy output. This information is vital for policymakers, researchers, and industry stakeholders who are working to shift energy production towards more sustainable and less environmentally damaging practices (EEA, 2020).

The European Environment Agency (EEA) provides comprehensive data on CO_2 emission intensity across different regions, illustrating the variations in emission levels associated with energy production. This data is crucial for understanding the broader impact of energy policies and technology adoption in reducing carbon emissions. More about this can be found on the EEA's visualization tool, which compares CO_2 emission intensity across various sectors and regions (EEA, 2020).

The CEII is an important metric for assessing the environmental dimension of sustainability by specifically measuring CO_2 emissions in energy systems. While it plays a key role in guiding the transition to a low-carbon economy, it is crucial to recognize that sustainability encompasses a broader range of environmental, economic, and social factors. Beyond carbon emissions, issues such as resource depletion, biodiversity loss, economic equity, and social well-being must also be considered in evaluating the overall sustainability of energy systems (NERINI *et al*., 2019).

Therefore, while the CEII is a valuable tool, it should be used alongside other indicators to ensure a comprehensive approach to sustainability. By providing a clear measure of the environmental costs of energy production, it supports the transition to a low-carbon economy, guiding policy decisions, and fostering more sustainable energy practices. As global energy needs continue to evolve, the relevance of this index in environmental policy and management remains more critical than ever.

As the Equation (17) bellow shows, the CEII quantifies the mass of carbon dioxide equivalent emissions (in 10^3 kg) per unit of exergy output (terajoule), providing a clear measure of the emission´s efficiency of different energy sources. This index is critical for evaluating how energy production contributes to carbon emissions, which is crucial for developing strategies aimed at reducing the carbon footprint of energy systems.

$$CEII = \frac{\text{CO2 Equivalent Emissions } (10^3 kg)}{Ex_O(TJ)} \qquad \text{(Equation 17)}$$

Where:

(1) Ex_O: Output Exergy. Electricity provided in TJ for societal usage in the case of an electrical energy producing process, considering the hole operational time during all the years of the facility´s production; and

(2) CO_2 Equivalent Emissions. Carbon dioxide equivalent emissions in 10^3 kg of an electrical energy producing process, considering the whole operational time during all the years of the facility´s production

4 CASE STUDIES

This section presents an examination of the five distinct energy production scenarios, each incorporating different technologies and fuel sources to assess their ExROEEI and CEII. The primary objective is to elucidate the premises, boundary conditions, calculations, and results associated with each case study. All cases are analyzed to provide 331 MW of net electricity to society to offer comparative insights how this innovative indicator can facilitate fair comparisons across diverse energy sources and conversion techniques within the context of an energy transition aimed at reducing CO_2 emissions.

1) **Coal-based Power Plant Equipped with Carbon Capture Technology:** This case study, based on the thesis of Castelo Branco (2012), represents the reference scenario and evaluates a traditional coal power plant equipped with carbon capture technology, serving as the baseline for comparison with the other cases.
2) **Natural Gas Brayton Cycle Power Plant Equipped with Carbon Capture Technology:** This case study examines a simple configuration of a Brayton cycle natural gas power plant equipped with carbon capture technology, highlighting the specific challenges associated with this configuration.
3) **Natural Gas Combined Cycle Power Plant Equipped with Carbon Capture Technology:** By integrating carbon capture technology into a combined cycle power plant, this case study aims to explore the advantages brought by a high-efficiency combined cycle in improving the exergy return and reducing greenhouse gas emissions. It is important to highlight that the CO_2 capture is more complicated than in the Brayton cycle configurations.
4) **Biogas Brayton Cycle Power Plant:** This case study shifts the focus to renewable energy sources by analyzing a biogas-fueled Brayton cycle power plant configuration.
5) **Biogas Combined Cycle Power Plant:** Extending the analysis to a more efficient system, this case investigates a biogas-powered combined cycle plant. The study evaluates how effectively this setup utilizes the biogas' energy content and its potential in minimizing environmental impacts compared to fossil-fuel-based systems.

Each case study is designed to provide a comprehensive understanding of the specific energy technologies under consideration. By comparing these diverse setups, the thesis aims to highlight critical factors that influence the exergy return on investment and GHG emissions in the life cycle.

4.1 KEY FACTORS E PREMISES

The key presumptions will be discussed in this subsection. These premises must allow for a reasonable and acceptable comparison between the five established cases. As a result, the energy service that must be provided to society must be specified first. Thus, the following parameters are utilized to determine the product deliverable for society using the base scenario of the coal-fired thermoelectric plant established in Castelo Branco (2012) as a reference:

- Net Electric Power ($\dot{Ex}_O$): 331 MW,
- Expected useful life for the thermoelectric: 40 years, and
- Utilization Factor: 85% (IEA, 2020)

Thermodynamics-related parameters, such as losses, energy efficiency, and energy penalty of the CCS (Carbon Capture and Storage) system, which are based on the maximum efficiency and minimum consumption information established at GREET (2022), are additional parameters that represent equal importance to obtain the fairest comparison possible. The ensuing subsections and the appendices will have a detailed presentation of these factors for each scenario.

Factors for converting labor into exergy (ee_L - equivalent primary energy resource embedded in one work-hour) and capital into exergy (ee_k - equivalent primary exergy resource embodied in one monetary unit) are also necessary, in addition to the thermodynamics needed to calculate each component. Specific investment costs based on the size of the enterprise, such as US$ per kW of energy produced for society (Capital Expenditure - CAPEX), and operational costs based on the size and complexity of the energy conversion facility (Operating Expenditure - OPEX), such as US$ per MWh of produced energy (Sciubba, 2011).

Setting the conditions that allow for the evaluation of each case's maximum energetic return is necessary. Therefore, the value of ee_k from Luxembourg presented by

Sciubba (2011) was utilized, which has a value of 2.05 MJ/Euro, to indicate economic features that constitute the lowest actual equivalent primary energy resource embodied in one monetary unit. This amount was changed to current value as of December 21, 2022, then converted to dollars based on information from the Bureau of Labor Statistics (2022). According to a Bureau of Labor Statistics (2022) index, the rate of inflation was estimated to have been 37.36% between January 1, 2011, and December 21, 2022. According to Fxtop (2022) business, the currency rate on January 1, 2011, was 1 EUR = 1.3362 USD. Consequently, the revised value of 3.76 MJ/US$ is assigned to the ee_k parameter in the model.

In relation to the ee_L parameter, the energy associated with human labor alone is comparatively insignificant when compared to all other resources, including human ones, associated with the operational phase of the installation for operation and maintenance. Hence, the capital ee_k parameter was used to convert OPEX to exergy.

The CAPEX and OPEX parameters represent also the minimum possible values and were obtained of IEA (2020). They will be presented in detail for each case in the following subsections.

Furthermore, it was assumed that the chemical exergy of the fuel has a relationship with the variation of Gibbs free energy and is quite close to it, for the purpose of converting the energy from combustion processes into exergy. Its value lies between the fuel's lower and upper thermal capacities (BEJAN, 2016). In this way, the following equation represents the theoretical formulation of the combustion exergy (air/fuel mix). In other words, to streamline the analysis and expedite the collection of the necessary data for calculating the fuel exergy in each case study, equation (9) was simplified. It was conservatively assumed, with minimal impact on the practical results, that, $ex_{ch} =$ LCV:

$$\dot{E}_F = \dot{m}_F . LCV \qquad \text{(Equation 18)}$$

Where:

$\dot{E}_F$ – Exergy flux from the Source of Energy from the Fuel (in this case,a mixture of fuel and air),

$\dot{m}_F -$ Mass fuel flow (in this case the air/fuel mixture),

LCV− Lower Calorific Value of the fuel used. The LCV value was conservatively used to calculate the ExROEEI,
ex_{ch} – Specific chemical exergy of the fuel (KAUSHIK; SINGH, 2014).

Regarding electricity, it was assumed that the energy quantities associated with this type of energy should be considered directly as exergy.

In relation to the calculation of the CO_2 Emission Intensity Index (CEII), the following assumptions were established:

1) To calculate direct emissions related to the energy used directly to produce the energy resource (Ex_d), the emissions factor in CO_2eq./TJ from GREET (2022) was used related to the energy conversion technology of each case under study;
2) In relation to indirect emissions related to Ex_{id} (Indirect Exergy), Ex_k (Capital Exergy) and Ex_{OP} (Operational Exergy), in order to maintain a fair and adequate assessment and as energy matrices around the world have participation from fossil and renewable sources, the emissions factor in CO_2eq./TJ from GREET (2022) for natural gas was considered, as this is the lowest of the factors between the two conversion technologies based on fossil sources among the 5 case studies, weighted by the average of 63% presence of fossil sources in the global energy matrix based on IEA (2019); and;
3) For direct emissions arising from the operation of the energy conversion installation in each case, the emissions factor in CO_2eq./TJ from GREET (2022) related to that energy conversion technology was used, considering for the cases of conversion technologies based in fossils, an efficiency of CCS systems of 90%, according to GREET (2022), that is, cases that use coal and natural gas present 10% of emissions in the operation of their respective energy conversion system.

In summary, the study's premises and boundary conditions were created to strike the best possible balance between minimizing emissions and achieving the highest energy efficiencies on the best-performing global scale, while also maintaining accuracy, facilitating fair comparisons among the case studies, and streamlining data sources and calculations. This methodology recognizes that various operating settings may have a substantial impact on the performance of each energy source and conversion technology, therefore it makes sure that each is assessed under circumstances that highlight both its potential efficiency and environmental impact.

By using international best practices and benchmarks, such as the lowest actual equivalent primary exergy resource values and the most advantageous economic and environmental parameters (such as those from Luxembourg for ee_k and the CO_2 emission estimations based on GREET data), the methodology used aims to reduce complexity. This deliberate decision recognizes that any particular case may provide different opportunities and problems while assisting in making the analysis as broadly applicable as feasible.

By defining these parameters, the study hopes to offer a thorough and impartial evaluation of every technology, emphasizing that although a generalized approach can yield insightful information, the true efficacy and sustainability of energy technologies can only be precisely determined when customized to the particular circumstances of each project. This nuanced approach avoids overly broad generalizations that might misrepresent the actual potential of certain technologies in particular contexts.

Table 2 – Key Factors and Premises bellow presents the list of key factors and premises.

Table 2 – Key Factors and Premises

(to be continued)

	Premisses	**Coal**	**GN Brayton**	**GN Combined**	**Bio Brayton**	**Bio Combined**	**Source**
General	Net Electric Power ($\dot{E}x_O$ – MW)	331					Castelo Branco (2012)
	Utilization Factor (%)	85%					NEA (https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf)
	Expected useful life for the thermoelectric (years)	40					Castelo Branco (2012)
	ee_k (MJ/US$) - equivalent primary exergy resource embodied in one monetary unit	3.76					2,05 MJ/EUR (Luxembourg) (SCIUBBA, 2011).
	T_0 (K)	298					Environment temperature: 25 ºC (CASTELO BRANCO, 2012)

Table 2 – Key Factors and Premises

(conclusion)

	Premisses	**Coal**	**GN** Brayton	**GN Combined**	**Bio Brayton**	**Bio Combined**	**Source**
Specific	CAPEX (US$/kW)	4766	1861	2522	885	1546	NEA (https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf, Coal - Table 3.3; GN Open - Table 3.2a; GN Closed - Table 3.2b; Bio - Table 3.7b)
	OPEX (US$/MWh)	19.34	7.50	12.87	7.50	12.87	Table 3.11a - NEA (https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf)
	T_{Lb} (K)	339	717	521	717	521	Castelo Branco (2012) and Turbine Rolls Royce TRENT 50
	Natural Gas Loss (%)	-	1	1	-	-	GREET (2022, TAB: NG; Cell AH25)
	LCV Fuel (MJ/kg)	20.55	48.91	48.91	32.49	32.49	GREET (2022, Fuel_Specs; C84, C81, C86); Bio (CARDOSO, 2017)
	Thermoelectric unit Energy Efficiency (%)	34.8	34.5	52.4	34.5	52.4	GREET (2022, TAB: Eletric, Cells: I29; O45; D45)
	Energy Penalty (%)	26	12	12	0	0	GREET (2022, TAB: Electric. Cells: C94:C99)

Source: Prepared by the author (2024).

4.2 CASE STUDY 1 – COAL-BASED POWER PLANT

The life cycle of a coal-fired power plant starts with the extraction of coal from mines. After being extracted, the coal is transported to the power plant site, where it is crushed into a fine powder to enhance efficient combustion. During the process of combustion in the boiler, the chemical energy stored inside the coal is transformed into thermal energy. This process heats water in the boiler tubes, producing high-pressure steam, which is then directed to a turbine, causing the turbine blades to rotate. This mechanical energy is transferred to a generator, where it is converted into electrical energy through electromagnetic induction.

Moreover, limestone has a crucial function in regulating sulfur emissions resulting from the burning of coal. Lime is not naturally occurring and must be acquired through the process of calcining limestone. The basic processes in lime production involve raw limestone mining, limestone preparation (crushing and sizing) for furnaces, limestone calcination, processing of lime further by hydration, and storage, handling, and transport operations. During the calcination process, limestone ($CaCO_3$) is heated at high temperatures to release CO_2 and produce calcium oxide (CaO), which is generally referred as lime (CASTELO BRANCO, 2012, CASTELO BRANCO *et al.*, 2013).

During the combustion process at the power plant, lime is added to the boiler. It then interacts with sulfur dioxide (SO_2) that is formed from burning coal. This reaction forms calcium sulfate ($CaSO_4$), which is then removed as a solid byproduct. This technique greatly decreases sulfur emissions. The lime derived from calcination is also utilized in several scrubbing procedures to counteract acidic gasses, so further diminishing emissions, particularly sulfur dioxide (SO_2).

Ultimately, the steam, having traversed the turbine, undergoes condensation in a condenser, transforming back into water, and is subsequently reintroduced into the boiler to commence the cycle once again. Contemporary coal-fired power plants have sophisticated emission control systems to catch and treat pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulates, in order to reduce their impact on the environment. Certain plants employ Carbon absorb and Storage (CCS) technologies, which effectively absorb carbon dioxide (CO_2) from the exhaust gases and securely store it underground, therefore significantly diminishing the plant's carbon footprint. This comprehensive strategy guarantees a consistent provision of power while also aiming to comply with environmental rules and foster the development of sustainable energy.

Moreover, in this case, the monoethanolamine (MEA) is used in post-combustion chemical absorption as the CO_2 capture method. This method is thought to be the most developed and appropriate for pulverized coal (PC) power plants that are currently in operation. Originally created in the 1960s, MEA is an organic chemical molecule that was used as a non-selective solvent to extract acid gases from natural gas streams, including CO_2 and H_2S. Later on, this procedure was modified to treat flue gasses. The easiest configuration to adopt for CO_2 capture in current plants is the post-combustion capture system, which works as an add-on to existing power production plants, similar to other gas treatment procedures already in place (CASTELO BRANCO, 2012, CASTELO BRANCO *et al.*, 2013).

The post-combustion CO_2 capture involves two main stages: energy conversion to generate electricity and CO_2 separation to obtain a concentrated CO_2 stream. Due to the low concentrations of CO_2 (about 13–15% v/v) and low pressure (~1 bar) used in this process, considerable gas volumes must be treated, which calls for larger equipment and more energy. This strategy is particularly relevant for global CO_2 capture projects due to its versatility and potential for short-term deployment. The MEA absorption process effectively addresses the challenge of removing CO_2 from flue gases, which contain impurities such as SOx, NOx, and particulates, thus ensuring comprehensive gas treatment (CASTELO BRANCO, 2012, CASTELO BRANCO *et al.*, 2013).

This case is the reference case for his study and is based on the Itaqui Port Coal Thermoelectric Power Plant presented by Castelo Branco (2012) is the reference case. With an installed capacity of 360 MW and net electric production of 331 MW, it is located in the city of São Luiz, State of Maranhão Brazil, 5 km from the Port of Itaqui – see Table 3. It occupies an area of about 50 ha. It generates electric power to the North and Northeast regions of Brazil’s Interconnected Power System, or SIN (CASTELO BRANCO, 2012, CASTELO BRANCO *et al.*, 2013, MOURA *et al.*, 2013).

The subsection 4.2.2 contains the data from Castelo Branco (2012) and GREET (2022) that is required to compute the exergy inputs at each stage of the processes, together with the entire calculation memory. Table 3 – Description of the evaluated processes – Coal-based power plant and Figure 2 indicate the processes that were included in the evaluation.

Table 3 – Description of the evaluated processes – Coal-based power plant

Process	Description
P1	Coal production
P2	Maritime transport of coal
P3	Rail transport of coal
P4	Calcareous mining
P5	Lime production
P6	Lime transport
P7	Thermoelectric unit
P8	Solvent production
P9	Solvent transport
P10	NaOH transport
P11	NaOH production

Source: Castelo Branco (2012, p. 81).

P1 – Coal production:

The stage of coal production considers the energy used during mine activities, such as mining and beneficiation. The data are defined with a reference flow of 1 kg of coal ready for rail transport.

P2 and P3 – Transport of coal:

Coal was anticipated to be delivered in two primary, separate phases during the raw material transport stage. The first stage (P3) entails rail transportation over an estimated 150 kilometers from the mine to the port in Colombia. The second step is maritime transport (P2), which travels from a port in Colombia to the port of Itaqui over an estimated 4,000 km (CASTELO BRANCO, 2012).

P4 and P5 – Calcareous mining and Lime production:

Lime is not found directly in nature and must be obtained by calcining limestone. The basic processes in lime production are raw limestone mining, limestone preparation (crushing and sizing) for furnaces, limestone calcination, processing of lime further by hydration, storage, handling and transport operations.

P6 – Lime transport:

From the state of Ceará, the lime needed for the Itaqui thermoelectric plant will be transported by road. It was chosen to obtain lime from the Sobral district, which is one of the closest and has the best highway access. The typical distance considered in this example to transport the material was 700 km (CASTELO BRANCO, 2012).

P7 – Thermoelectric unit:

The generation unit comprises a pulverized coal boiler with subcritical pressure, which is provided by the DOOSAN company, with BABCOCK technology, with a capacity of 1,125 t/h and 90% thermal efficiency (CASTELO BRANCO, 2012).

P8 – Solvent production:

The premise used is the acquisition of the solvent in the national market. It is predicted that 2.96 t/h of solvent will be consumed. Statistics from the Ecoinvent database were used because there were no data on the process's energy use (CASTELO BRANCO, 2012).

P9 – Solvent transport:

The distances of the two land routes from the solvent-producing company to the Itaqui thermoelectric plant are 1,553 km and 1,704 km, respectively. Both the BR-316 and BR-407 highways are used on the first route, whereas only the BR-316 is used on the second. 1,157 kg/h of solvent was expected to be consumed. Solvent usage would be about 6,086 tonnes per year based on 5,260 hours of operation. Therefore, 203 journeys from the Bahia production plant to Itaqui would be required during the course of a year. The hypothesis accounted for the truck's outbound and backward journeys (without a load) along the shortest path (CASTELO BRANCO, 2012).

P10 – NaOH transport:

A business in the city of Maceió, in Pontal da Barra, will provide the NaOH. In this instance, transportation from Pontal da Barra in Maceió to Itaqui will be accomplished via road (CASTELO BRANCO, 2012).

P11 – NaOH production:

NaOH is added to react with the HSS(Heat Stable Salts) and recover part of the degraded solvent (MEA). In this reaction, each mole of NaOH regenerates one mole of MEA. It was considered that the production of NaOH will be carried out in a chlorine and caustic soda production unit located in Alagoas (CASTELO BRANCO, 2012).

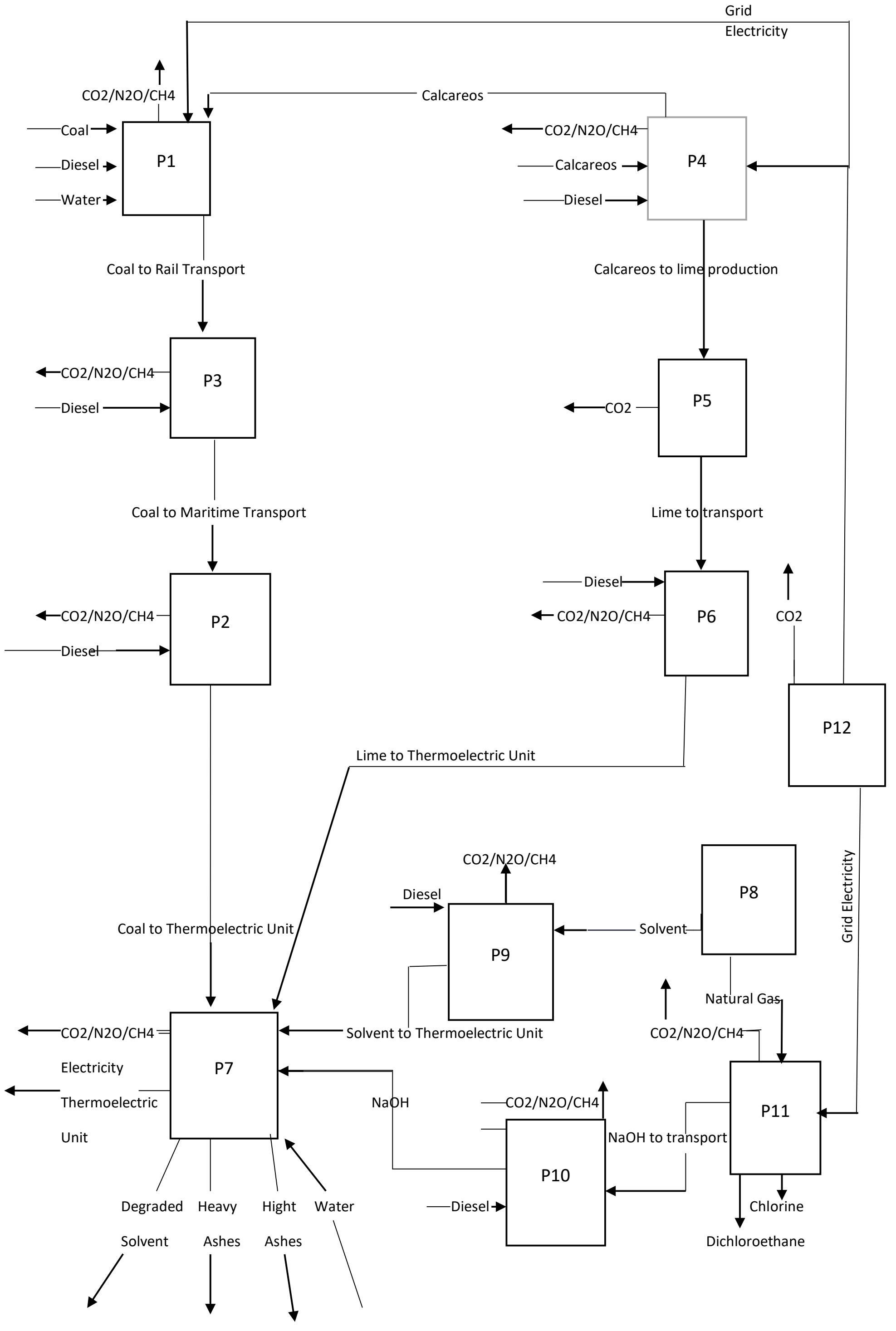

Figure 2 – Process flowchart for the case with CCS

Source: Castelo Branco (2012, p. 79).

Regarding the CAPEX, to evaluate the maximum exergy return, the minimum investment costs of 4,766 US$/kW from IEA (2020) was considered. With the same reasoning, the minimum operation and maintenance costs (OPEX) considered from IEA (2020) was 19.34 US$/MWh.

4.2.1 Results and Discussion

From Equations (8), (15), (16) and (17) the values of each part of the indicators presented in Table 4, ExROEEI, EROI, ExROI and CEII can be calculated. The complete calculation memory is available in the subsection 4.2.2.

Table 4 – Case 1 (Coal) – ExROEEI, ExROI and EROI Calculations for 40 years of operation and an utilization factor of 85%

ExROEEI Calculation	**TJ**	**%**
Indicator parts		
Ex_O	354906	-
Ex_d	23299	15.59
Ex_{id}	88	0.06
Ex_K	7474	5.00
Ex_{OP}	9033	6.04
Ex_{Env}	17287	11.57
Ex_{CO2}	92276	61.74
Indicators	**X:Y**	
ExROEEI	**2.37**	
EROI	60.9	
ExROI	15.2	
CO_2 Intensity (metric-tonCO_2/TJ)	**131.8**	
Total $CO_{2eq.}$ (Tg)	46.8	

Source: Prepared by the author (2024).

For 40 years of operation, the contribution of each component of the input of the indicator is 61,74% for Ex_{CO2}, 15.59% for Ex_d, 11.57% for Ex_{Env}, 6.04% for Ex_{OP}, 5.00 % for Ex_K, and 0.06% for Ex_{id}. This means that the exergy needed for carbon capture and sequestration has a significant impact on lowering the net energy services provided to society by the coal-fired thermal power plant.

4.2.2 Calculation Memory – Coal Thermoelectric

Ex_O calculation:

As electric energy is considered as pure exergy, this portion represents the exergy sent to society, as described in the subsection 3.1. In this case study, as described in the subsection 4.1, this portion is represented as a power rate of: $\dot{Ex}_O$ = 331 MW

For 40 years of operation and utilization factor of 85% the total exergy amount is:

$$\mathbf{Ex_O = 354{,}906\ TJ}$$

P1 – Coal production and Ex_d Calculation:

Material and energy inputs for the process. Data from this process from Castelo Branco (2012):

- Electric power: 0.012755 kWh/processed coal kg
- Diesel: 0.00026245 kg/processed coal kg
- Calcareous: 0.016263 kg/produced coal kg

A 20% loss of coal is assumed in this production stage.

From this information, it is possible to calculate the energy or direct exergy to produce coal as a primary energy source.

For this, it is first necessary to calculate the exergy inputs per MJ of electrical energy produced by the installation:

- Electric power: 0.0656 MJ/MJ Produced Electric Energy
- Diesel: 0.00005 kg/MJ Produced Electric Energy

In this way, these two exergy intake parcels are represented by Ex_d. To calculate the exergy portion related to diesel, the Equation (18) is used. As a result, the following results are obtained:

$$Ex_d = 21.73\ \text{MW}$$

For 40 years of operation and an 85% utilization rate:

$$\mathbf{Ex_d = 23{,}298.97\ TJ}$$

The amount of coal produced is 0.556 kg per MWh of electrical energy produced, or 0.1544 kg every MJ of produced electricity.

At this time, the Standard EROI of coal production technology, with data from the case study of Castelo Branco (2012), can be determined, agreeing to Hall *et al*. (2014), with Equation (15).

According to GREET (2022), the LCV of coal at 20.55 MJ/kg and the gross electric power is: Net Electric Power (331 MW) + Energy Penalty (86 MW – see Ex_{CO2} calculation bellow in this subsection) = 417 MW.

At this stage (Coal Production), the energy return to society is calculated as from the coal chemical energy that can be provided, that is converted to thermal energy in the boiler and is delivered as heat ($\dot{Q}_H$) as the input energy to the thermodynamic cycle.

So, the energy returned to society can be calculated as:

$$\text{Energy return to society} = 20.55 \text{ x } 0.1544 \text{ x } 417 = 1{,}323 \text{ MW}$$

Thus,

$$\mathbf{EROI = 60.92:1}$$

P2 – Maritime transport of coal:

Material and energy inputs for the process. Data from this process from Castelo Branco (2012):

- Diesel: 0.005673 kg/produced coal kg

Again, the energy input per MJ of electrical energy produced by the facility must be calculated:

- Diesel: 0.000876 kg/MJ Produced Electric Energy

Process 2 corresponds to one of the indirect uses of exergy that will be called Ex_{idP2}. Equation (18) is used to convert the mass of diesel into exergy.

$$\mathbf{Ex_{idP2} = 0.037\ MW}$$

P3 – Rail transport of coal:

Material and energy inputs for the process. Data from this process from Castelo Branco (2012):

- Diesel: 0.0028106 kg/produced coal kg

Again, the exergy input per MJ of electrical energy produced by the facility must be calculated:

- Diesel: 0.00043 kg/MJ Produced Electric Energy

Process 3 corresponds to one of the indirect uses of exergy that will be called Ex_{idP3}. Equation (9) is used to convert the mass of diesel into exergy.

$$\mathbf{Ex_{idP3} = 0.018\ MW}$$

P4 – Calcareous mining:

Material and energy inputs for the process. Data from this process from Castelo Branco (2012):

- Electric power: 0.469 kWh/produced calcareous kg
- Diesel: 0.0099 kg/produced calcareous kg

Calculating exergy inputs per MJ of electrical energy produced by the facility:

- Electric power: 1.688 MJ/MJ Produced Electric Energy
- Diesel: 0.00005 kg/MJ Produced Electric Energy

Process 4 corresponds to one of the indirect uses of exergy that will be called Ex_{idP4}. Equation (18) is used to convert the mass of diesel into exergy.

$$\mathbf{Ex_{idP4} = 0.0109\ MW}$$

P5 – Lime production:

Material input for the process. Data from this process from Castelo Branco (2012):

- Calcareous: 2.00 kg/ lime kg

P6 – Lime transport:

Material and energy inputs for the process:

- Diesel: 0.014 kg/ lime kg

Again, the exergy input per MJ of electrical energy produced by the facility must be calculated:

- Diesel: 0.000014 kg/MJ Produced Electric Energy

Process 6 corresponds to one of the indirect uses of exergy that will be called Ex_{idP6}. Equation (18) is used to convert the mass of diesel into exergy.

$$\mathbf{Ex_{idP6} = 0.0006\ MW}$$

P7 – Thermoelectric unit:

Material inputs for the process. Data from this process from Castelo Branco (2012):

- Lime: 0.00369 kg/kWh Produced Electric Energy
- Coal: 0.556 kg/kWh Produced Electric Energy
- Solvent: 0.0035 kg/kWh Produced Electric Energy

- NaOH: 0.00426 kg/kWh Produced Electric Energy

These material inputs must be placed on the same chosen basis (kg/MJ of electrical energy produced).

- Lime: 0.001025 kg/MJ Produced Electric Energy
- Coal: 0.1544 kg/MJ Produced Electric Energy
- Solvent: 0.00097 kg/MJ Produced Electric
- Energy NaOH: 0.00118 kg/MJ Produced Electric Energy

P8 – Solvent production:

Information considered in the previous process (P7).

P9 – Solvent transport:

Material and energy inputs for the process. Data from this process from Castelo Branco (2012):

- Diesel: 0.0312 kg/ solvent kg

Again, the exergy input per MJ of electrical energy produced by the facility must be calculated:

- Diesel: 0.00003 kg/MJ Produced Electric Energy

Process 9 corresponds to one of the indirect uses of exergy that will be called Ex_{idP9}. Equation (18) is used to convert the mass of diesel into exergy.

$$\mathbf{Ex_{idP9} = 0.00128\ MW}$$

P10 – NaOH transport:

Material and energy inputs for the process. Data from this process from Castelo Branco (2012):

- Diesel: 0.0309 kg/ NaOH kg

Again, the exergy input per MJ of electrical energy produced by the facility must be calculated:

- Diesel: 0.00004 kg/MJ Produced Electric Energy

Process 10 corresponds to one of the indirect uses of exergy that will be called Ex_{idP10}. Equation (18) is used to convert the mass of diesel into exergy.

$$\mathbf{Ex_{idP10} = 0.0015\ MW}$$

P11 NaOH production:

Energy input for the process. Data from this process from Castelo Branco (2012):

- Electric power: 2.94 kWh/NaOH kg

Calculating this energy input per MJ of electrical energy produced by the facility:

- Electric power: 0.0125 MJ/MJ Produced Electric Energy

Process 11 corresponds to one of the indirect uses of exergy that will be called Ex_{idP11}. As this is just an energy input, Ex_{idP11} is equal to the previous electricity input value, like this:

$$\mathbf{Ex_{idP11} = 0.0125\ MW}$$

P12 – Electricity production:

This process only represents the electrical energy output of the process that is directed to society.

Ex_{id} Calculation:

From the identification of all previous processes and their indirect uses of exergy, the indirect exergy used in the energy conversion process (Ex_{id}) can be calculated as follows:

$$Ex_{id} = Ex_{idP2} + Ex_{idP}3 + Ex_{idP4} + Ex_{idP6} + Ex_{idP9} + Ex_{idP10} + Ex_{idP11}$$

$$Ex_{id} = 0.0822 \text{ MW}$$

For 40 years of operation and utilization factor of 85%, according to IEA (2020):

$$\mathbf{Ex_{id} = 88.20\ TJ}$$

Ex_K Calculation:

This part relates to the exergy used during the project's development and the establishment of the business, in this case, the coal-fired thermoelectric plant. IEA (2020) brings minimum estimative for investment costs in thermoelectric plants of the size and type under investigation of 4,766 US$/kW.

Knowing the 417 MW gross power provides the following information:

CAPEX = 417,000 kW x 4,766 US$/kW / 1000 = 1,987,708 kUS$

Using the ee_k, which has a value of 3.76 MJ/US$ and is defined as "equivalent primary energy resource embodied in one monetary unit" (SCIUBBA, 2011, p. 1.064) as presented in subsection 4.1, it follows that:

$$\mathbf{Ex_K = 7{,}473.78\ TJ}$$

Ex_{OP} Calculation:

This part is equivalent to the energy used for the installation's maintenance and operation (OPEX). According to research presented by IEA (2020), minimum estimative for operation and maintenance expenses is US$ 19.34/MWh. Agreeing to IEA (2020), 297,840 hours are the installation's actual operational hours when considering the project's 40-year useful life and 85% utilization rate. So:

OPEX = 417 x 297,840 x 19.34 / 1000 = 2,402,360 kUS$

Again, using the ee_k, which has a value of 3.76 MJ/US$ and is defined as "equivalent primary energy resource embodied in one monetary unit" (SCIUBBA, 2011, p. 1.064), as presented in subsection 4.1, it follows:

$$\mathbf{Ex_{OP} = 9{,}032.87\ TJ}$$

<u>Ex_{Env} Calculation:</u>

The flue gases in the boiler exhaust and the cooling water are the two main energy effluents in this conversion process. In relation to the first effluent, according to Castelo Branco (2012), the boiler has a 90% energy efficiency, meaning that 10% of the total heat given by coal flows with the flue gases: $Q_{Lb} = 0.1 \times Q_H$

Where Q_H is the heat produced by coal for the energy conversion process and Q_{Lb} is the heat flowing with the flue gases from the boiler exhaust.

As it was seen in the process 1 above:

$$\dot{Q}_H = 1{,}323 \text{ MW}$$

$$\text{Thus, } \dot{Q}_{Lb} = 132.37 \text{ MW.}$$

Based on Bejan (2016), the following equation converts this thermal energy flow into exergy:

$$\dot{EQ}_{Lb} = \dot{Q}_{\text{Lb}} \cdot \left(1 - \frac{T_0}{T_{Lb}}\right) \qquad \text{(Equation 19)}$$

Where:

$\dot{EQ}_{Lb}$ – Exergy from the effluent flue gas flow from the boiler exhaust.

T_0 – Environment temperature. Used the value of 25º C, absolute temperature of 298 K.

T_{Lb} – Temperature of flue gases from boiler exhaust. 66.33º C according to Castelo Branco (2012), absolute temperature of 339.33 K.

Thereby, $\dot{EQ}_{Lb}$ = 16.12 MW.

According to Castelo Branco (2012), the second effluent (cooling water) is discharged into the environment at 35°C, a temperature very close to the ambient level.

In other words, its exergy is negligible. Given the minimal temperature difference between the effluent and the environment, this portion is not considered to have a significant environmental impact from the energy system.

As a result, it was decided not to include this effluent in the analysis.

Thus, the following was used: $Ex_{Env} = EQ_{Lb}$

Consequently, given an 85% utilization factor and 40 years of operation:

$$\mathbf{Ex_{Env} = 17{,}286.67\ TJ}$$

<u>Ex_{CO2} Calculation:</u>

This is the part of the sentence pertaining to the exergy requested for carbon capture and sequestration (CCS). In this case study, it is considered an energy penalty of 26% for this process, that consists to the greater efficiency CCS value obtained from GREET (2022) that corresponds to a value of 86.06 MW used by the CCS process.

It is crucial to highlight the methodology's use of abstraction. It is assumed that the amount of electrical power delivered to society in both scenarios—with and without CCS— would be the same. However, to encourage comparison with other technologies that eventually emit no CO_2, the portion of exergy related to use for CCS returns as Ex_{CO2} to be assumed in the model as a kind of exergy use.

So, for 40 years of operation and utilization factor of 85%, according to IEA (2020):

$$\mathbf{Ex_{CO2} = 92{,}275.60\ TJ}$$

<u>CEII Calculation:</u>

1) CO_2 eq. (C1) emitted by the processes related to the energy used directly to produce the energy resource (Ex_d).
   $C1 = Ex_d$ x 275630.58 kg CO_2eq./TJ (GREET, 2022) = 6,421,909,328 kg CO_2eq.
2) CO_2 eq. (C2) emitted by the processes related to the energy used indirectly to produce the energy resource (Ex_{id}). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the

global matrix of 63% based on IEA (2019) was used to calculate these emissions.

$C2 = Ex_{id}$ x 119303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 6,629,319 kg CO_2eq.

3) CO_2 eq. (C3) related to the emissions from the operation of the thermoelectric facility (Q_H). As it is used a CCS system with 90% capture efficiency (GREET, 2022), only 10% of the equivalent CO_2 emission is considered.

$C3 = Q_H$ .x275630.58 kg CO_2eq./TJ (GREET, 2022) x 0.1 = 3.9 x 10^{10} kg CO_2eq.

4) CO_2 eq. (C4) emitted by during the design, construction, and installation phases of the enterprise (Ex_K). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

C4 = ExK x 119303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 561,738,466 kg CO_2eq.

5) CO_2 eq. (C5) emitted used throughout the operational phase of the enterprise (Ex_{OP}). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

$C5 = Ex_{OP}$ x 119303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 678,921,589 kg CO_2eq.

As seen in Equation (17), the CEII calculation is:

$$CO_2 \text{ Equivalent Emissions} / Ex_O$$

$$CO_2 \text{ Equivalent Emissions} = C1+C2+C3+C4+C5) = 4.68 \times 10^{10} \text{ kg } CO_2\text{eq.}$$

$$\mathbf{CEII = 131.8\ 10^3\ kg\ CO_2eq./TJ}$$

4.3 CASE STUDY 2 – BRAYTON-CYCLE NATURAL GAS POWER PLANT

The lifecycle of natural gas power plant begins with the extraction of natural gas. Natural gas is often found in association with petroleum reserves and is extracted in oil production facilities. Once separated from oil, the natural gas undergoes processing to remove impurities and separate natural gas liquids (NGL), ensuring the gas meets the required quality standards for combustion. The processed natural gas is then transported via pipelines to the power plant.

In the Brayton cycle, at the power plant, the natural gas is directed to the combustion chamber of a gas turbine. In the combustion chamber, the natural gas mixes with compressed air and is ignited, causing a high-temperature, high-pressure gas stream. This gas stream expands rapidly, driving the turbine blades and converting thermal energy into mechanical energy. This mechanical energy is used to spin a shaft connected to an electrical generator, where electromagnetic induction occurs, generating electricity (BOYCE, 2011).

The exhaust gases from the combustion process, which still contain a significant amount of thermal energy, are expelled into the atmosphere in a simple cycle power plant. This type of plant is known for its operational simplicity and ability to provide rapid power generation, making it suitable for meeting peak electricity demand. However, the overall thermal efficiency of a simple cycle gas turbine is lower compared to combined cycle configurations, as the waste heat from the exhaust is not utilized for additional power generation (BOYCE, 2011).

To address environmental concerns, modern natural gas power plants incorporate carbon capture and storage (CCS) systems to reduce CO_2 emissions. The CCS process begins with the capture of CO_2 from the flue gases produced during combustion. This is typically done using post-combustion capture technologies, such as amine-based solvents that chemically absorb CO_2. Once captured, the CO_2 is compressed and transported via pipelines to a suitable storage site. Common storage methods include injecting the CO_2 into deep geological formations, such as depleted oil and gas fields or saline aquifers, where it can be securely stored for long periods (CASTELO BRANCO, 2012).

Additionally, emission control technologies are implemented to reduce nitrogen oxide (NOx) emissions, such as water or steam injection and selective catalytic reduction (SCR). These advancements in turbine technology and combustion control strategies have significantly reduced pollutant emissions of gas turbine power plants. Despite these measures, the simple cycle configuration remains less efficient than combined cycle plants, which recover and utilize waste heat to produce additional electricity (COSTA *et al.*, 2018). Integrating CCS systems into simple cycle plants helps mitigate their environmental impact by significantly reducing greenhouse gas emissions.

As the subsection 4.1 shows, the energy service that must be provided to society shall the same for the five cases. Thus, this case and all the next cases are hypothetic with their parameters related to determine the product deliverable for society were based on the base scenario (subsection 4.2) of the coal-fired thermoelectric plant established in

Castelo Branco (2012) as a reference, with net electric power of 331 MW and the expected useful life for the thermoelectric of 40 years.

The subsection 4.2.2 contains the data, specially from GREET (2022), that is required to compute the exergy inputs at each stage of the processes, together with the entire calculation memory. Table 5 and Figure 3 indicate the processes that were included in the evaluation (the same for cases 2 and 3).

Table 5 – Description of the evaluated processes – Natural Gas Power Plant

Process	Description
P1	Oil and Gas production
P2	NG transport to Gas process unit
P3	NG processing unit
P4	NG transport to thermoelectric
P5	Thermoelectric unit
P6	CCS system

Source: Prepared by the author (2024).

P1 – Oil and Gas production:

The stage of Oil and Gas production considers the energy used during the production activities. The data are defined with a reference flow of 1 kg of NG ready for pipeline transport to the processing unit.

P2 and P4 – NG Transport:

NG was anticipated to have two transport stages. The first stage (P2) entails pipeline transportation from the offshore oil and gas production unit to the NG processing facility. The second step is the pipeline transport (P3) from the NG processing unit to the thermoelectric plant.

P3 – NG processing unit:

The stage of NG processing considers the energy used to process and specify the NG to its end uses as in the thermoelectric units. The data are defined with a reference flow of 1 kg of NG ready for pipeline transport to the thermoelectric unit.

P5 – Thermoelectric unit:

The generation unit comprises the necessary equipment and systems to convert the NG chemical energy content in electric power.

P6 – CCS (Carbon Capture and Sequestration) system:

The premise used is the use of a energy penalty from GREET (2022) to calculate necessary exergy used to capture and sequestrated CO_2 from the flue gas of the thermoelectric.

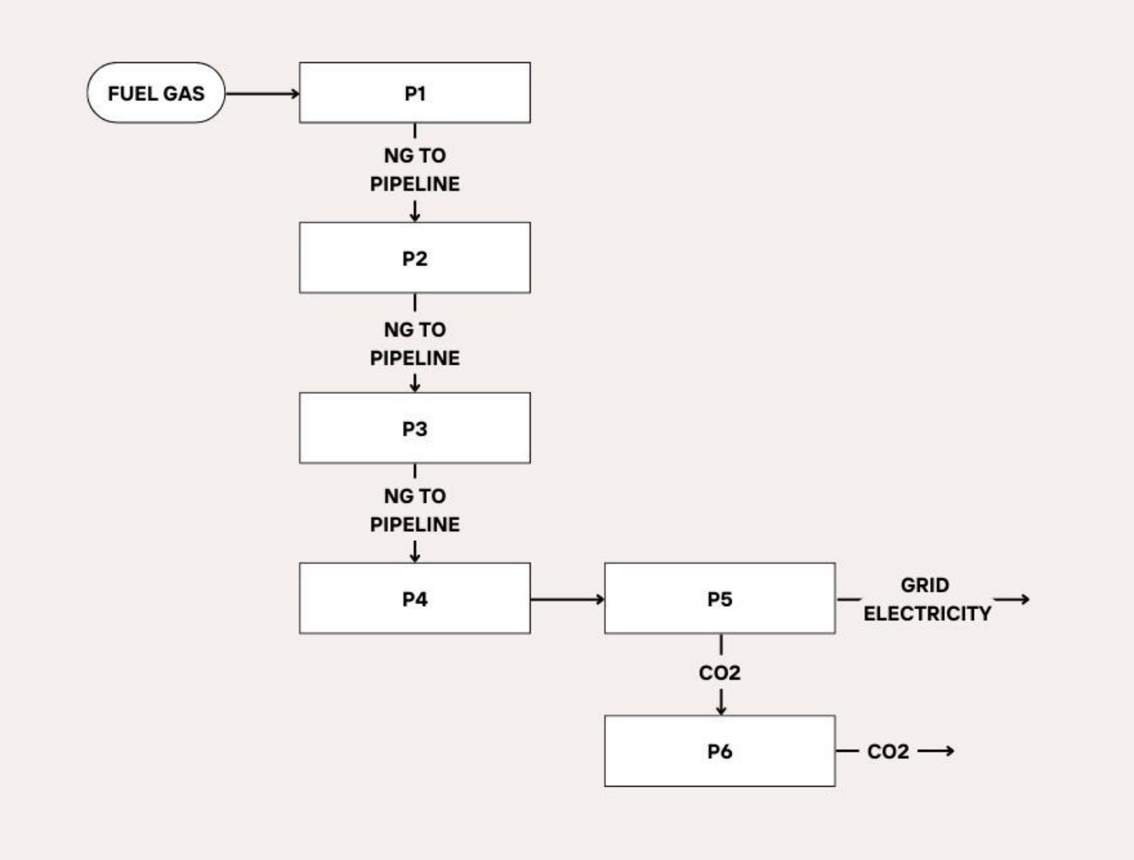

Figure 3 – Process flowchart for the NG cases

Source: Prepared by the author (2024).

Regarding the CAPEX, to evaluate the maximum exergy return, the minimum investment costs of 1,861 US$/kW from IEA (2020) was considered. With the same reasoning, the minimum operation and maintenance costs (OPEX) considered from IEA (2020) was 7.50 US$/MWh.

4.3.1 Results and Discussion

From Equations (8), (15), (16) and (17) the values of each part of the indicators presented in Table 6, ExROEEI, EROI, ExROI and CEII can be calculated. The complete calculation memory is available in the subsection 4.3.2.

Table 6 – Case 2 (NG Simple Cycle) – ExROEEI, ExROI and EROI Calculations for 40 years of operation and an utilization factor of 85%

ExROEEI Calculation Indicator parts	**TJ**	**Weight (%)**
Ex_O	354906	-
Ex_d	12200	2.38
Ex_{id}	12079	2.36
Ex_K	2590	0.51
Ex_{OP}	3109	0.61
Ex_{Env}	440344	85.95
Ex_{CO2}	41988	8.20
Indicators	**X:Y**	
ExROEEI	**0.69**	
EROI	94.3	
ExROI	29.1	
CO_2 Intensity (metric-ton CO_2/TJ)	**46.5**	
Total CO_{2eq}. (Tg)	16.5	

Source: Prepared by the author (2024).

For 40 years of operation, the contribution of each component of the input of the indicator is 85.95% for Ex_{Env}, 8.20% for Ex_{CO2}, 2.38% for Ex_d, 2.36% for Ex_{id}, 0.61% for Ex_{OP}, and 0.51% for Ex_K. This means that the exergy that is wasted to the environment has a significant impact on lowering the net energy services provided to society by the natural gas simple cycle thermal power plant.

4.3.2 Calculation Memory – Brayton-Cycle Natural Gas

Ex_O calculation:

As electric energy is considered as pure exergy, this portion represents the exergy sent to society, as described in the subsection 3.1. In this case study, as described in the subsection 4.1, this portion is represented as a power rate of: $\dot{Ex_O}$ = 331 MW

For 40 years of operation and utilization factor of 85% the total exergy amount is:

$$\mathbf{Ex_O = 354{,}906\ TJ}$$

P1 – Gas production and Ex_d Calculation:

For NG production and processing (Process 1 and 3), GREET (2022) has ‘energy efficiency’ values, which can be converted for the application. In row 23 of the NG tab the efficiencies of conventional NG recovery and processing can be found (GREET, 2022, Tab: NG. Cell: AH23. 97,9%).

It represents that 2.1% from the natural Gas mass is utilized in the processes of gas productions and processing. For each kg of natural produced, 0.021 kg is required for these processes. Thus, it was assumed that each process uses the half part of this amount, resulting in 0.0105 kg for each process.

Material and energy inputs for the process. Data from this process from GREET (2022):

- Fuel Gas: 0.01 kg/kg produced Natural Gas
- LCV (Fuel Gas): 48.91 (MJ/kg)
- A 1% loss of natural gas is assumed in this production stage

With this information, the necessary mass flow of produced gas is 22.16 kg/s (21.94 kg/s is required to produce the gross electric power, but it is necessary to consider the 1% production loss) and the energy added from the fuel gas to produce this amount is 0.51 MJ/kg of produced gas.

Multiplying the above values, the Ex_d is:

$$Ex_d = 11.38 \text{ MW}$$

For 40 years of operation and an 85% utilization rate:

$$\mathbf{Ex_d = 12,200.19\ TJ}$$

At this time, the Standard EROI of natural gas production technology can be determined, agreeing to Hall (2014), by Equation (15).

At this stage (Natural Gas Production), the energy return to society is calculated as from the gas chemical energy that can be provided, that is converted to thermal energy in gas turbine and is delivered as heat ($\dot{Q}_H$) as the input energy to the thermodynamic cycle.

The thermodynamic efficiency (η) of the simple cycle is 34,5% (GREET, 2022) and according to Bejan (2016) is calculated as:

$$\eta = \frac{\dot{W}}{\dot{Q}_H} \qquad \text{(Equation 20)}$$

Considering the gross electric power ($\dot{W}$) that is produced at the power plant as the net electric power (331 MW) plus the energy penalty that is necessary to run the CCS system, it is possible to calculate the energy return to society, assuming that it is equal to $\dot{Q}_H$.

According to GREET (2022), the energy penalty represents an increase of 12% in the net power. Therefore:

Energy return to society = (331 + 39.16) / 0.345= 1,073 MW

Thus,

EROI = 94.30:1

P2 – Transport of Gas to Gas Processing Unit:

It was considered that this consumption was already measured in the production facility, as the compression system for gas export is part of the production unit.

$Ex_{idP2} = 0$

P3 – Gas Processing Unit:

Material for the process. Data from this process from GREET (2022):

- Fuel Gas: 0.01 kg/kg produced Natural Gas

Process 3 corresponds to one of the indirect uses of exergy that will be called Ex_{idP3}. Equation (18) is used to convert the mass of gas into exergy.

So, the necessary exergy used in this process is: 0.01 x LCV = 0.51 MJ/kg of processed natural gas.

$$Ex_{\mathbf{idP3}} = 0.51 \text{ MJ/kg x } 21.94 \text{ kg/s} = 11.27 \text{ MW}$$

$$\mathbf{Ex_{idP3} = 11.27\ MW}$$

P4 – Transport of Gas to Thermoelectric Unit:

It was considered that this consumption was already measured in the processing facility, considering that the processing and the thermoelectric units are in the same location.

$$\mathbf{Ex_{idP4} = 0}$$

Ex_{id} Calculation:

From the identification of all previous processes and their indirect uses of exergy, the indirect exergy used in the energy conversion process (Ex_{id}) can be calculated as follows:

$$Ex_{id} = Ex_{idP2} + Ex_{idP}3 + Ex_{idP4}$$

$$Ex_{id} = 11.27 \text{ MW}$$

For 40 years of operation and utilization factor of 85%:

$$\mathbf{Ex_{id} = 12{,}079.19\ TJ}$$

P5 – Thermoelectric unit:

Data for this process from GREET (2022):

- Thermoelectric unit Energy Efficiency: 34.5%

With this information and using the Equation (18) and Equation (20), it is possible to determine the mass flow of fuel gas that is required to produce the gross electric power:

$$\text{Required Fuel Gas} = 370.16 / (48.91 \text{ x } 0.345) = 21.94 \text{ kg/s}$$

P6 – Electricity production:

This process only represents the electrical energy output of the process that is directed to society.

Ex_K Calculation:

This part relates to the exergy used during the project's development and the establishment of the business, in this case, the natural gas thermoelectric plant in an simple cycle. IEA (2020) brings minimum estimative for investment costs in thermoelectric plants of the size and type under investigation of 1,861 US$/kW.

Knowing the 370,16 MW (331 MW + 39.16) gross power provides the following information:

CAPEX = (331,000 + 39,160) kW x 1,861 US$/kW / 1000 = 688,870 kUS$

Using the ee_k, which has a value of 3.76 MJ/US$ and is defined as "equivalent primary energy resource embodied in one monetary unit" (SCIUBBA, 2011, p. 1.064), as presented in subsection 4.1, it follows that:

$$\mathbf{Ex_K = 2{,}590.14\ TJ}$$

Ex_{OP} Calculation:

This part is equivalent to the energy used for the installation's maintenance and operation (OPEX). According to research presented by IEA (2020), minimum estimative for operation and maintenance expenses is US$ 7.50/MWh. Agreeing to IEA (2020), 297,840 hours are the installation's actual operational hours when considering the project's 40-year useful life and 85% utilization rate. So:

OPEX = (331 + 39,16) x 297,840 x 7.50 / 1000 = 826,860 kUS$

Again, using the ee_k, which has a value of 3.76 MJ/US$ and is defined as "equivalent primary energy resource embodied in one monetary unit" (SCIUBBA, 2011, p. 1.064), as presented in subsection 4.1, it follows:

$$\mathbf{Ex_{OP} = 3{,}109.01\ TJ}$$

Ex_{Env} Calculation:

The flue gas from the turbine exhaust is the main energy effluent in this conversion process. From Equation (14), it is necessary to calculate EQ_{Lb} to obtain the Ex_{Env}.

According to Bejan (2016), the first law of thermodynamics in this cycle is:

$$Q_H - Q_{Lb} = W \qquad \text{(Equation 21)}$$

Where Q_H is the heat produced by the fuel gas for the energy conversion process, Q_{Lb} is the heat flowing with the flue gases from the turbine exhaust and W is the work delivered by the cycle.

As it was shown in the process 1 above:

$$\dot{Q}_H = \ 1{,}072.93 \text{ MW}$$

Thus from the Equation (20), $\dot{Q}_{Lb} = \dot{Q}_H - \dot{W}$
$\dot{Q}_{Lb} = 1{,}072.93 - (331 + 39.16) = 702.77$ MW

Based on Bejan (2016), the following Equation (19) that was presented in the subsection 4.2.2 converts this thermal energy flow into exergy:

$$\dot{EQ}_{Lb} = \dot{Q}_{\text{Lb}} \cdot \left(1 - \frac{T_0}{T_L}\right)$$

Where:

$\dot{EQ}_{Lb}$ – Exergy from the effluent flue gas flow from the turbine exhaust.
T_0 – Environment temperature. Used the value of 25° C, absolute temperature of 298 K.
T_{Lb} – Temperature of flue gases from the turbine exhaust. 444° C according to Lim (2009a and 2009b), absolute temperature of 717 K.
Thereby, $\dot{EQ}_{Lb}$ = 410.68 MW
Thus, the following was used: $Ex_{Env} = EQ_{Lb}$
Consequently, given an 85% utilization factor and 40 years of operation:

Ex_{Env} = 440,344 TJ

Ex$_{CO_2}$ Calculation:

This is the part of the sentence pertaining to the exergy requested for carbon capture and sequestration (CCS). In this case study, it is considered an energy penalty of 12% for this process, that consists to the greater efficiency CCS value obtained from GREET (2022) that corresponds to a value of 39.16 MW used by the CCS process.

It is crucial to highlight the methodology's use of abstraction. It is assumed that the amount of electrical power delivered to society in both scenarios—with and without CCS— would be the same. However, to encourage comparison with other technologies that eventually emit no CO_2, the portion of exergy related to use for CCS returns as Ex$_{CO_2}$ to be assumed in the model as a kind of exergy use.

So, for 40 years of operation and utilization factor of 85%, according to IEA (2020):

$$\mathbf{Ex_{CO2} = 41{,}988.29\ TJ}$$

CEII Calculation:

1) CO_2 eq. (C1) emitted by the processes related to the exergy used directly to produce the energy resource (Ex$_d$).

   C1 = Ex$_d$ x 119,303.50 kg CO_2eq./TJ (GREET, 2022) = 1,455,525,374 kg CO_2eq.
2) CO_2 eq. (C2) emitted by the processes related to the energy used indirectly to produce the energy resource (Ex$_{id}$). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

   C2 = Ex$_{id}$ x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 907,901,966 kg CO_2eq.
3) CO_2 eq. (C3) related to the emissions from the operation of the thermoelectric facility (Q_H). As it is used a CCS system with 90% capture efficiency (GREET, 2022), only 10% of the equivalent CO_2 emission is considered.

   C3 = Q_H x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.1 = 1.4×10^{10} kg CO_2eq.
4) CO_2 eq. (C4) emitted by during the design, construction, and installation phases of the enterprise (Ex$_K$). As the indirect processes are related to the energetic

matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

$C4 = Ex_K$ x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 174,082,836 kg CO_2eq.

5) CO_2 eq. (C5) emitted used throughout the operational phase of the enterprise (Ex_{OP}). As the indirect processes are related to the energetic matrices, as seen in section 3.1 subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

$C5 = Ex_{OP}$ x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 208,955,529kg CO_2eq.

As seen in Equation (17), the CEII calculation is:

CO_2 Equivalent Emissions / Ex_O

CO_2 Equivalent Emissions= C1+C2+C3+C4+C5) = 1.65 x 10^{10} kg CO_2eq.

CEII = 46.4 x 10^3 kg CO_2eq./TJ

4.4 CASE STUDY 3 – COMBINED-CYCLE NATURAL GAS POWER PLANT

In a combined cycle natural gas power plant, the process begins exactly as the previous case related to the simple cycle with the extraction and processing of natural gas. Once at the power plant, the natural gas undergoes combustion in a gas turbine, operating first on the Brayton cycle, to produce electricity.

Regarding to the Brayton cycle, the process is the same in comparison to the previous case related to the simple cycle, driving a first electrical generator. Although, as the exhaust gases from the gas turbine still hold a significant amount of thermal energy, it is then directed to a heat recovery steam generator (HRSG) (BOYCE, 2011).

In the HRSG, the exhaust heat is used to produce steam from water. This steam is then directed to a steam turbine, which operates on the Rankine cycle. The steam turbine drives a second generator, producing additional electricity. This combination of gas and steam turbines in a single plant allows for significantly higher efficiency compared to a simple cycle gas turbine plant, as it utilizes the waste heat from the gas turbine to generate extra power (BOYCE, 2011).

Furthermore, combined cycle plants can be equipped also with Carbon Capture and Storage (CCS) systems to mitigate environmental impact. This integration of CCS with high efficient combined cycle technology reduces the carbon footprint of electricity generation from natural gas, aligning with global sustainability goals and regulatory requirements.

As the subsection 4.1 shows, the energy service that must be provided to society shall the same for the five cases. Thus, this case is hypothetic with its parameters related to determine the product deliverable for society were based on the base scenario (subsection 4.2) of the coal-fired thermoelectric plant established in Castelo Branco (2012) as a reference, with net electric power of 331 MW and the expected useful life for the thermoelectric of 40 years.

The subsection 4.4.2 contains the data, specially from GREET (2022), that are required to compute the exergy inputs at each stage of the processes, together with the entire calculation memory.

Regarding the CAPEX, to evaluate the maximum exergy return, the minimum investment costs of 2,522 US$/kW from IEA (2020) was considered. With the same reasoning, the minimum operation and maintenance costs (OPEX) considered from IEA (2020) was 12.87 US$/MWh.

4.4.1 Results and Discussion

From Equations (8), (15), (16) and (17) the values of each part of the indicators presented in Table 7, ExROEEI, EROI, ExROI and CEII can be calculated. The complete calculation memory is available in the subsection 4.4.2.

Table 7 – Case 3 (NG Combined Cycle) – ExROEEI, ExROI and EROI Calculations for 40 years of operation and an utilization factor of 85%

ExROEEI Calculation **Indicator parts**	**TJ**	**(%)**
Ex_O	354906	
Ex_d	8033	3.63
Ex_{id}	7953	3.60
Ex_K	3510	1.59
Ex_{OP}	5335	2.41
Ex_{Env}	154341	70.08
Ex_{CO2}	41988	18.99
Indicators	**X:Y**	
ExROEEI	**1.60**	
EROI	94.3	
ExROI	44.2	
CO_2 Intensity (metric-ton CO_2/TJ)	**31.7**	
Total CO_{2eq}. (Tg)	11.3	

Source: Prepared by the author (2024).

For 40 years of operation, the contribution of each component of the input of the indicator is 70.08% for Ex_{Env}, 18.99% for Ex_{CO2}, 3.63% for Ex_d, 3.60% for Ex_{id}, 2.41% for Ex_{OP} and 1.59% for Ex_K. This means that the exergy that is wasted to the environment has a significant impact on lowering the net energy services provided to society by the natural gas combined cycle thermal power plant.

4.4.2 Calculation Memory – Combined-Cycle Natural Gas

Ex_O calculation:

As electric energy is considered as pure exergy, this portion represents the exergy sent to society, as described in the subsection 3.1. In this case study, as described in the subsection 4.1, this portion is represented as a power rate of: $\dot{Ex}_O$ = 331 MW

For 40 years of operation and utilization factor of 85% the total exergy amount is:

$$\mathbf{Ex_O = 354{,}906\ TJ}$$

P1 – Gas production and Ex_d Calculation:

For NG production and processing (Process 1 and 3), GREET (2022) has ‘energy efficiency’ values, which can be converted for the application. In row 23 of the NG tab the efficiencies of conventional NG recovery and processing can be found (GREET, 2022, Tab: NG. Cell: AH23. 97,9%).

It represents that 2.1% from the natural Gas mass is utilized in the processes of gas productions and processing. For each kg of natural produced, 0.021 kg is required for these processes. Thus, it was assumed that each process uses the half part of this amount, resulting in 0.0105 kg for each process.

Material and energy inputs for the process. Data from this process from GREET (2022):

- Fuel Gas: 0.01 kg/kg produced Natural Gas.
- LCV (Fuel Gas): 48.91 (MJ/kg).
- A 1% loss of natural gas is assumed in this production stage.

With this information, the necessary mass flow of produced gas is 14.59 kg/s (14.44 kg/s is required to produce the gross electric power, but it is necessary to consider the 1% production loss) and the energy added from the fuel gas to produce this amount is 0.51 MJ/kg of produced gas.

Multiplying the above values, the Ex_d is:

$$Ex_d = 7.49 \text{ MW}$$

For 40 years of operation and an 85% utilization rate:

$$\mathbf{Ex_d = 8{,}032.66\ TJ}$$

At this time, the Standard EROI of natural gas production technology can be determined, agreeing to Hall *et al*. (2014), with Equation (15).

At this stage (Natural Gas Production), the energy return to society is calculated as from the gas chemical energy that can be provided, that is converted to thermal energy in gas turbine and is delivered as heat ($\dot{Q}_H$) as the input energy to the thermodynamic cycle.

The thermodynamic efficiency (η) of the simple cycle is 34,5% (GREET, 2022) and according to Bejan (2016) is calculated as already shown in the Equation (20):

$$\eta = \frac{\dot{W}}{\dot{Q}_H}$$

Considering the gross electric power ($\dot{W}$) that is produced at the power plant as the net electric power (331 MW) plus the energy penalty that is necessary to run the CCS system, it is possible to calculate the energy return to society, assuming that it is equal to $\dot{Q}_H$.

According to GREET (2022), the energy penalty represents an increase of 12% in the net power. Therefore:

$$\text{Energy return to society} = (331 + 39.16)/0.524 = 706 \text{ MW}$$

Thus,

EROI = 94.30:1

P2 – Transport of Gas to Gas Processing Unit:

It was considered that this consumption was already measured in the production facility, as the compression system for gas export is part of the production unit.

$$\mathbf{Ex_{idP2} = 0}$$

P3 – Gas Processing Unit:

Material for the process. Data from this process from GREET (2022):

- Fuel Gas: 0.01 kg/kg produced Natural Gas

Process 3 corresponds to one of the indirect uses of exergy that will be called Ex_{idP3}. Equation (18) is used to convert the mass of gas into exergy.

So, the necessary exergy used in this process is: 0.01 x LCV = 0.51 MJ/kg of processed natural gas.

$$Ex_{idP3} = 0.51 \text{ MJ/kg} \times 14.4 \text{ kg/s} = 7.42 \text{ MW}$$

$$\mathbf{Ex_{idP3} = 7.42\ MW}$$

P4 – Transport of Gas to Thermoelectric Unit:

It was considered that this consumption was already measured in the processing facility, considering that the processing and the thermoelectric units are in the same location.

$$\mathbf{Ex_{idP4} = 0}$$

Ex_{id} Calculation:

From the identification of all previous processes and their indirect uses of exergy, the indirect exergy used in the energy conversion process (Ex_{id}) can be calculated as follows:

$$Ex_{id} = Ex_{idP2} + Ex_{idP}3 + Ex_{idP4}$$

$$Ex_{id} = 7.42 \text{ MW}$$

For 40 years of operation and utilization factor of 85%:

$$\mathbf{Ex_{id} = 7{,}953.04\ TJ}$$

P5 – Thermoelectric unit:

Data for this process from GREET (2022):

- Thermoelectric unit Energy Efficiency: 52.4%

With this information and using the Equation (18) and Equation (20), it is possible to determine the mass flow of fuel gas that is required to produce the gross electric power:

$$\text{Required Fuel Gas} = 370.16 / (48.91 \times 0.524) = 14.44 \text{ kg/s}$$

P6 – Electricity production:

This process only represents the electrical energy output of the process that is directed to society.

Ex_K Calculation:

This part relates to the exergy used during the project's development and the establishment of the business, in this case, the natural gas thermoelectric plant in a combined cycle. IEA (2020) brings minimum estimative for investment costs in thermoelectric plants of the size and type under investigation of 2,522 US$/kW.

Knowing the 370,16 MW (331 MW + 39.16) gross power provides the following information:

CAPEX = (331,000 + 39,160) kW x 2,522 US$/kW / 1000 = 933,540 kUS$

Using the ee_k, which has a value of 3.76 MJ/US$ and is defined as "equivalent primary energy resource embodied in one monetary unit" (SCIUBBA, 2011, p. 1.064), as presented in subsection 4.1, it follows that:

Ex_K = 3,510.12 TJ

Ex_{OP} Calculation:

This part is equivalent to the energy used for the installation's maintenance and operation (OPEX). According to research presented by IEA (2020), minimum estimative for operation and maintenance expenses is US$ 12.87/MWh. Agreeing to IEA (2020), 297,840 hours are the installation's actual operational hours when considering the project's 40-year useful life and 85% utilization rate. So:

OPEX = (331 + 39,16) x 297,840 x 12.87 / 1000 = 1,418,900 kUS$

Again, using the ee_k, which has a value of 3.76 MJ/US$ and is defined as "equivalent primary energy resource embodied in one monetary unit" (SCIUBBA, 2011, p. 1.064), as presented in subsection 4.1, it follows:

Ex_{OP} = 5,335.06 TJ

Ex_{Env} Calculation:

The flue gas from the boiler exhaust of the Rankine Cycle and the cooling water are the two main energy effluents in this conversion process. From Equation (14), it is necessary to calculate EQ_{Lb} to obtain the Ex_{Env}.

According to Bejan (2016), the first law of thermodynamics in this cycle, according to Equation (21) is:

$$Q_H - Q_{Lb} = W$$

Where Q_H is the heat produced by the fuel gas for the energy conversion process, Q_{Lb} is the heat flowing with the flue gases from the Rankine cycle exhaust and W is the work delivered by the cycle.

As it was seen in the process 1 above:

$$\dot{Q}_H = \ 706 \text{ MW}$$

Thus from the Equation (20), $\dot{Q}_{Lb} = \dot{Q}_H - \dot{W}$
$\dot{Q}_{Lb} = 706.41 - (331 + 39.16) = 336$ MW

Based on Bejan (2016), the Equation (19) that was presented in the subsection 4.2.2 converts this thermal energy flow into exergy:

$$\dot{EQ}_{Lb} = \dot{Q}_{\text{Lb}} \cdot \left(1 - \frac{T_0}{T_L}\right)$$

Where:

$\dot{EQ}_{Lb}$ – Exergy from the effluent flue gas flow from the turbine exhaust.

T_0 – Environment temperature. Used the value of 25º C, absolute temperature of 298 K.

T_{Lb} – Temperature of flue gases from the turbine exhaust. 248º C, absolute temperature of 521 K.

To calculate the temperature T_{Lb} of this case, it is necessary to return to the T_{Lb} of 717 K of the simple cycle in the previous case, based on Lim (2009a and 2009b) and use the Equation (22) bellow related to the efficiency of a reversible cycle (BEJAN, 2016):

$$\eta = 1 - \frac{T_{Lb}}{T_H} \qquad \text{(Equation 14)}$$

Using all the known information of the simple cycle ($\eta = 34.5\%$ and $T_{Lb} = 717\ K$), it is possible to calculate the T_H = 1,095 K.

Assuming the same T_H of the gas turbine to this combined cycle case, it is possible, using the same Equation (22) above, to determine the new temperature T_{Lb} of the combined cycle. Thus:

$$T_{Lb} = 521\ K$$

And, thereby, $\dot{EQ}_{Lb}$ = 143.94 MW

As shown in the subsection 4.2.2, the second effluent (cooling water) is discharged to the environment at a very low temperature, close to the environment temperature, or, in other words, with negligible exergy.

As a result, it was decided not to include this effluent in the analysis.

Thus, the following was used: $Ex_{Env} = EQ_{Lb}$

Consequently, given an 85% utilization factor and 40 years of operation:

$$\mathbf{Ex_{Env} = 154{,}340.79\ TJ}$$

Ex_{CO2} Calculation:

This is the part of the sentence pertaining to the exergy requested for carbon capture and sequestration (CCS). In this case study, it is considered an energy penalty of 12% for this process, that consists to the greater efficiency CCS value obtained from GREET (2022) that corresponds to a value of 39.16 MW used by the CCS process.

It is crucial to highlight the methodology's use of abstraction. It is assumed that the amount of electrical power delivered to society in both scenarios—with and without CCS— would be the same. However, to encourage comparison with other technologies that eventually emit no CO_2, the portion of exergy related to use for CCS returns as Ex_{CO2} to be assumed in the model as a kind of exergy use.

So, for 40 years of operation and utilization factor of 85%, according to IEA (2020):

$$\mathbf{Ex_{CO2} = 41{,}988.29\ TJ}$$

CEII Calculation:

1) CO_2 eq. (C1) emitted by the processes related to the exergy used directly to produce the energy resource (Ex_d).

   $C1 = Ex_d$ x 119,303.50 kg CO_2eq./TJ (GREET, 2022) = 958,313,462 kg CO_2eq.
2) CO_2 eq. (C2) emitted by the processes related to the energy used indirectly to produce the energy resource (Ex_{id}). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

   $C2 = Ex_{id}$ x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 597,759,882 kg CO_2eq.
3) CO_2 eq. (C3) related to the emissions from the operation of the thermoelectric facility (Q_H). As it is used a CCS system with 90% capture efficiency (GREET, 2022), only 10% of the equivalent CO_2 emission is considered.

   $C3 = Q_H$ x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.1 = 9.0×10^9 kg CO_2eq.
4) CO_2 eq. (C4) emitted by during the design, construction, and installation phases of the enterprise (Ex_K). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

   $C4 = Ex_K$ x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 263,825,127 kg CO_2eq.
5) CO_2 eq. (C5) emitted used throughout the operational phase of the enterprise (Ex_{OP}). As the indirect processes are related to the energetic matrices, as seen in section 3.1 subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

   $C5 = Ex_{OP}$ x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 400,989,170 kg CO_2eq.

As seen in Equation (17), the CEII calculation is:

$$CO_2 \text{ Equivalent Emissions} / Ex_O$$

$$CO_2 \text{ Equivalent Emissions} = C1+C2+C3+C4+C5) = 1.13 \times 10^{10} \text{ kg } CO_2\text{eq.}$$

$$\mathbf{CEII = 31.7 \times 10^{3}\ kg\ CO_2eq./TJ}$$

4.5 CASE STUDY 4 – BRAYTON-CYCLE BIOGAS POWER PLANT

A biogas power plant operating on a simple cycle begins with the collection of raw materials, such as forest residues, agricultural waste, and another biomass. These materials are gathered from various sources and transported to the biogas plant. The transportation of biomass to the plant is typically carried out using trucks or other suitable transport methods, ensuring that the biomass is delivered in an efficient and timely manner to maintain a steady supply for the digestion process (CARDOSO, 2017).

Upon arrival at the plant, the biomass undergoes preprocessing, which includes shredding and homogenizing to facilitate the anaerobic digestion process. The processed biomass is then fed into large anaerobic digesters, where it is broken down by microorganisms in the absence of oxygen. This digestion process produces biogas, a mixture primarily composed of methane (CH_4) and carbon dioxide (CO_2), along with trace amounts of other gases. The biogas is collected and purified to remove impurities such as hydrogen sulfide (H_2S), moisture, and other contaminants, enhancing its quality for combustion (CARDOSO, 2017).

The purified biogas is then fed into a gas turbine, operating on the Brayton cycle, for electricity generation. In the gas turbine, the biogas is mixed with compressed air and ignited in the combustion chamber. The resulting high-temperature, high-pressure combustion gases expand through the turbine blades, driving the turbine to spin and generate mechanical energy. This mechanical energy is converted into electrical energy by a connected generator. The exhaust gases from the turbine are released into the atmosphere, and since biogas is a renewable resource, the net CO_2 emissions are considerably lower compared to fossil fuels, contributing to a more sustainable energy production process (BOYCE, 2011).

As the subsection 4.1 shows, the energy service that must be provided to society shall the same for the five cases. Thus, this case is hypothetic with its parameters related to determine the product deliverable for society were based on the base scenario (subsection 4.2) of the coal-fired thermoelectric plant established in Castelo Branco (2012) as a reference, with net electric power of 331 MW and the expected useful life for the thermoelectric of 40 years.

The subsection 4.5.2 contains the data, specially from GREET (2022), that is required to compute the exergy inputs at each stage of the processes, together with the entire calculation memory. Table 8 and Figure 4 indicate the processes that were included in the evaluation (the same for cases 4 and 5).

Table 8 – Description of the evaluated processes – Biogas Power Plant

Process	Description
P1	Residue collection
P2	Feedstock transportation
P3	Biogas transport to thermoelectric unit
P4	Feedstock processing unit
P5	Thermoelectric unit
P6	CCS system

Source: Prepared by the author (2024).

P1 – Residue collection:

The stage of residue collection considers the energy used during the collection activities. The data are defined with a reference flow of 1 kg of residue ready for transport to the processing unit.

P2 – Feedstock transportation:

This stage entails the residue transportation from the collection area to the feedstock processing facility and biogas production.

P3 – Biogas transport to thermoelectric unit:

This step is the pipeline transport from the feedstock processing unit to the thermoelectric plant.

P4 – Feedstock processing unit:

The stage of Feedstock processing considers the energy used to process the feedstock to produce and specify the biogas to its end uses as in the thermoelectric units. The data are defined with a reference flow of 1 kg of biogas ready for pipeline transport to the thermoelectric unit.

P5 – Thermoelectric unit:

The generation unit comprises the necessary equipment and systems to convert the biogas chemical energy content in electric power.

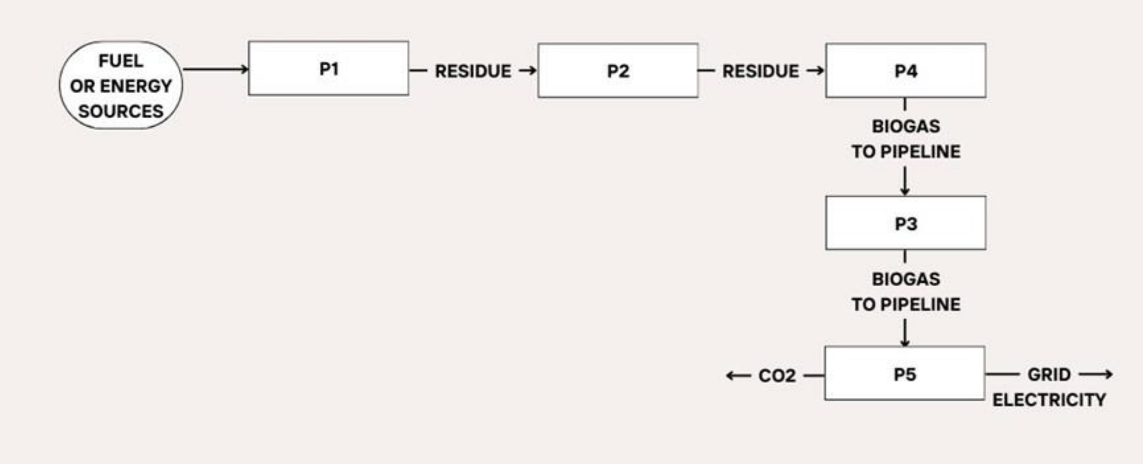

Figure 4 – Process flowchart for the Biogas cases

Source: Prepared by the author (2024).

Regarding the CAPEX, to evaluate the maximum exergy return, the minimum investment costs of 885 US$/kW from IEA (2020) was considered. With the same reasoning, the minimum operation and maintenance costs (OPEX) considered from IEA (2020) was 7.50 US$/MWh.

4.5.1 Results and Discussion

From Equations (8), (15), (16) and (17) the values of each part of the indicators presented in Table 9, ExROEEI, EROI, ExROI and CEII can be calculated. The complete calculation memory is available in the subsection 4.5.2.

Table 9 – Case 4 (Biogas Simple Cycle) – ExROEEI, ExROI and EROI Calculations for 40 years of operation and an utilization factor of 85%

(to be continued)

ExROEEI Calculation	**TJ**	**(%)**
Indicator parts		
Ex_O	354906	
Ex_d	52936	11.09
Ex_{id}	26732	5.60
Ex_K	1101	0.23
Ex_{OP}	2780	0.58
Ex_{Env}	393759	82.50
Ex_{CO2}	0	0.00
Indicators	**X:Y**	
ExROEEI	**0.74**	
EROI	19.4	

Table 9 – Case 4 (Biogas Simple Cycle) – ExROEEI, ExROI and EROI Calculations for 40 years of operation and an utilization factor of 85%

(conclusion)

ExROI	6.7
CO_2 Intensity (metric-ton CO_2/TJ)	**16.4**
Total $CO_{2eq.}$ (Tg)	5.8

Source: Prepared by the author (2024).

For 40 years of operation, the contribution of each component of the input of the indicator is 82.50% for Ex_{Env}, 11.09% for Ex_d, 5.60% for Ex_{id}, 0.58% for Ex_{OP}, 0.23% for E_{xK} and 0% for Ex_{CO2}. This means that the exergy that is wasted to the environment has a significant impact on lowering the net energy services provided to society by the biogas simple cycle thermal power plant.

4.5.2 Calculation Memory – Brayton-Cycle Biogas

Ex_O calculation:

As electric energy is considered as pure exergy, this portion represents the exergy sent to society, as described in the subsection 3.1. In this case study, as described in the subsection 4.1, this portion is represented as a power rate of: $\dot{Ex}_O$ = 331 MW

For 40 years of operation and utilization factor of 85% the total exergy amount is:

$$\mathbf{Ex_O = 354{,}906\ TJ}$$

P1 – Residue Collection:

Material and energy inputs for the process. Data from this process from GREET (2022):

- Energy requirement for residue collection: 0.04 MJ / kg of residue
- LCV (Fuel Gas): 32.49 (MJ/kg)
- A 1% loss of biogas is assumed in this production stage

With this information and the required fuel gas for the thermoelectric unit (see calculation in the process 5 bellow), the necessary mass flow of produced biogas is 29.82

kg/s (29.53 kg/s is required to produce the gross electric power, but it is necessary to consider the 1% production loss).

With the energy requirement of this process and the residue required calculated in the process 4 bellow, it is possible to determine the exergy required in this residue collection process:

$$Ex_{idP1} = 0.04 \text{ MJ/kg x } 295.26 \text{ kg/MJ}$$

$$\mathbf{Ex_{idP1} = 12.87\ MW}$$

P2 – Feedstock transportation:

Material and energy inputs for the process. Data from this process from GREET (2022):

- Transport Fuel Gas / Transported Residue: 0.04 MJ/kg

With this information and the required residue calculated in the process 4 bellow, it is possible to determine the exergy demand of this process:

P2 Exergy demand = 295.26 kg Residue /MJ produced electricity x 0.04 Fuel MJ/kg Transported Residue = 12.06 MW

$$\mathbf{Ex_{idP2} = 12.06\ MW}$$

P3 – Transport of Biogas to Thermoeletric Unit:

It was considered that this consumption was already measured in the processing facility, considering that the processing and the thermoelectric units are in the same location.

$$\mathbf{Ex_{idP3} = 0}$$

Ex_{id} Calculation:

From the identification of all previous processes and their indirect uses of exergy, the indirect exergy used in the energy conversion process (Ex_{id}) can be calculated as follows:

$$Ex_{id} = Ex_{idP1} + Ex_{idP2} + Ex_{idP3}$$

$$Ex_{id} = 24.93 \text{ MW}$$

For 40 years of operation and utilization factor of 85%:

$$\mathbf{Ex_{id} = 26,731.62TJ}$$

<u>P4 – Feedstock Processing Unit:</u>

This process is considered to determine Direct Exergy, as it corresponds to the amount of energy used directly to produce the energy resource utilized.

Material and energy inputs for the process:

- Fuel Gas / Processed Residue: 0.17 MJ/kg (GREET, 2022)
- 10 kg of residue is required to produce 1 kg of biogas (CARDOSO, 2017)

Using the required fuel gas that is necessary in the thermoelectric unit of 29.53 kg / MJ of produced electricity (see calculation in the process 5 bellow) and the relation between required residue and biogas production of 10 to 1 above, it is required 295.26 kg of residue for MJ of produced electricity.

Thus:

Fuel Gas Required in this process = 0.17 Fuel Gas MJ x 295.36 Residue kg / MJ Produced electricity = 49.37 MW

Therefore:

$$Ex_d = 49.37 \text{ MW}$$

For 40 years of operation and an 85% utilization rate:

Ex_d = 52,935.86 TJ

At this time, the Standard EROI of natural gas production technology can be determined, agreeing to Hall *et al*. (2014), by Equation (15).

At this stage (Biogas Production), the energy return to society is calculated as from the biogas chemical energy that can be provided, that is converted to thermal energy in gas turbine and is delivered as heat ($\dot{Q}_H$) as the input energy to the thermodynamic cycle.

The thermodynamic efficiency (η) of the simple cycle is 34.5% (GREET, 2022) and according to Equation (20) is calculated as:

$$\eta = \frac{\dot{W}}{\dot{Q}_H}$$

Considering the gross electric power ($\dot{W}$) that is produced at the power plant as the net electric power (331 MW), as this case does not require a CCS system, it is possible to calculate the energy return to society, assuming that it is equal to $\dot{Q}_H$.

Energy return to society = 331 / 0.345= 959 MW

Thus,

EROI = 19.43:1

P5 – Thermoelectric unit:

Data for this process from GREET (2022):

- Thermoelectric unit Energy Efficiency: 34.5%

With this information and using the Equation (18) and Equation (20), it is possible to determine the mass flow of fuel gas that is required to produce the gross electric power:

Required Fuel Gas = 331 / (32.49 x 0.345) = 29.53 kg/s

P6 – Electricity production:

This process only represents the electrical energy output of the process that is directed to society.

Ex_K Calculation:

This part relates to the exergy used during the project's development and the establishment of the business, in this case, the biogas thermoelectric plant. IEA (2020) brings minimum estimative for investment costs in thermoelectric plants of the size and type under investigation of 885 US$/kW.

Knowing the 331 MW gross power provides the following information:

CAPEX = 331,000 kW x 885 US$/kW / 1000 = 292,940 kUS$

Using the ee_k, which has a value of 3.76 MJ/US$ and is defined as "equivalent primary energy resource embodied in one monetary unit" (SCIUBBA, 2011, p. 1.064), as presented in subsection 4.1, it follows that:

$$\mathbf{Ex_K = 1{,}101.44\ TJ}$$

Ex_{OP} Calculation:

This part is equivalent to the energy used for the installation's maintenance and operation (OPEX). According to research presented by IEA (2020), minimum estimative for operation and maintenance expenses is US$ 7.50/MWh. Agreeing to IEA (2020), 297,840 hours are the installation's actual operational hours when considering the project's 40-year useful life and 85% utilization rate. So:

OPEX = 331 x 297,840 x 7.50 / 1000 = 739,390 kUS$

Again, using the ee_k, which has a value of 3.76 MJ/US$ and is defined as "equivalent primary energy resource embodied in one monetary unit" (SCIUBBA, 2011, p. 1.064), as presented in subsection 4.1, it follows:

$$\mathbf{Ex_{OP} = 2{,}780.10\ TJ}$$

Ex_{Env} Calculation:

The flue gas from the turbine exhaust is the main energy effluent in this conversion process. From Equation (14), it is necessary to calculate EQ_{Lb} to obtain the Ex_{Env}.

According to Equation (21), the first law of thermodynamics in this cycle is:

$$Q_H - Q_{Lb} = W$$

Where Q_H is the heat produced by the fuel gas for the energy conversion process, Q_{Lb} is the heat flowing with the flue gases from the turbine exhaust and W is the work delivered by the cycle.

As it was shown in the process 4 above:

$$\dot{Q}_H = 959.42 \text{ MW}$$

Thus from the Equation (20), $\dot{Q}_{Lb} = \dot{Q}_H - \dot{W}$
$\dot{Q}_{Lb} = 959.42 - 331 = 628.42$ MW

Based on Bejan (2016), the following Equation (19) that was presented in the subsection 4.2.2 converts this thermal energy flow into exergy:

$$\dot{EQ}_{Lb} = \dot{Q}_{\text{Lb}} \cdot \left(1 - \frac{T_0}{T_L}\right)$$

Where:

$\dot{EQ}_{Lb}$ – Exergy from the effluent flue gas flow from the turbine exhaust.

T_0 – Environment temperature. Used the value of 25° C, absolute temperature of 298 K.

T_{Lb} – Temperature of flue gases from the turbine exhaust. 444° C according to Lim (2009a and 2009b), absolute temperature of 717 K.

Thereby, $\dot{EQ}_{Lb}$ = 367.24 MW

Thus, the following was used: $Ex_{Env} = EQ_{Lb}$

Consequently, given an 85% utilization factor and 40 years of operation:

$$\mathbf{Ex_{Env} = 393{,}759\ TJ}$$

Ex_{CO_2} Calculation:

This is the part of the sentence pertaining to the exergy requested for carbon capture and sequestration (CCS). In this case study, the CCS system is not required.

So:

$$\mathbf{Ex_{CO2} = 0}$$

CEII Calculation:

1) CO_2 eq. (C1) emitted by the processes related to the exergy used directly to produce the energy resource (Ex_d). As the biogas is consumed, it is considered renewable with no CO_2 emissions.

   C1 = 0.

2) CO_2 eq. (C2) emitted by the processes related to the energy used indirectly to produce the energy resource (Ex_{id}). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

   CEx_{idP1} = Ex_{idP1} x 457,296.27 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 3,976,361,951 kg CO_2eq.

   CEx_{idP2} = Ex_{idP2} x 119,303.50 kg CO_2eq./TJ (GREET, 2022) = 1,542,527,546 kg CO_2eq.

   C2 = CEx_{idP1} + CEx_{idP2} = 5,518,889,498 kg CO_2eq.

3) CO_2 eq. (C3) related to the emissions from the operation of the thermoelectric facility (Q_H). As the biogas is consumed, it is considered renewable with no CO_2 emissions.

   C3 = 0

4) CO_2 eq. (C4) emitted by during the design, construction, and installation phases of the enterprise (Ex_K). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

   C4 = Ex_K x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 82,785,228 kg CO_2eq.

5) CO_2 eq. (C5) emitted used throughout the operational phase of the enterprise (Ex_{OP}). As the indirect processes are related to the energetic matrices, as seen

in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

$C5 = Ex_{OP}$ x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 208,955,529 kg CO_2eq.

As seen in Equation (17), the CEII calculation is:

$$CO_2 \text{ Equivalent Emissions} / Ex_O$$

$$CO_2 \text{ Equivalent Emissions} = C1+C2+C3+C4+C5) = 5.8 \times 10^9 \text{ kg } CO_2\text{eq.}$$

$$\mathbf{CEII = 16.4 \times 10^3 \text{ kg } CO_2\text{eq./TJ}}$$

4.6 CASE STUDY 5 – COMBINED-CYCLE BIOGAS POWER PLANT

In a combined cycle biogas power plant, the process begins similarly with the collection and transportation of biomass to be processed in a biogas plant, to produce and purify the biogas.

In a combined cycle power plant, the purified biogas is first utilized in a gas turbine operating on the Brayton cycle. The biogas is combusted with compressed air in the combustion chamber of the gas turbine, generating high-temperature, high-pressure gases. These gases expand through the turbine, causing it to spin and generate mechanical energy, which is converted into electrical energy by an attached generator. Unlike the simple cycle, the exhaust gases from the gas turbine in a combined cycle plant are not immediately released into the atmosphere but are instead directed to a HRSG (BOYCE, 2011).

The HRSG uses the waste heat from the gas turbine exhaust to produce steam. This steam is then fed into a steam turbine operating on the Rankine cycle. The high-pressure steam expands through the steam turbine, driving it to produce additional mechanical energy, which is converted into more electrical energy by a second generator. This combined cycle process significantly increases the overall efficiency of the power plant by utilizing the waste heat from the gas turbine to generate additional electricity, thereby maximizing the energy extracted from the biogas. This setup not only enhances the plant's efficiency but also reduces the environmental impact by minimizing waste heat and making the most out of the renewable biogas resource (BOYCE, 2011).

As the subsection 4.1 shows, the energy service that must be provided to society shall the same for the five cases. Thus, this case is hypothetic with its parameters related to determine the product deliverable for society were based on the base scenario (subsection 4.2) of the coal-fired thermoelectric plant established in Castelo Branco (2012) as a reference, with net electric power of 331 MW and the expected useful life for the thermoelectric of 40 years.

The subsection 4.6.2 contains the data, specially from GREET (2022), that is required to compute the exergy inputs at each stage of the processes, together with the entire calculation memory.

Regarding the CAPEX, to evaluate the maximum exergy return, the minimum investment costs of 1,546 US$/kW from IEA (2020) was considered. With the same reasoning, the minimum operation and maintenance costs (OPEX) considered from IEA (2020) was 12.87 US$/MWh.

4.6.1 Results and Discussion

From Equations (8), (15), (16) and (17) the values of each part of the indicators presented in Table 10, ExROEEI, EROI, ExROI and CEII can be calculated. The complete calculation memory is available in the subsection 4.6.2.

Table 10 – Case 5 (Biogas Combined Cycle) – ExROEEI, ExROI and EROI Calculations for 40 years of operation and an utilization factor of 85%

ExROEEI Calculation	**TJ**	**(%)**
Indicator parts		
Ex_O	354906	
Ex_d	34853	17.68
Ex_{id}	17600	8.93
Ex_K	1924	0.98
Ex_{OP}	4771	2.42
Ex_{Env}	137993	70.00
Ex_{CO2}	0	0.00
Indicators	**X:Y**	
ExROEEI	**1.8**	
EROI	19.4	
ExROI	10.2	
CO_2 Intensity (metric-ton CO_2/TJ)	**11.2**	
Total $CO_{2eq.}$ (Tg)	4.0	

Source: Prepared by the author (2024).

For 40 years of operation, the contribution of each component of the input of the indicator is 70.00% for Ex_{Env}, 17.68% for Ex_d, 8.93% for Ex_{id}, 2.42% for Ex_{OP}, 0.98%

for E_{xK} and 0% for Ex_{CO2}. This means that the exergy that is wasted to the environment has a significant impact on lowering the net energy services provided to society by the biogas simple cycle thermal power plant.

4.6.2 Calculation Memory – Combined-Cycle Biogas

Ex_O calculation:

As electric energy is considered as pure exergy, this portion represents the exergy sent to society, as described in the subsection 3.1. In this case study, as described in the subsection 4.1, this portion is represented as a power rate of: $\dot{Ex}_O$ = 331 MW

For 40 years of operation and utilization factor of 85% the total exergy amount is:

$$\mathbf{Ex_O = 354{,}906\ TJ}$$

P1 – Residue Collection:

Material and energy inputs for the process. Data from this process from GREET (2022):

- Energy requirement for residue collection: 0.04 MJ / kg of residue
- LCV (Fuel Gas): 32.49 (MJ/kg)
- A 1% loss of biogas is assumed in this production stage

With this information and the required fuel gas for the thermoelectric unit (see calculation in the process 5 bellow), the necessary mass flow of produced biogas is 19.63 kg/s (19.44 kg/s is required to produce the gross electric power, but it is necessary to consider the 1% production loss).

With the energy requirement of this process and the residue required calculated in the process 4 bellow, it is possible to determine the exergy required in this residue collection process:

$$Ex_{idP1} = 0.04\ \text{MJ/kg} \times 194.4\ \text{kg/MJ}$$

$$\mathbf{Ex_{idP1} = 8.48\ MW}$$

P2 – Feedstock transportation:

Material and energy inputs for the process. Data from this process from GREET (2022):

- Transport Fuel Gas / Transported Residue: 0.04 MJ/kg

With this information and the required residue calculated in the process 4 bellow, it is possible to determine the exergy demand of this process:

P2 Exergy demand = 194.4 kg Residue /MJ produced electricity x 0.04 Fuel MJ/kg Transported Residue = 7.94 MW

$$\mathbf{Ex_{idP2} = 7.94\ MW}$$

P3 – Transport of Biogas to Thermoeletric Unit:

It was considered that this consumption was already measured in the processing facility, considering that the processing and the thermoelectric units are in the same location.

$$\mathbf{Ex_{idP3} = 0}$$

Ex_{id} Calculation:

From the identification of all previous processes and their indirect uses of exergy, the indirect exergy used in the energy conversion process (Ex_{id}) can be calculated as follows:

$$Ex_{id} = Ex_{idP1} + Ex_{idP2} + Ex_{idP3}$$

$$Ex_{id} = 16.41\ MW$$

For 40 years of operation and utilization factor of 85%:

$$\mathbf{Ex_{id} = 17{,}600.02\ TJ}$$

P4 – Feedstock Processing Unit:

This process is considered to determine Direct Exergy, as it corresponds to the amount of energy used directly to produce the energy resource utilized.

Material and energy inputs for the process:

- Fuel Gas / Processed Residue: 0.17 MJ/kg (GREET, 2022)
- 10 kg of residue is required to produce 1 kg of biogas (CARDOSO, 2017)

Using the required fuel gas that is necessary in the thermoelectric unit of 19.44 kg / MJ of produced electricity (see calculation in the process 5 bellow) and the relation between required residue and biogas production of 10 to 1 above, it is required 194.4 kg of residue for MJ of produced electricity.

Thus:

$$\text{Fuel Gas Required in this process} = 0.17 \text{ Fuel Gas MJ x } 194.40 \text{ Residue kg / MJ Produced electricity} = 32.51 \text{ MW}$$

Therefore:

$$Ex_d = 32.51 \text{ MW}$$

For 40 years of operation and an 85% utilization rate:

$$\mathbf{Ex_d = 34{,}852.81TJ}$$

At this time, the Standard EROI of natural gas production technology can be determined, agreeing to Hall *et al*. (2014), by Equation (15).

At this stage (Biogas Production), the energy return to society is calculated as from the biogas chemical energy that can be provided, that is converted to thermal energy in gas turbine and is delivered as heat ($\dot{Q}_H$) as the input energy to the thermodynamic cycle.

The thermodynamic efficiency (η) of the combined cycle is 52.4% (GREET, 2022) and according to Equation (20) is calculated as:

$$\eta = \frac{\dot{W}}{\dot{Q}_H}$$

Considering the gross electric power ($\dot{W}$) that is produced at the power plant as the net electric power (331 MW), as this case does not require a CCS system, it is possible to calculate the energy return to society, assuming that it is equal to $\dot{Q}_H$.

Energy return to society = 331 / 0.524 = 632 MW

Thus,

EROI = 19.43:1

P5 – Thermoelectric unit:

Data for this process from GREET (2022):

- Thermoelectric unit Energy Efficiency: 52.4%

With this information and using the Equation (18) and Equation (20), it is possible to determine the mass flow of fuel gas that is required to produce the gross electric power:

Required Fuel Gas = 331 / (32.49 x 0.524) = 19.44 kg/s

P6 – Electricity production:

This process only represents the electrical energy output of the process that is directed to society.

Ex_K Calculation:

This part relates to the exergy used during the project's development and the establishment of the business, in this case, the biogas thermoelectric plant. IEA (2020) brings minimum estimative for investment costs in thermoelectric plants of the size and type under investigation of 1,546 US$/kW.

Knowing the 331 MW gross power provides the following information:

CAPEX = 331,000 kW x 1,546 US$/kW / 1000 = 511,730 kUS$

Using the ee_k, which has a value of 3.76 MJ/US$ and is defined as "equivalent primary energy resource embodied in one monetary unit" (SCIUBBA, 2011, p. 1.064), as presented in subsection 4.1, it follows that:

Ex_K = 1,924.09TJ

Ex_{OP} Calculation:

This part is equivalent to the energy used for the installation's maintenance and operation (OPEX). According to research presented by IEA (2020), minimum estimative for operation and maintenance expenses is US$ 12.87/MWh. Agreeing to IEA (2020), 297,840 hours are the installation's actual operational hours when considering the project's 40-year useful life and 85% utilization rate. So:

OPEX = 331 x 297,840 x 12.87 / 1000 = 1,268,790 kUS$

Again, using the ee_k, which has a value of 3.76 MJ/US$ and is defined as "equivalent primary energy resource embodied in one monetary unit" (SCIUBBA, 2011, p. 1.064), as presented in subsection 4.1, it follows:

Ex_{OP} = 4,770.65 TJ

Ex_{Env} Calculation:

The flue gas from the boiler exhaust of the Rankine Cycle and the cooling water are the two main energy effluents in this conversion process. From Equation (14), it is necessary to calculate EQ_{Lb} to obtain the Ex_{Env}.

According to Bejan (2016), the first law of thermodynamics in this cycle, according to Equation (21) is:

$$Q_H - Q_{Lb} = W$$

Where Q_H is the heat produced by the fuel gas for the energy conversion process, Q_{Lb} is the heat flowing with the flue gases from the Rankine cycle exhaust and W is the work delivered by the cycle.

As it was seen in the process 1 above:

$$\dot{Q}_H = \ 631 \text{ MW}$$

Thus from the Equation (20), $\dot{Q}_{Lb} = \dot{Q}_H - \dot{W}$ $\dot{Q}_{Lb} = 631.68 - 331 = 300.68$ MW

Based on Bejan (2016), the Equation (19) that was presented in the subsection 4.2.2 converts this thermal energy flow into exergy:

$$\dot{EQ}_{Lb} = \dot{Q}_{\text{Lb}} \cdot \left(1 - \frac{T_0}{T_L}\right)$$

Where:

$\dot{EQ}_{Lb}$ – Exergy from the effluent flue gas flow from the turbine exhaust.

T_0 – Environment temperature. Used the value of 25° C, absolute temperature of 298 K.

T_{Lb} – Temperature of flue gases from the turbine exhaust. 248 ºC, absolute temperature of 521 K.

To calculate the temperature T_{Lb} of this case, it is necessary to return to the T_{Lb} of 717 K of the simple cycle in the previous case, based on Lim (2009a and 2009b) and use the Equation (22) bellow:

$$\eta = 1 - \frac{T_{Lb}}{T_H}$$

Using all the known information of the simple cycle ($\eta = 34.5\%$ and $T_{Lb} = 717\ K$), it is possible to calculate the T_H = 1,095 K.

Assuming the same T_H of the gas turbine to this combined cycle case, it is possible, using the same Equation (22) above, to determine the new temperature T_{Lb} of the combined cycle. Thus:

$$T_{Lb} = 521 \text{ K}$$

And, thereby, $\dot{EQ}_{Lb}$ = 128.70 MW

As shown in the subsections 4.2.2 and 4.4.2, the second effluent (cooling water) is discharged to the environment at a very low temperature, close to the environment temperature, or, in other words, with negligible exergy.

As a result, it was decided not to include this effluent in the analysis.

Thus, the following was used: $Ex_{Env} = EQ_{Lb}$

Consequently, given an 85% utilization factor and 40 years of operation:

$$\mathbf{Ex_{Env} = 137{,}992.77TJ}$$

Ex$_{CO_2}$ Calculation:

This is the part of the sentence pertaining to the exergy requested for carbon capture and sequestration (CCS). In this case study, the CCS system is not required.

So:

$$\mathbf{Ex_{CO_2} = 0}$$

CEII Calculation:

1) CO_2 eq. (C1) emitted by the processes related to the exergy used directly to produce the energy resource (Ex_d). As the biogas is consumed, it is considered renewable with no CO_2 emissions.
   C1 = 0.
2) CO_2 eq. (C2) emitted by the processes related to the energy used indirectly to produce the energy resource (Ex_{id}). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

CEx_{idP1} = Ex_{idP1} x 457,296.27 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 2,618,024,567 kg CO_2eq.

CEx_{idP2} = Ex_{idP2} x 119,303.50 kg CO_2eq./TJ (GREET, 2022) = 1,015,595,427 kg CO_2eq.

C2 = CEx_{idP1} + CEx_{idP2} = 3,633,619,994 kg CO_2eq.

3) CO_2 eq. (C3) related to the emissions from the operation of the thermoelectric facility (Q_H). As the biogas is consumed, it is considered renewable with no CO_2 emissions.

   C3 = 0

4) CO_2 eq. (C4) emitted by during the design, construction, and installation phases of the enterprise (Ex_K). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

   C4 = Ex_K x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 144,616,907 kg CO_2eq.

5) CO_2 eq. (C5) emitted used throughout the operational phase of the enterprise (Ex_{OP}). As the indirect processes are related to the energetic matrices, as seen in subsection 4.1, the share of fossils in the global matrix of 63% based on IEA (2019) was used to calculate these emissions.

   C5 = Ex_{OP} x 119,303.50 kg CO_2eq./TJ (GREET, 2022) x 0.63 (IEA, 2019) = 208,955,529 kg CO_2eq.

As seen in Equation (17), the CEII calculation is:

CO_2 Equivalent Emissions / Ex_O

CO_2 Equivalent Emissions= C1+C2+C3+C4+C5) = 4.0 x 10^9 kg CO_2eq.

CEII = 11.2 x 10^3 kg CO_2eq./TJ

5 DISCUSSIONS AND COMPARISON BETWEEN CASES

In this section, the case studies are compared and discussed sensitive topics, technical challenges, and ways to improve the Energy and Environmental Return on Exergy Investment (ExROEEI). Every case study focuses on integrating energy analysis and CO_2 capture technology to maximize energy and ecological efficiency, highlighting various opportunities and problems within the larger framework of the energy transition.

Ultimately, the analysis highlights the need of including CO_2 capture and exergy (not only its physical component) in energy transition simulations. From a thermodynamic standpoint, actually, every industrial operation is a shift from a lower entropy state (energy, raw materials) to a higher entropy stage (waste and energy effluents in a more scattered form). Although nature can absorb high entropy fluxes to some extent, as an ideal thermal and chemical reservoir (SZARGUT *et al*., 1988, VALERO *et al*., 2006), the environment's ability to support all living species, including humans, is limited. However, regardless of how long these flows can continue before the environment becomes unsustainable, the logic of economic science is predicated on profit and high levels of production and consumption, or continuous and limitless growth (ROCKSTRÖM *et al*., 2009). When creating models, factors related to the environment must be taken into consideration as this economic theory of endless development is intrinsically unsustainable from a thermodynamic perspective (GEORGESCU-ROEGEN, 1971).

To minimize negative effects on the environment and create alternatives to repair any harm already done, it is worthwhile to develop and implement energy and ecologically efficient technologies. The assessment of thermodynamics' first and second laws is made possible by an exergy analysis. Next, using exergy rather than energy allows for the following (BEJAN, 2016):

- Improved utilization of energy resources. In particular, it assesses the usage of energy wastes from conversion processes,
- Analyzing process integration and examining the viability of reusing energy wastes from one process in another, and
- More accurate identification of the processes' true environmental effects based on the imbalance between the ecosystem's physical and chemical characteristics and the waste they discharge into the environment. Particularly

> noteworthy here is the concept of chemical exergy in addition to the physical exergy (SCIUBBA, 1999).

Therefore, even while a growing body of research indicates that fossil fuels have a higher energy return on investment (EROI) than renewable sources (Hall, 2014), it is crucial to modify the analytical methodology, and this study specifically suggests doing so. This may provide insightful information about the approaches currently used to assess energy pathways, such as those based on Life Cycle Assessments (LCA) – see, for instance (HERTWICH *et al*., 2015, NAEGLER *et al*., 2022, PORTUGAL-PEREIRA *et al*., 2016), and Integrated Assessment Models – IAMs (BAPTISTA *et al*., 2022, BRAUNREITER *et al*., 2021, WILSON *et al*., 2021).

Indeed, there is a conceptual scientific frontier in energy analysis based on Integrated Assessment Models (IAMs), which supports the development of energy transition scenarios, as IAM are usually designed according to the First Law of Thermodynamics (CHEN *et al*., 2020, KÖBERLE *et. al*., 2022, PAHUD; DE TEMMERMAN, 2022). Furthermore, exergy, especially in its chemical form, is typically not considered when comparing exergy applications in life cycle analyses of available energy sources. Additionally, there is a lack of consistency in the EROI calculations, which results in different studies carrying out the same procedure to establish the control volumes and analysis boundaries (CHEN *et al*., 2020). Therefore, the suggested method needs to be precise and repeatable, easy to use, and allow for a full and accurate comparison of the different energy sources and conversion methods.

At the end, although the EROI concept has been around for 50 years and has proven to be very helpful throughout that period, if not extended (or on its simple form), it might not be able to capture one of the most important aspects of the current energy transition, which is the requirement to limit CO_2 emissions (HALL, 2017, HALL *et al*., 2009 and 2014, PAHUD; DE TEMMERMAN, 2022). The current energy transition thus faces the difficulty of purposefully substituting sources with a higher EROI for ones with a lower EROI, which is exactly the opposite tendency of earlier energy revolutions (FOUQUET; PEARSON, 2012, SMIL, 2011), if CO_2 emissions are not accounted for. The hypothesis of this study is that by accounting CO_2 control or evaluating all energy sources according to their chemical and physical exergy, including the CO_2 control, the fossil fuel advantages will vanish partially or fully.

Therefore, as seen in the Table 11 bellow, the case studies reveal significant variations in ExROEEI values, particularly low in natural gas simple cycle case (0.69:1) and biogas simple cycle case (0.74:1). The predominant factor affecting these indices is the Exergy Equivalent of Environmental Impacts (Ex_{Env}) term, accounting for over 82.5% of the exergy flux in biogas and 85.95% in natural gas cases. This high proportion is mostly caused by simple cycles' low energy efficiency (34.5%), which leads to a large amount of energy being wasted to the environment as high-temperature exhaust rather than being used. Using a Cheng cycle, switching to mixed cycle systems, or specifically integrating co-generation processes could all help to improve the ExROEEI in these situations. These processes could potentially utilize low-quality thermal energy through technologies such as the Organic Rankine Cycle (ORC).

Table 11 – ExROEEI and CEII Comparative analysis between cases

Case	**ExROEEI**	**EROI**	**CEII (Ton $C0_2$/TJ)**	**Challenge**
Coal	2,37:1	60,9:1	131,8	$ExCO_2$ – 62%
Biogas (Open Cycle)	0,74:1	19,4:1	16,4	Ex_{Env} – 82%
Biogas (Combined Cycle)	1,8:1	19,4:1	11,2	Ex_{Env} – 70%
NG (Open Cycle)	0,69:1	94,3:1	46,5	Ex_{Env} – 86%
NG (Combined Cycle)	1,60:1	94,3:1	31,7	Ex_{Env} – 70%

Source: Prepared by the author (2024).

Conversely, the combined cycle cases for natural gas and biogas show higher ExROEEI values, with natural gas at 1.60:1 and biogas at 1.80:1. Although these systems already exhibit higher efficiency, further improvements are more challenging but can follow similar enhancements as suggested for simple cycles.

The coal-based case study stands out with the highest ExROEEI of 2.37:1, predominantly influenced by the CO_2 exergy (Ex_{CO2}), which constitutes 61.74% of the exergy denominator. The lower temperature of thermal effluent in this case offers a comparative advantage, moreover, the higher concentration of CO_2 in the plume in this case facilitates its capture. However, it also poses the highest carbon emission challenge with a CO_2 Emission Intensity Index (CEII) of 131.8 metric-ton CO_2eq./TJ. Enhancing the efficiency of Carbon Capture and Storage (CCS) processes could improve both the ExROEEI and reduce CEII in this scenario.

As would be predicted, the biogas examples exhibit the lowest CEII and the most favorable CO_2 emissions results; the simple cycle emits 16.4 metric-ton CO_2eq./TJ, whereas the combined cycle emits just 11.3 metric-ton. In comparison to the biogas examples, the natural gas cases show a higher CEEI of 31.7 metric-ton CO_2eq./TJ for combined cycles and 46.5 for simple cycle, which represents the CO_2 emissions throughout the operating phase. In these situations, 10% of CO_2 equivalent emissions are discharged into the environment despite a 90% effectiveness in CCS.

The natural gas and coal-based power plant scenarios both demonstrated notable CO_2 emission intensities, despite the coal-based power plant case having the greatest ExROEEI. This highlights the need for increased CO_2 capture efficiency. In contrast, the natural gas and biogas cycles—especially in their simple cycle configurations—exhibited significantly lower ExROEEI because of notable energy inefficiencies and environmental energy losses. This emphasizes how important it is to incorporate the lifecycle and environmental effects into exergy calculations beyond the conventional EROI paradigm, particularly the thermodynamic costs related to reducing CO_2 emissions. In the ongoing transition towards more sustainable, lower-carbon solutions, these findings support a more comprehensive, broader approach to energy evaluation that emphasizes alignment with global sustainability objectives in addition to direct energy consideration.

Moreover, it is crucial to consider the situation in which natural gas (NG) is connected to petroleum production when assessing the performance of NG systems. From a conceptual standpoint, splitting the direct exergy (Ex_d) between petroleum and NG would marginally improve the ExROEEI because Ex_d barely makes up 3% of Ex_{Env} in the simple cycle scenario, which is the lowest amount of the total exergy balance. Sensitivity study shows that while the CO_2 Emission Intensity Index (CEII) slightly reduces from 46.5 metric-ton CO_2/TJ to 44.5 metric-ton CO_2/TJ, decreasing Ex_d by half raises the ExROEEI from 0.69:1 to 0.70:1 (Case A in Table 12).

Furthermore, it is remarkable and counterintuitive that coal-based power plants perform better in ExROEEI than combined cycle gas turbine (CCGT) plants. This phenomenon results from CCGT systems' considerable exergy waste, which is represented by a greater Ex_{Env}. If the exhaust gas temperature in CCGT plants is simulated to be the same as in the coal-based case, the ExROEEI increases significantly from 1.60:1 to 3.19:1, exceeding the 2.37:1 ExROEEI of the coal plant (Case C in Table 12). Additionally, the ExROEEI rises from 1.60:1 to 1.67:1 in the case where the Ex_d for CCGT NG is totally devoted to oil production, resulting in an Ex_d of zero for NG (Case B in Table 12). These calculations highlight the complex interactions between exergy components and the possibility of maximizing energy recovery, especially in the case of high-temperature exhaust from CCGT reactors.

As the utilization factor of 85% is not practical for a thermoelectric operating in simple cycle, another sensitivity analysis was conducted by reducing the utilization factor to 20% for both simple cycle cases (NEA,2020), resulting in more than a fourfold increase in power output to maintain the same total electric energy delivery to society over the 40-year lifespan of the project. The findings revealed that for natural gas (NG) in a simple cycle, the ExROEEI slightly decreased from 0.69:1 to 0.67:1, with a perceptible increase in the contribution of Ex_K from 0.51% to 2.07% and Ex_{OP} from 0.61% to 2.49%, while Ex_{Env} decreased from 85.95% to 82.87% (Case D in Table 12). Similarly, for biogas in a simple cycle, the ExROEEI dropped from 0.74:1 to 0.72:1, with Ex_K increasing from 0.23% to 0.96% and Ex_{OP} rising from 0.58% to 2.41%, leading to a reduction in Ex_{Env} from 82.5% to 80.37% (Case E in Table 12). As expected, the changes were relatively minor, and the previous overall analyses and conclusions remained consistent.

The Table 12 bellow presents all the above-mentioned sensitivity cases:

Table 12 – ExROEEI and CEII Comparative analysis between sensitivity cases

#	Sentitivity Cases	ExROEEI	CEII (metric-ton CO_2/TJ)	Challenge
A	NG Brayton Cycle - E_{Xd}: 50%	0.70:1	44.5	Ex_{Env} – 87%
B	NG Combined Cycle - E_{Xd}: 0	1.67:1	29.0	Ex_{Env} – 72%
C	NG Combined Cycle - T_{Lb}: 66º C	3.19:1	31.7	Ex_{Env} – 40%
D	NG Brayton Cycle - Utilization Factor: 20%	0.67:1	50.5	Ex_{Env} – 83%
E	Biogas Brayton Cycle - Utilization Factor: 20%	0.72:1	19.0	Ex_{Env} – 80%

Source: Prepared by the author (2024).

Last but not least, in the context of biogas cases, it is essential to explicitly address the treatment of Ex_{CO2} due to the biogenic nature of the carbon, which inherently implies a neutral carbon balance. Since biogenic carbon does not contribute to net CO_2 emissions, the Ex_{CO2} was set to zero in these scenarios. Because capturing biogenic CO_2 would lead to a negative carbon balance, no CCS system was installed. As the biogas processing plant uses its own biogas as fuel, this method implies that both the CO_2 equivalent emissions from the thermoelectric operation and the emissions related to the production of biogas are zero. Therefore, in the biogas scenarios, Ex_{CO2} and Ex_d both produce zero emissions. Introducing a CCS system in these scenarios would indeed result in negative emissions from the thermoelectric operation, further highlighting the environmental benefits of biogas over natural gas and coal. But this would require changes to the Gross Electric

Power to meet the energy requirements of the CCS system, which would significantly change the biogas cases. Consequently, by upholding the existing framework and clearly outlining these factors and their consequences, biogas's comparative advantage in terms of CO_2 emissions is made apparent, highlighting its importance in sustainable energy systems.

The methodology proposed in this thesis significantly advances energy system evaluations by broadening the analytical framework to encompass not only the full energy lifecycle but also environmental exergy costs and CO_2 mitigation efforts. By integrating both physical and chemical exergy into the Exergy Return on Environment and Energy Investment (ExROEEI) framework, this approach fills a critical gap left by traditional energy assessment methods, which often prioritize energy quantity over the environmental and exergy penalties associated with energy inefficiencies, effluents, and greenhouse gas emissions. This expanded perspective enables a more comprehensive understanding of how different energy technologies perform within the context of a problem-driven energy transition that prioritizes decarbonization and sustainability.

The inclusion of environmental exergy and CO_2 exergy within the ExROEEI framework, as demonstrated by the case studies, reveals a significant reduction in ExROEEI values when accounting for the environmental costs of energy effluents and CO_2 control measures. This decrease reflects the true energetic and environmental costs of these factors, underscoring the need for an integrated evaluation that moves beyond simplistic energy returns. The methodology offers a robust, nuanced tool for assessing the balance between energy efficiency and the urgent imperative to reduce greenhouse gas emissions. In doing so, it highlights that without these considerations, some energy sources may be misrepresented as more efficient than they actually are. This approach provides a fairer, more accurate view of energy system performance and offers essential guidance for policymakers and researchers navigating the decarbonization-driven energy transition.

6 CONCLUSIONS

The need to decarbonize the economy is what makes the current energy transition unique. The basic energy transformations required for human economic and social activities typically have a declining economic return on investment. Thus, to compare energy options in a way that is appropriate for the goals of the current transition, an approach that integrates energy and environmental issues—particularly those pertaining to GHG emissions—must be developed. Although there are already academic options accessible, some gaps still need to be filled.

To evaluate energy conversion facilities, this thesis took into account the quality of energy, the life cycle of activities, and global environmental targets, particularly those pertaining to CO_2 emissions. It also provided a thorough analysis of five case studies using the CO_2 Emission Intensity Index (CEII) and the Energy and Environmental Return on Exergy Investment (ExROEEI) as a lens.

The groundwork for comprehending Exergy's role and Energy Return on Investment (EROI) in the larger framework of the current energy transition and decarbonization requirements is laid out in the initial section, where the objective was to make the project's goals clear, give an overview of the current energy transition environment, and chart the development of EROI and the idea of exergy over time. Important queries answered are as follows:

- Why is the current energy transition distinct?
- Why focus on exergy instead of energy?
- Why does traditional EROI fail to fully assess current energy challenges?

The project’s main contribution is the methodology to assess the Exergy Return on Environment and Energy Investment (ExROEEI) that was clearly, explaining each component of the indicator thoroughly to ensure a comprehensive understanding of its application and relevance.

In order to provide a detailed analysis of each case and explain the subtleties and operational outcomes of each energy system, the ExROEEI and CEII calculations and results were carried out for five different case studies: a coal-based power plant with carbon capture technology; a natural gas simple cycle power plant with carbon capture technology; a natural gas combined cycle power plant with carbon capture technology; a biogas simple cycle power plant; and a biogas combined cycle power plant.

Additionally, the cases were contrasted and compared, emphasizing delicate elements, technological obstacles, and chances to improve the Exergy Return on Environment and Energy Investment (ExROEEI) across various technologies. This included concentrating on the unique effects of every system, the inherent challenges presented by every technology, and identifying possible areas where energy and environmental returns could be improved.

Each case study demonstrated unique energy dynamics and environmental impacts, underscoring the nuanced complexities of energy technologies and the importance of case-specific evaluations.

The integration of exergy analysis, particularly incorporating both physical and chemical components, alongside advanced CO_2 capture techniques, emerged as a pivotal approach for enhancing both energy and ecological efficiencies. By expanding the ExROEEI framework to include environmental exergy and CO_2 exergy, the methodology captures a more realistic picture of energy system sustainability. The inclusion of these broader environmental impacts ensures that the assessment reflects the real exergy penalties associated with energy inefficiencies and environmental burdens such as CO_2 emissions. This comprehensive perspective on energy system performance is critical in a decarbonization-driven transition, providing a more equitable evaluation of both renewable and fossil fuel-based technologies.

The comparative analysis highlighted the critical need for evaluating energy systems beyond traditional EROI, which often faces difficulties to capture the full spectrum of environmental impacts and the lifecycle considerations of energy conversion technologies.

Mainly, the study underscores that generalizing the performance of energy conversion technologies can lead to misleading conclusions and potentially unjust demonization of certain technologies that, under specific conditions, might offer substantial benefits. It's evident from the case studies that the operational context dramatically influences the performance metrics such as ExROEEI and CEII. For instance, while coal-based power plants showed higher ExROEEI values, they also exhibited significant CO_2 emissions, necessitating enhanced CO_2 capture efficiencies. Conversely, natural gas and biogas systems, particularly in simple cycle configurations, displayed lower ExROEEI due to their substantial energy inefficiencies and high exergy losses.

Initially, there was an expectation that this thesis would establish a generic and comprehensive method for evaluating all energy sources and conversion technologies. However, it became apparent through the research that assessments must be fitted specifically to each case and project, considering the unique advantages or disadvantages presented by each situation for the respective sources and technologies involved. This realization emphasizes the necessity of context-specific evaluations to accurately gauge the sustainability and efficiency of energy systems.

The expanded analytical framework introduced in this thesis represents a significant contribution to energy studies. By integrating the exergy penalties associated with environmental impacts — encompassing solid, liquid, and gaseous effluents — the methodology provides a more nuanced understanding of the broader environmental consequences of energy systems. The inclusion of CO_2 exergy, whether or not Carbon Capture and Sequestration (CCS) is implemented, addresses a critical gap in traditional assessments, as it incorporates the exergy cost of mitigating environmental degradation. This broadens the scope of analysis, aligning with Odum's concept of emergy, which emphasizes the environmental effort required to address the emissions produced by energy conversion processes. This holistic perspective ensures that energy systems are evaluated not only on the energy services they provide but also on the environmental costs associated with their operation.

As a result, the research has effectively achieved its goals by creating a transparent and repeatable technique that permits energy analysis, providing a strong substitute for conventional EROI and supplementing the current academic approaches. This novel method is based on the introduction of the new exergy-based indicator, ExROEEI, which reorients the focus towards more efficient and sustainable energy transition scenarios. This thesis has shown the significant advantages of this systematic approach over traditional methods through in-depth comparative evaluations. These analyses show how well exergy and environmental considerations can be integrated, particularly when it comes to the exergy required to reduce CO_2 emissions. The ExROEEI framework's ability to integrate these environmental and exergy costs provides a robust foundation for future research, ensuring that the methodology can be applied in various energy contexts and provide accurate assessments of the trade-offs involved in the global energy transition.

This comprehensive approach has the potential to reshape how energy systems are evaluated in academic research and policy discussions, ensuring that future energy strategies are aligned with global sustainability and decarbonization objectives. They also show how broadly applicable and adaptable the methodology can be in various economic contexts, ensuring that it can effectively guide future energy policies, development strategies, and comparisons between energy sources and technological alternatives.

The results from these studies articulate a clear message: energy sources and processes should be evaluated based on an "exergoenvironmental" basis, which extends the analysis boundary to incorporate emission controls (or the chemical exergy needed for that). This adjusted perspective is crucial for a realistic appraisal of fossil-based and renewable energy sources in the context of sustainable development and climate change mitigation, as it reduces the net exergy surplus of fossil sources and redefines the way their advantages and drawbacks can be seen.

This thesis provides a novel, exergy-based framework that allows for a more nuanced evaluation of energy systems, which enhances the area of energy studies academically. ExROEEI, as opposed to traditional Energy Return on Investment (EROI), takes into account the thermodynamic costs and lifecycle effects of energy transformations, especially CO_2 emissions. This more comprehensive viewpoint makes it possible to assess the sustainability and effectiveness of energy systems more precisely while exposing the shortcomings of conventional approaches, which frequently ignore important operational and environmental aspects.

Looking ahead, these innovations in methodology pave the way for future research to explore diverse energy scenarios and technologies under varying operational conditions. The ExROEEI and its comprehensive approach offer a valuable tool for policymakers and researchers, guiding the development of energy strategies that are not only efficient but also environmentally responsible and aligned with the principles of sustainable development.

Thus. the application of the ExROEEI metric should be expanded to include a broader range of energy systems and conditions. Future research should focus on refining the methodologies for ExROEEI and CEII to enhance their accuracy and applicability across different geographic and operational scenarios. This expansion will allow for a more comprehensive evaluation of the energy transition from an exergy investment perspective, helping to identify potential pathways for more sustainable, efficient, and environmentally responsible energy futures. Additionally, automating the calculations and analyses with an integrated computerized system linked to relevant economic and technological databases will streamline the process, ensuring more dynamic and accurate assessments.

Future studies should expand on the use of ExROEEI to compare various energy sources, especially in petroleum frontier regions where natural gas and crude oil are essential to the economy of energy-exporting nations. The integration of the ExROEEI indicator with other sustainability concerns, such biodiversity and water quality, where energy is used to preserve ecological equilibrium, would offer a more comprehensive understanding of the environmental effects of energy systems.

An intriguing case study for direct comparison with the base case of coal-fired power plants would involve a power plant using biomass directly as fuel, bypassing the biomass gasification step seen in the biogas scenario previously presented. This study could be explored further in future research.

As previously mentioned in the subsection 3.1, future studies should also focus on expanding the application of the Exergy Equivalent of Environmental Impacts (Ex_{Env}) to incorporate broader environmental considerations beyond the gaseous effluents that were the primary focus of this thesis. While the formulation in this work allows for the inclusion of solid, liquid, and gaseous exergy effluents, only the gaseous effluents were considered in the case studies. Future research could investigate the exergy costs associated with solid and liquid effluents, as well as other environmental factors such as water usage, land use, and biodiversity loss, which can be critical factors in the sustainability of energy systems but often overlooked due to the complexity of quantifying their energy restoration costs. Incorporating these additional elements would provide a more comprehensive understanding of the environmental impacts of energy systems. Additionally, future research could explore how this expanded Ex_{Env} framework interacts with different energy technologies, allowing for a more detailed comparison of the environmental trade-offs and benefits across various energy sources. This holistic approach would not only enhance the ExROEEI methodology but also align with global sustainability goals by providing policymakers and researchers with a more robust tool for assessing long-term ecological impacts.

To shed light on fresh perspectives and opportunities, a conceptual debate of the energy transition from an energetic investment viewpoint should be conducted. The shortcomings of the energy-based scenarios that are now in use will be examined, along with the potential applications and ramifications of exergy-based assessments. In doing so, it can provide more lucid choices about energy integration and the application of one process's energy residuals in other processes, opening doors for improving system efficiencies and optimizing energy sources in a variety of operating scenarios. By taking this approach, future energy policies and practices will be guided towards more integrated and sustainable outcomes by fostering a deeper knowledge of the complex relationships between energy production, environmental sustainability, and economic viability.

In conclusion, this thesis advances knowledge of energy transitions both theoretically and practically by putting forth a sophisticated analytical strategy that takes environmental and energy factors into account. It paves the way for later research that may make use of this integrated approach to offer more in-depth understandings of the efficiency and sustainability of energy systems, assisting with well-informed policymaking and strategic planning within the energy industry. In the quest for a more ecologically conscious and sustainable energy landscape, this work not only extends the theoretical foundation for energy analysis but also offers a useful toolkit for evaluating and optimizing energy solutions.

REFERENCES

ARVIDSSON, R., “Inventory Indicators in Life Cycle Assessment”. *In*: CIROTH, A., ARVIDSSON, R. (eds.). *LCA Compendium – The Complete World of Life Cycle Assessment*. Berlin, Springer, pp. 171-190, 2021. Avaiable in: <https://doi.org/10.1007/978-3-030-62270-1_8>. Accessed on: December 5th, 2023.

BAPTISTA, L. B., SCHAEFFER, R., VAN SOEST, H. L. *et al*. “Good practice policies to bridge the emissions gap in key countries”, *Global Environmental Change*, v. 73, pp. 102472, 2022. Avaiable in: <https://doi.org/10.1016/j.gloenvcha.2022.102472>. Accessed on: November 14th, 2023.

BARACSKAY, D. *Cost-Benefit Analysis: Concepts and Practice*. Cambridge, Cambridge University Press, 1998.

BEJAN, A. *Advanced Engineering Thermodynamics*. 4 ed. Hoboken, Wiley, 2016. Originally published in 1988.

BHANDARI, K. P., COLLIER, J. M., ELLINGSON, R. J. *et al*. “Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis”, *Renewable and Sustainable Energy Reviews*, v. 47, pp. 133-141, 2015. Avaiable in: <https://doi.org/10.1016/j.rser.2015.02.057>. Accessed on: December 7th, 2023.

BOYCE, M. P. *Gas turbine engineering handbook*. Amsterdam, Elsevier, 2011.

BRANDT, A. R., ENGLANDER, J., BHARADWAJ, S. “The energy efficiency of oil sands extraction: Energy return ratios from 1970 to 2010”, *Energy*, v. 55, pp. 693-702, 2013. Avaiable in: <https://doi.org/10.1016/j.energy.2013.03.080>. Accessed on: May 5th, 2024.

BRAUNREITER, L., VAN BEEK, L., HAJER, M. *et al*. “Transformative pathways – Using integrated assessment models more effectively to open up plausible and desirable low-carbon futures”, *Energy Research & Social Science*, v. 80, pp. 102220, 2021. Avaiable in: <https://doi.org/10.1016/j.erss.2021.102220>. Accessed on: December 18th, 2023.

BROCKWAY, P. E., OWEN, A., BRAND-CORREA, L. I. *et al*. “Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources”, *Nature Energy*, v. 4, n. 7, pp. 612-621, 2019. Avaiable in: <https://doi.org/10.1038/s41560-019-0425-z>. Accessed on: March 10th, 2024.

BUREAU OF LABOR STATISTICS. 2022. Avaiable in: <https://www.bls.gov>. Accessed on: December 21st, 2022.

CARDOSO, F. (2017). *Elaboração de Roadmaps Tecnológicos da Produção de Biogás a partir de Palha e Vinhaça*. Masters dissertation, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, 2017.

CASTELO BRANCO, D. A. *Avaliação do real potencial de redução das emissões de CO_2 equivalente com uso da captura em uma UTE a carvão*. Doctoral thesis, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, 2012.

CASTELO BRANCO, D. A., MOURA, M. C. P., SZKLO, A. *et al*. "Emissions reduction potential from CO_2 capture: A life-cycle assessment of a Brazilian coal-fired power plant", *Energy Policy*, v. 61, pp. 1221-1235, 2013. Avaiable in: <https://doi.org/10.1016/j.enpol.2013.06.043>. Accessed on: February 10th, 2024.

CHEN, Y., FENG, L., TANG, S. *et al*. "Extended-exergy based energy return on investment method and its application to shale gas extraction in China", *Journal of Cleaner Production*, v. 260, pp. 120933, 2020. Avaiable in: <https://doi.org/10.1016/j.jclepro.2020.120933>. Accessed on: December 8th, 2023.

CHEN, Y., FENG, L., WANG, J. *et al*. "Emergy-based energy return on investment method for evaluating energy exploitation", *Energy*, v. 128, pp. 540-549, 2017. Avaiable in: <https://doi.org/10.1016/j.energy.2017.04.058>. Accessed on: November 5th, 2023.

CLEVELAND, C., COSTANZA, R., HALL, C. *et al*. "Energy and the US Economy: a biophysical perspective", *Science*, v. 225, n. 4665, pp. 890-897, 1984.

COSTA, A. N., FLUTT, A. F., NEVES, M. V. S. *Eficiência energética na produção de petróleo e em centrais termelétricas*. Rio de Janeiro, Interciência, 2018.

COTTRELL, F. *Energy and Society: The Relation Between Energy, Social Change and Economic Development*. New York, McGraw-Hill, 1955.

COURT, V. "An Estimation of Different Minimum Exergy Return Ratios Required for Society", *BioPhysical Economics and Resource Quality*, v. 4, n. 11, pp. 1-13, 2019. Avaiable in: <https://doi.org/10.1007/s41247-019-0059-6>. Accessed on: March 9th, 2023.

CRONIN, J., HUGHES, N., TOMEI, J. *et al*. "Embedding justice in the 1.5°C transition: A transdisciplinary research agenda", *Renewable and Sustainable Energy Transition*, v. 1, pp. 100001, 2021. Avaiable in: <https://doi.org/10.1016/j.rset.2021.100001>. Accessed on: December 5th, 2023.

DALE, M., KRUMDIECK, S., BODGER, P. "Global energy modelling – A biophysical approach (GEMBA) Part 2: Methodology", *Ecological Economics*, v. 73, pp. 158-167, 2012. Avaiable in: <https://doi.org/10.1016/j.ecolecon.2011.10.028>. Accessed on: April 15th, 2024.

ERTESVÅG, I. S. "Energy, exergy, and extended-exergy analysis of the Norwegian society 2000", *Energy*, v. 30, n. 5, pp. 649-675, 2005. Avaiable in: <https://doi.org/10.1016/j.energy.2004.05.025>. Accessed on: December 5th, 2023.

ERTESVÅG, I. S. “Society exergy analysis: a comparison of different societies”, *Energy*, v. 26, n. 3, pp. 253-270, 2001. Avaiable in: <https://doi.org/10.1016/S0360-5442(00)00070-0>. Accessed on: May 25th, 2024.

EUROPEAN ENVIRONMENT AGENCY. CO_2 emission intensity. *EEA*, Copenhagen, 2020. Avaiable in: <https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-5#tab-googlechartid_chart_11_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%22pre_config_ugeo%22%3A%5B%22European%20Union%20(current%20composition)%22%5D%7D%7D>. Accessed on: April 10th, 2024.

FANKHAUSER, S., SMITH, S. M., ALLEN, M. *et al*. “The meaning of net zero and how to get it right”, *Nature Climate Change*, v. 12, n. 1, pp. 15-21, 2022. Avaiable in: <https://doi.org/10.1038/s41558-021-01245-w>. Accessed on: February 10th, 2024.

FOUQUET, R., PEARSON, P. J. G. “Past and prospective energy transitions: Insights from history”, *Energy Policy*, v. 50, pp. 1-7, 2012. Avaiable in: <https://doi.org/10.1016/j.enpol.2012.08.014>. Accessed on: February 8th, 2024.

FOXON, T., KÖHLER, J., OUGHTON, C. (eds.). *Innovation for a low carbon economy: economic, institutional and management approaches*. Cheltenham, Edward Elgar Publishing, 2008.

FTHENAKIS, V., KIM, H. C. “Life-cycle uses of water in U.S. electricity generation”, *Renewable and Sustainable Energy Reviews*, v. 14, n. 7, pp. 2039-2048, 2010. Avaiable in: <https://doi.org/10.1016/j.rser.2010.03.008>. Accessed on: March 2nd, 2024.

FXTOP. 2022. Avaiable in: <https://fxtop.com>. Accessed on: December 21st, 2022.

GAGGIOLI, R. A. “The concept of available energy”, *Chemical Engineering Science*, v. 16, n. 1-2, pp. 87-96, 1961. Avaiable in: <https://doi.org/10.1016/0009-2509(61)87010-3>. Accessed on: November 17th, 2023.

GAGNON, N., HALL, C. A. S., BRINKER, L. (2009). “A preliminary investigation of energy return on energy investment for global oil and gas production”, *Energies*, v. 2, n. 3, 490-503, 2009. Avaiable in: <https://doi.org/10.3390/en20300490>. Accessed on: May 16th, 2024.

GASPARATOS, A., EL-HARAM, M., HORNER, M. “Assessing the sustainability of the UK society using thermodynamic concepts: Part 2”, *Renewable and Sustainable Energy Reviews*, v. 13, n. 5, pp. 956-970, 2009. Avaiable in: <https://doi.org/10.1016/j.rser.2008.03.005>. Accessed on: December 7th, 2023.

GEORGESCU-ROEGEN, N. *The Entropy Law and the Economic Process*. Cambridge, Harvard University Press, 1971.

GIBBS, J. W. “A method of geometrical representation of the thermodynamic properties of substances by means of surfaces”, *Transactions of the Connecticut Academy of Arts and Sciences*, v. 2, pp. 382-404, 1873.

GILLILAND, M. W. “Energy Analysis and Public Policy”, *Science*, v. 189, n. 4208, pp. 1051-1056, 1975. Avaiable in: <https://doi.org/10.1126/science.189.4208.1051/>. Accessed on: February 24th, 2024.

GRANDELL, L., HALL, C. A. S., HÖÖK, M. “Energy return on investment for Norwegian oil and gas from 1991 to 2008”, *Sustainability*, v. 3, n. 11, pp. 2050-2070, 2011. Avaiable in: <https://doi.org/10.3390/su3112050>. Accessed on: May 14th, 2024.

GREET. GREET Model 2022. Argonne National Laboratory. *GREET*, Argonne, 2022. Avaiable in: <https://greet.es.anl.gov/>. Accessed on: February 20th, 2024.

GRUBB, M., JAMASB, T., POLLITT, M. G. *Delivering a low carbon electricity system: technologies, economics and policy*. Cambridge, Cambridge University Press, 2008.

GRUBLER, A., JOHANSSON, T. B., MUNDACA, L. *et al*. *Energy Primer*. Cambridge, Cambridge University Press and IIASA, 2012. *E-book*. Avaiable in: <https://iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Chapter1_lowres.pdf>. Accessed on: May 3rd, 2024.

GUILFORD, M. C., HALL, C. A. S., O’CONNOR, P. *et al*. “A New Long Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production”, *Sustainability*, v. 3, n. 10, pp. 1866-1887, 2011. Avaiable in: <https://doi.org/10.3390/su3101866>. Accessed on: November 11th, 2023.

GUPTA, A. Energy Return on Energy Invested (EROI) and Energy Payback Time (EPBT) for PVs. *In*: LETCHER, T., FTHENAKIS, V. M. (eds.). *A Comprehensive Guide to Solar Energy Systems: With Special Focus on Photovoltaic Systems*. Cambridge, Academic Press, pp. 407-425, 2018. Avaiable in: <https://doi.org/10.1016/B978-0-12-811479-7.00021-X>. Accessed on: March 13th, 2024.

GUPTA, A. K., HALL, C. A. S. “A Review of the Past and Current State of EROI Data”, *Sustainability*, v. 3, n. 10, pp. 1796-1809, 2011. Avaiable in: <https://doi.org/10.3390/su3101796>. Accessed on: February 20th, 2024.

HALL, C. A. S. *Energy return on investment: A unifying principle for biology, economics and development*. New York, Springer, 2017.

HALL, C. A. S., BALOGH, S., MURPHY, D. J. “What is the minimum EROI that a sustainable society must have?”, *Energies*, v. 2, n. 1, pp. 25-47, 2009. Avaiable in: <https://doi.org/10.3390/en20100025>. Accessed on: December 15th, 2023.

HALL, C. A. S., CLEVELAND, C. J. “Petroleum drilling and production in the United States: Yield per effort and net energy analysis”, *Science*, v. 211, pp. 576-579, 1981.

HALL, C. A. S., LAMBERT, J. G., BALOGH, S. B. “EROI of different fuels and the implications for society”, *Energy Policy*, v. 64, pp. 141-152, 2014. Avaiable in: <https://doi.org/10.1016/j.enpol.2013.05.049>. Accessed on: February 24th, 2024.

HASSAN, A. M., AYOUB, M., EISSA, M. *et al*. “Exergy return on exergy investment analysis of natural-polymer (Guar-Arabic gum) enhanced oil recovery process”, *Energy*, v. 181, pp. 162-172, 2019. Avaiable in: <https://doi.org/10.1016/j.energy.2019.05.137>. Accessed on: December 17th, 2023.

HERTWICH, E. G., GIBON, T., BOUMAN, E. A. *et al*. “Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies”, *Proceedings of the National Academy of Sciences*, v. 112, n. 20, pp. 6277-6282, 2015. Avaiable in: <https://doi.org/10.1073/pnas.1312753111>. Accessed on: March 4th, 2024.

HU, Y., HALL, C. A. S., WANG, J. *et al*. “Energy Return on Investment (EROI) of China’s conventional fossil fuels: Historical and future trends”, *Energy*, v. 54, pp. 352-364, 2013. Avaiable in: <https://doi.org/10.1016/j.energy.2013.01.067>. Accessed on: March 4th, 2024.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. *ISO 14040: Environmental management - Life cycle assessment - Principles and framework*. Geneva, ISO, 2006.

KAUSHIK, S. C., SINGH, O. K. “Estimation of chemical exergy of solid, liquid and gaseous fuels used in thermal power plants”, *Journal of Thermal Analysis and Calorimetry*, v. 115, n. 1, pp. 903-908, 2014. Avaiable in: <https://doi.org/10.1007/s10973-013-3323-9>. Accessed on: March 4th, 2024.

KING, L. C., VAN DEN BERGH, J. C. J. M. “Implications of net energy-return-on-investment for a low-carbon energy transition”, *Nature Energy*, v. 3, n. 4, pp. 334-340, 2018. Avaiable in: <https://doi.org/10.1038/s41560-018-0116-1>. Accessed on: February 21st, 2024.

KLITGAARD, K., KRALL, L. “Ecological economics, degrowth, and institutional change”, *Ecological Economics*, v. 84, pp. 158-196, 2012.

KÖBERLE, A. C., DAIOGLOU, V., ROCHEDO, P. *et al*. “Can global models provide insights into regional mitigation strategies? A diagnostic model comparison study of bioenergy in Brazil”, *Climatic Change*, v. 170, n. 2, pp. 1-31, 2022. Avaiable in: <https://doi.org/10.1007/s10584-021-03236-4>. Accessed on: May 8th, 2024.

KUBISZEWSKI, I., CLEVELAND, C. J., ENDRES, P. K. “Meta-analysis of net energy return for wind power systems”, *Renewable Energy*, v. 35, n. 1, pp. 218-225, 2010. Avaiable in: <https://doi.org/10.1016/j.renene.2009.01.012>. Accessed on: May 5th, 2024.

LAMBERT, J. G., HALL, C. A. S., BALOGH, S. *et al*. “Energy, EROI and quality of life”, *Energy Policy*, v. 64, pp. 153-167, 2014. Avaiable in: <https://doi.org/10.1016/j.enpol.2013.07.001>. Accessed on: April 9th, 2024.

LAMBERT, J. G., HALL, C. A. S., BALOGH, S. *et al*. *EROI of Global Energy Resources! Status, Trends and Social Implications*. [*S. l.: s. n.*], 2013. Avaiable in: <https://doi.org/10.13140/2.1.2419.8724>. Accessed on: November 17th, 2023.

LEAL FILHO, W., BRANDLI, L. L., BECKER, D. *et al*. "Sustainable development policies as indicators and pre-conditions for sustainability efforts at universities: Fact or fiction?", *International Journal of Sustainability in Higher Education*, v. 19, n. 1, pp. 85-113, 2018. Avaiable in: <https://doi.org/10.1108/IJSHE-01-2017-0002>. Accessed on: March 26th, 2024.

LIM, M. *Croydon Decentralised Energy Study*. Hertfordshire, AECOM, 2009a. *E-book*. Avaiable in: <https://www.croydon.gov.uk/sites/default/files/2022-01/decentralised-energy-study-executive-summary.pdf>. Accessed on: March 4th, 2024.

LIM, M. *Section D. Examines the feasibility of conversion and utilisation of the existing Rolls Royce power plant in factory Lane*. Hertfordshire, AECOM, 2009b. PDF. Avaiable in: <https://www.croydon.gov.uk/sites/default/files/2022-01/decentralised-energy-study-section-d.pdf>. Accessed on: March 4th, 2024.

LIOR, N. "Exergy, Energy, and Gas Flow Analysis of Hydrofractured Shale Gas Extraction", *Journal of Energy Resources Technology*, v. 138, n. 6, pp. 061601, 2016. Avaiable in: <https://doi.org/10.1115/1.4032240>. Accessed on: November 17th, 2023.

LOZANO, M. A., BARTOLOMÉ, J. L., VALERO, A. *et al*. Thermoeconomic diagnosis of energy systems. *94º Florence World Energy Research Symposium*, Florence, pp. 6-8, 1994.

MOURA, M. C. P., BRANCO, D. A. C., PETERS, G. P. *et al*. "How the choice of multi-gas equivalency metrics affects mitigation options: The case of CO_2 capture in a Brazilian coal-fired power plant", *Energy Policy*, v. 61, pp. 1357-1366, 2013. Avaiable in: <https://doi.org/10.1016/j.enpol.2013.05.097>. Accessed on: April 14th, 2024.

MULDER, K., HAGENS, N. J. "Energy Return on Investment: Toward a Consistent Framework", *AMBIO: A Journal of the Human Environment*, v. 37, n. 2, pp. 74-79, 2008. Avaiable in: <https://doi.org/10.1579/0044-7447(2008)37[74:EROITA]2.0.CO;2>. Accessed on: May 6th, 2024.

MURPHY, D. J., HALL, C. A. S., DALE, M. *et al*. "Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels", *Sustainability*, v. 3, n. 10, pp. 1888-1907, 2011. Avaiable in: <https://doi.org/10.3390/su3101888>. Accessed on: February 23rd, 2024.

NAEGLER, T., BUCHGEISTER, J., HOTTENROTH, H. *et al*. "Life cycle-based environmental impacts of energy system transformation strategies for Germany: Are climate and environmental protection conflicting goals?", *Energy Reports*, v. 8, pp. 4763-4775, 2022. Avaiable in: <https://doi.org/10.1016/j.egyr.2022.03.143>. Accessed on: March 27th, 2024.

NERINI, F. F., SOVACOOL, B., HUGHES, N. *et al*. “Connecting climate action with other Sustainable Development Goals”, *Nature Sustainability,* v. 2, pp. 674-680, 2019. Avaiable in: <https://doi.org/10.1038/s41893-019-0334-y>. Accessed on: March 25th, 2024.

NEVES, M. V. da S., SZKLO, A., & SCHAEFFER, R. (2023). Fossil fuel facilities exergy return for a frontier of analysis incorporating CO_2 capture: The case of a coal power plant. *Energy, 284,* 128541. Avaiable in: <https://doi.org/10.1016/j.energy.2023.128541>..

ODUM, H. T. “Energy, ecology, and economics”, *Ambio,* v. 2, n. 6, pp. 220-227, 1973. Avaiable in: <https://www.jstor.org/stable/4312030>. Accessed on: March 14th, 2024.

PAHUD, K., DE TEMMERMAN, G. Overview of the EROI, a tool to measure energy availability through the energy transition. *8th International Youth Conference on Energy*, Eger, pp. 1-14, 2022. Avaiable in: <https://doi.org/10.1109/IYCE54153.2022.9857542>. Accessed on: May 28th, 2024.

PALMER, G. “Household Solar Photovoltaics: Supplier of Marginal Abatement, or Primary Source of Low-Emission Power?”, *Sustainability*, v. 5, n. 4, pp. 1406-1442, 2013. Avaiable in: <https://doi.org/10.3390/su5041406>. Accessed on: May 28th, 2024.

PORTUGAL-PEREIRA, J., KÖBERLE, A. C., SORIA, R. *et al*. “Overlooked impacts of electricity expansion optimisation modelling: The life cycle side of the story”, *Energy,* v. 115, pp. 1424-1435, 2016. Avaiable in: <https://doi.org/10.1016/j.energy.2016.03.062>. Accessed on: April 26th, 2024.

PTASINSKI, K. J., KOYMANS, M. N., VERSPAGEN, H. H. G. “Performance of the Dutch Energy Sector based on energy, exergy and Extended Exergy Accounting”, *Energy,* v. 31, n. 15, pp. 3135-3144, 2006. Avaiable in: <https://doi.org/10.1016/j.energy.2006.03.010>. Accessed on: May 28th, 2024.

RANT, Z. “Exergy, a new word for technical available work”, *Forsch. Ing. Wis*, v. 22, n. 1, pp. 36-37, 1956.

RAUGEI, M. “Net energy analysis must not compare apples and oranges”, *Nature Energy,* v. 4, n. 2, pp. 86-88, 2019. Avaiable in: <https://doi.org/10.1038/s41560-019-0327-0>. Accessed on: March 26th, 2024.

RIAHI, K., SCHAEFFER, R., ARANGO, J. *et al*. Mitigation pathways compatible with long-term goals. *In*: THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, Cambridge University Press, pp. 295-408, 2023. *E-book*. Avaiable in: <https://doi.org/10.1017/9781009157926.005>. Accessed on: March 26th, 2024.

ROCCO, M. V., COLOMBO, E., SCIUBBA, E. “Advances in exergy analysis: a novel assessment of the Extended Exergy Accounting method”, *Applied Energy*, v. 113, pp. 1405-1420, 2014. Avaiable in: <https://doi.org/10.1016/j.apenergy.2013.08.080>. Accessed on: November 17th, 2023.

ROCKSTRÖM, J., STEFFEN, W., NOONE, K. *et al.* "A safe operating space for humanity", *Nature,* v. 461, pp. 472-475, 2009. Avaiable in: <https://doi.org/10.1038/461472a>. Accessed on: April 9th, 2024.

SCIUBBA, E. "A revised calculation of the econometric factors α- and β for the Extended Exergy Accounting method", *Ecological Modelling*, v. 222, n. 4, pp. 1060-1066, 2011. Avaiable in: <https://doi.org/10.1016/j.ecolmodel.2010.11.003>. Accessed on: April 9th, 2024.

SCIUBBA, E. "Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems", *International Journal of Exergy*, v. 1, n. 2, pp. 68-84, 2001. Avaiable in: <https://doi.org/10.1016/S1164-0235(01)00012-7>. Accessed on: April 5th, 2024.

SCIUBBA, E. "Exergy as a Direct Measure of Environmental Impact", *Advanced Energy Systems*, pp. 573-581, 1999. Avaiable in: <https://doi.org/10.1115/IMECE1999-0870>. Accessed on: May 7th, 2024.

SCIUBBA, E. "From Engineering Economics to Extended Exergy Accounting: A Possible Path from Monetary to Resource-Based Costing", *Journal of Industrial Ecology*, v. 8, n. 4, pp. 19-40, 2004. Avaiable in: <https://doi.org/10.1162/1088198043630397>. Accessed on: May 5th, 2024.

SERS, M. R., VICTOR, P. A. "The Energy-emissions Trap", *Ecological Economics*, v. 151, pp. 10-21, 2018. Avaiable in: <https://doi.org/10.1016/j.ecolecon.2018.04.004>. Accessed on: May 7th, 2024.

SMIL, V. "Energy (r)evolutions take time", *World Energy*, v. 44, pp. 10-14, 2019.

SMIL, V. "World history and energy", *Encyclopedia of Energy*, v. 6, pp. 549-561, 2004. Avaiable in: <http://vaclavsmil.com/wp-content/uploads/docs/smil-article-2004 world-history-energy.pdf>. Accessed on: May 17th, 2024.

SMIL, V. Science, energy, ethics, and civilization. *In*: CHIAO, R. Y., COHEN, M. L., LEGGETT, A. J. (eds.). *Visions of Discovery: New Light on Physics, Cosmology, and Consciousness*. Cambridge, Cambridge University Press, pp. 709-729, 2011. Avaiable in: <https://books.google.com.br/books?hl=pt-BR&lr=&id=BhcpiZN2MOIC&oi=fnd&pg=PR7&dq=SMIL,+Vaclav.+2010.+Science,+energy,+ethics,+and+civilization.+Cambridge:+Visions+of+Discovery:+New+Light+on+Physics,+Cosmology,+and+Consciousness,+R.Y.+Chiao+et+al.+eds.,+pp.+709-729+-+Cambridge+University+Press.&ots=GXdAwNtzzh&sig=3VJVb1XUG_dzgtaQ5Q9dZZwOoXc#v=onepage&q&f=false>. Accessed on: April 9th, 2024.

SOVACOOL, B. "How long will it take? Conceptualizing the temporal dynamics of energy transitions", *Energy Research & Social Science*, v. 13, pp. 202-215, 2015.

SOVACOOL, B. K. "The importance of comprehensiveness in renewable electricity and energy-efficiency policy", *Energy Policy*, v. 37, n. 4, pp. 1529-1541, 2009.

Avaiable in: <https://doi.org/10.1016/j.enpol.2008.12.016>. Accessed on: February 20th, 2024.

SZARGUT, J. *Exergy method: technical and ecological applications*. Southampton, WIT Press, 2005. *E-book*. Avaiable in: <https://books.google.com.br/books?hl=pt-BR&lr=&id=ZL2BTTkR35QC&oi=fnd&pg=PP1&dq=Szargut,+J.,+2005.+Exergy+Method:+Technical+and+Ecological+Application.+WIT+Press,+Southampton.&ots=_nBS6nHOFH&sig=z2tCy4-8lzMQmu116jti-G4D0mQ#v=onepage&q&f=false>. Accessed on: February 20th, 2024.

SZARGUT, J., MORRIS, D. R., STEWARD, F. R. *Exergy analysis of thermal, chemical, and metallurgical processes*. [*S. l.*], Springer, 1988.

THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. *IPCC*, Geneva, 2019. Avaiable in: <https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html>. Accessed on: April 27th, 2024.

THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. *Climate Change 2022. Mitigation of Climate Change. Summary for Policymakers*. Geneva, IPCC, 2022. *E-book*. Avaiable in: <https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf>. Accessed on: April 26th, 2024.

THE INTERNATIONAL ENERGY AGENCY. CO_2 Emissions in 2023. *IEA*, Paris, 2023. Avaiable in: <https://www.iea.org/reports/CO2-emissions-in-2023>. Accessed on: May 7th, 2024.

THE INTERNATIONAL ENERGY AGENCY. *Projected Costs of Generating Electricity. 2020 Edition*. Paris, IEA, 2020. *E-book*. Avaiable in: <https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf>. Accessed on: February 19th, 2024.

THE INTERNATIONAL ENERGY AGENCY. World gross electricity production by source, 2019. *IEA*, Paris, 2019. Avaiable in: <https://www.iea.org/data-and-statistics/charts/world-gross-electricity-production-by-source-2019>. Accessed on: April 26th, 2024.

VALERO, A., SERRA, L., UCHE, J. "Fundamentals of exergy cost accounting and thermoeconomics. Part I: Theory", *Journal of Energy Resources Technology, Transactions of the ASME*, v. 128, n. 1, pp. 1-8, 2006.

VALERO, A., VALERO, A., STANEK, W. "Assessing the exergy degradation of the natural capital: From Szargut's updated reference environment to the new thermoecological-cost methodology", *Energy*, v. 163, pp. 1140-1149, 2018. Avaiable in: <https://doi.org/10.1016/j.energy.2018.08.091>. Accessed on: December 19th, 2023.

VAN SOEST, H. L., DEN ELZEN, M. G. J., VAN VUUREN, D. P. "Net-zero emission targets for major emitting countries consistent with the Paris Agreement", *Nature Communications*, v. 12, n. 1, pp. 2140, 2021. Avaiable in: <https://doi.org/10.1038/s41467-021-22294-x>. Accessed on: December 25th, 2023.

WALL, G. “Exergy conversion in the Swedish society”, *Resources and Energy*, v. 9, n. 1, pp. 55-73, 1987. Avaiable in: <https://doi.org/10.1016/0165-0572(87)90023-5>. Accessed on: February 24th, 2024.

WALL, G. *Exergy-a useful concept within resource accounting. Chalmers tekniska högskola*. Göteborg, Göteborgs universitet, 1977.

WANG, C., ZHANG, L., CHANG, Y. *et al*. “Energy return on investment (EROI) of biomass conversion systems in China: Meta-analysis focused on system boundary unification”, *Renewable and Sustainable Energy Reviews*, v. 137, pp. 110652, 2021. Avaiable in: <https://doi.org/10.1016/j.rser.2020.110652>. Accessed on: February 20th, 2024.

WEIßBACH, D., RUPRECHT, G., HUKE, A. *et al*. “Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants”, *Energy*, v. 52, pp. 210-221, 2013. Avaiable in: <https://doi.org/10.1016/j.energy.2013.01.029>. Accessed on: May 7th, 2024.

WILSON, C., GUIVARCH, C., KRIEGLER, E. *et al*. “Evaluating process-based integrated assessment models of climate change mitigation”, *Climatic Change*, v. 166, n. 3, pp. 1-2, 2021. Avaiable in: <https://doi.org/10.1007/s10584-021-03099-9>. Accessed on: March 5th, 2024.

APPENDIX A – DATA AND CALCULATION SUMMARY TABLES FOR CASE 1 – COAL THERMOELECTRIC

P1 – Coal production	
Energy Inputs	
Electricity (kwh/kg coal)	0,0127550
Electricity (MJ/kg coal)	0,0459180
Electricity (MJ/MJ produced electricity)	0,0000000
Diesel kg/kg coal	0,0002625
Diesel kg/MJ electricity	0,0000507
Coal loss %	20,00%
Processed coal kg/kwh electricity	0,6950000
Processed coal kg/MJ electricity	0,1930556
Calcareous kg/kg Processed coal	0,0162630
Calcareous kg/MJ electricity	0,0031397
Output	
Coal kg/kwh electricity	0,5560000
Coal kg/MJ electricity	0,1544444
MJ produced electricity	331,00
LCV coal (MJ/kg)	20,55
Q_H MW	1323,68
Exd (MW)	21.73
EROI	**60.92:1**

P3 – Rail Transport of Coal	
Energy Inputs	
Diesel kg/kg coal	0,0028106
Diesel kg/MJ electricity	0,0004341
LCV Diesel) kcal/kg	10100
LCV Diesel) MJ/kg	42,2584000
ExIdP3 (Rail Transport) MW	0,0183437

P2 – Maritime transport of coal	
Energy Inputs	
Diesel kg/kg coal	0,0056730
Diesel kg/MJ electricity	0,0008762
ExIdP2 (Maritime transport) MW	0,0370253

P4 – Calcareous mining	
Energy Inputs	
Calcareous kg/MJ produced electricity(1)	0,0031397
Calcareous kg/kg Lime	2,00
Calcareous kg/MJ produced electricity (2)	0,00205
Calcareous kg/MJ produced electricity	0,005189663
Electricity (kwh/kg calcareous)	0,4690000
Electricity (MJ/kg calcareous)	1,6884
Diesel kg/kg calcareous	0,0099000
Diesel kg/MJ electricity	0,0000514
ExIdP4 (calcareous mining) MW	0,010933364

P5 – Lime production	
Input	
Calcareous kg/kg lime	2,00

P6 – Lime transport	
Energy Inputs	
Diesel kg/kg lime	0,014
Diesel kg/MJ electricity	0,00001435
ExIdP6 (Lime transport) MW	0,000606408

P7 – Thermoelectric unit	
Inputs	
Lime kg/kwh	0,00369
Lime kg/MJ produced electricity	0,001025
Coal kg/kwh electricity	0,556
Solvent MEA to thermoelectric kg/kwh	0,0035
Solvent MEA to thermoelectric kg/MJ electricity	0,000972222
NaOH to thermoelectric kg/kwh	0,00426
NaOH to thermoelectric kg/MJ electricity	0,001183333

Energy Inputs	
Diesel kg/kg solvent	0,0312000
Diesel kg/MJ electricity	0,0000303
ExIdP9 (Solvent transport) MJ/MJ electricity	0,0012818

P10 – NaOH transport	
Energy Inputs	
Diesel kg/kg NaOH	0,0309000
Diesel kg/MJ electricity	0,0000366
ExInd10 (NaOH transport) MJ/MJ electricity	0,0015452

P11 – NaOH production	
Energy Inputs	
Electricity (kwh/kg NaOH)	2,94
Electricity (MJ/kg NaOH)	10,5840000
ExInd11[(NaOH production) MJ/MJ electricity	0,0125244

Coal Thermoelectric Plant	
Castelo Branco (2012)	
Net Electric Power (MW):	331
Energy Penalty (MW)	86,06
Energy Penalty (%)	26%
Utilization Factor (%)	0,85
Coal Mean EROI (Hall et al., 2014)	46
Expected useful life for the thermoelectric (years)	40
Exo (TJ)	354906,14
Exd (TJ)	23298.97
ExROI	15.23:1
ExK	7473,78
CAPEX (10^6 US$)	1987,708
Exid	88,20
Ex_{OP} (TJ)	9032,87
OPEX (10^6 US$)	2402,360
T_0 (K)	298
T_{Lb} (K)	339,33
Q_{Lb} (MW)	132,37
EQ_{Lb} (MW)	16,12
Ex_{Env} (TJ)	17286,67
Ex_{CO_2} (TJ)	92275,60

ExROEEI	**2,81**
Exergy Return on Environment and Energy Investment	

Premises – Sciubba, 2011:	**Present Value (21/12/2022)**
ee_L (MJ/wh)	
ee_K (MJ/US$)	3,76

Premissas TOLMASQUIM, 2016:	**Present Value(21/12/2022)**
CAPEX (US$/kW) 1800 -4000	4766
OPEX (US$/MWh)	19,34
Useful life (years)	40
Average Capacity Factor (%)	85

Legend:
Castelo Branco (2012)
IEA (2020)
Hall et al. (2014)
Calculated cell
Greet (2022)

APPENDIX B – DATA AND CALCULATION SUMMARY TABLES FOR CASE 2 – BRAYTON CYCLE NATURAL GAS THERMOELECTRIC

P1 – Gas production	
Energy Inputs	
Fuel Gas kg/kg Produced Natural Gas*	0,01
Fuel Gas MJ/kg Produced Natural Gas	0,51
LCV Fuel Gas (MJ/kg)	48,91
Gross Electric Power (MW):	370,16
Required Fuel Gas kg/s (Total power-Energy Service)	21,94
Natural Gas Loss	1%
Produced Natural Gas kg/s (Total power-Energy Service)	22,16
Output	
Q_H MW	1072,93
Exd (MW)	11,38
EROI	**94,30**

P2 – Transport of Gas to Gas Processing Unit	
Energy Inputs	
Fuel Gas MJ/kg Transported Natural Gas	-
Fuel Gas MJ/MJ electricity	-
ExIdP3 (Maritime transport) MJ/MJ electricity	0,00

P4 – Transport of Gas to Thermoelectric Unit	
Energy Inputs	
Fuel Gas MJ/kg Transported Fuel Gas	-
Fuel Gas MJ/MJ electricity	-
ExIdP3 MW	0,00

P3 – Gas Processing Unit	
Energy Inputs	
Fuel Gas kg/kg Procssed Natural Gas*	0,01
Fuel Gas MJ/kg Processed Natural Gas	0,51
Fuel Gas MW	11,27
ExIdP3 MW	11,27

P5 – Thermoelectric unit	
Inputs	
Thermoelectric unit Energy Efficiency	34,50%
Fuel Gas kg/s (Total power-Energy Service)	21,94

Natural Gas Thermoelectric Plant	
Brayton Cycle	
Net Electric Power (MW):	331
Energy Penalty (MW)	39,16
Energy Penalty (%)	12
Utilization Factor (%)	0,85
Gas Mean EROI (Hall et al., 2014)	20
Expected useful life for the thermoelectric (years)	40
Ex_O (TJ)	354906,14
Exd (TJ)	12200,19
ExROI	29,09
ExK	2590,14
CAPEX (10^6 US$)	688,87
Exid	12079,40
Ex_{OP} (TJ)	3109,01
OPEX (10^6 US$)	826,86
T_0 (K)	298
T_{Lb} (K)	717
Q_{Lb} (MW)	702,77
EQ_{Lb} (MW)	410,68
Ex_{Env} (TJ)	440344,00
$Exco_2$ (TJ)	41988,29

ExROEEI	**0,69**
Exergy Return on Environment and Energy Investment	

Premises – Sciubba, 2011:	**Present Value (21/12/2022)**
ee_L (MJ/wh)	-
ee_K (MJ/US$)	3,76

Premises TOLMASQUIM, 2016:	**Present Value(21/12/2022)**
CAPEX (US$/kW)	1861,00
OPEX (US$/MWh)	7,50
Useful life (years)	40
Average Capacity Factor (%)	85

Legend:
GREET (2022)
IEA (2020)
Hall et al. (2014)
Calculated cell

APPENDIX C – DATA AND CALCULATION SUMMARY TABLES FOR CASE 3 – COMBINED-CYCLE NATURAL GAS THERMOELECTRIC

P1 – Gas production	
Energy Inputs	
Fuel Gas kg/kg Produced Natural Gas*	0,01
Fuel Gas MJ/kg Produced Natural Gas	0,51
LCV Fuel Gas (MJ/kg)	48,91
Gross Electric Power (MW):	370,16
Required Fuel Gas kg/s (Total power-Energy Service)	14,44
Natural Gas Loss	1%
Produced Natural Gas kg/s (Total power-Energy Service)	14,59
Output	
Q_H MW	706,41
Exd (MW)	7,49
EROI	**94,30**

P2 – Transport of Gas to Gas Prossessing Unit	
Energy Inputs	
Fuel Gas MJ/kg Transported Natural Gas	-
Fuel Gas MJ/MJ electricity	-
ExIdP2 (Maritime transport) MJ/MJ electricity	0,00

P4 – Transport of Gas to Thermoeletric Unit	
Energy Inputs	
Fuel Gas MJ/kg Transported Fuel Gas	-
Fuel Gas MJ/MJ electricity	-
ExId4 MW	0,00

P3 – Gas Prossessing Unit	
Energy Inputs	
Fuel Gas MJ/kg Prosseced Natural Gas*	0,01
Fuel Gas MJ/kg Prosseced Natural Gas	0,51
Fuel Gas MJ/MJ electricity	7,42
ExIdP3 MW	7,42

P5 – Thermoelectric unit	
Inputs	
Thermoelectric unit Energy Efficiency	52,40%
Fuel Gas kg/MJ produced electricity	14,44

Natural Gas Thermoelectric Plant	
Brayton Cycle	
Net Electric Power (MW):	331
Energy Penalty (MW)	39,16
Energy Penalty (%)	12
Utilization Factor (%)	0,85
Gas Mean EROI (Hall et al., 2014)	20
Expected useful life for the thermoelectric (years)	40
Ex_O (TJ)	354906,14
Exd (TJ)	8032,57
ExROI	44,18
ExK	3510,12
CAPEX (10^6 US$)	933,54
Exid	7953,04
Ex_{OP} (TJ)	5335,06
OPEX (10^6 US$)	1418,90
T_0 (K)	298
T_{Lb} (K)	521
Q_{Lb} (MW)	336,25
EQ_{Lb} (MW)	143,94
Ex_{Env} (TJ)	154340,79
$Exco_2$ (TJ)	41988,29
ExROEEI	**1,60**
Exergy Return on Environment and Energy Investment	

Premises – Sciubba, 2011:	**Present Value (21/12/2022)**
ee_L (MJ/wh)	-
ee_K (MJ/US$)	3,76

Premises TOLMASQUIM, 2016:	**Present Value(21/12/2022)**
CAPEX (US$/kW)	2522,00
OPEX (US$/MWh)	12,87
Useful life (years)	40
Average Capacity Factor (%)	85

Legend:
GREET (2022)
IEA (2020)
Hall et al. (2014)
Calculated cell

APPENDIX D – DATA AND CALCULATION SUMMARY TABLES FOR CASE 4 – BRAYTON CYCLE BIOGAS THERMOELECTRIC

P1 – Residue collection	
Energy Inputs	
Fuel MJ/kg Residue	0,04
LCV Fuel Gas (MJ/kg)	32,49
Gross Electric Power (MW):	331,00
Required Fuel Gas kg/MJ produced electricity	29,53
Residue Loss	1%
Produced Biogas kg / MJ electricity	29,82
Output	
Q_H MW	959,42
MJ Fuel Gas/MJ electricity	12,87
ExidP1 (MW)	12,87
EROI	**19,43**

P2 – Feedstock transportation	
Energy Inputs	
Fuel MJ/kg Transported Residue	0,04
Fuel MW	12,06
ExIdP2 (transport) MW	12,06

P3 – Transport of Biogas to Thermoeletric Unit	**Considered inside the processing unit**

P4 – Feedstock processing Unit	
Energy Inputs	
Residue kg / Processed Biogas kg	10,00
Redidue kg / MJ produced electricity	295,26
Fuel Gas MJ/kg Processed Residue*	0,17
Fuel Gas MW	49,37
Exd MW	49,37

P5 – Thermoelectric unit	
Inputs	
Thermoelectric unit Energy Efficiency	34,50%
Fuel Gas kg/MJ produced electricity	29,53

Biogas Thermoelectric Plant	
Brayton Cycle	
Net Electric Power (MW):	331
Energy Penalty (MW)	0,00
Energy Penalty (%)	0,00
Utilization Factor (%)	0,85
Gas Mean EROI (Hall et al., 2014)	20
Expected useful life for the thermoelectric (years)	40
Ex_O (TJ)	354906,14
Exd (TJ)	52935,86
ExROI	6,70
ExK	1101,44
CAPEX (10^6 US$)	292,94
Exid	26731,62
Ex_{OP} (TJ)	2780,10
OPEX (10^6 US$)	739,39
T_0 (K)	298
T_{Lb} (K)	717
Q_{Lb} (MW)	628,42
EQ_{Lb} (MW)	367,24
Ex_{Env} (TJ)	393759,09
Ex_{CO_2} (TJ)	0,00

ExROEEI	**0,74**
Exergy Return on Environment and Energy Investment	

Premises – Sciubba, 2011:	**Present Value (21/12/2022)**
ee_L (MJ/wh)	-
ee_K (MJ/US$)	3,76

Premises TOLMASQUIM, 2016:	**Present Value(21/12/2022)**
CAPEX (US$/kW)	885,00
OPEX (US$/MWh)	7,50
Useful life (years)	40
Average Capacity Factor (%)	85

Legend:
GREET (2022)
IEA (2020)
Hall et al. (2014)
Calculated cell
Cardoso (2017)

APPENDIX E – DATA AND CALCULATION SUMMARY TABLES FOR CASE 4 – COMBINED CYCLE BIOGAS THERMOELECTRIC

P1 – Residue collection	
Energy Inputs	
Fuel MJ/kg Residue	0,04
LCV Fuel Gas (MJ/kg)	32,49
Gross Electric Power (MW):	331,00
Required Fuel Gas kg/MJ produced electricity	19,44
Residue Loss	1%
Produced Biogas kg / MJ electricity	19,63
Output	
Q_H MW	631,68
MJ Fuel Gas/MJ electricity	8,48
ExidP1 (MW)	8,48
EROI	**19,43**

P2 – Feedstock transportation	
Energy Inputs	
Fuel Gas MJ/kg Transported Residue	0,04
Fuel Gas MJ/MJ electricity	7,94
ExIdP2 (transport) MW	7,94

P3 – Transport of Biogas to Thermoeletric Unit	**Considered inside the processing unit**

P4 – Feedstock processing Unit	
Energy Inputs	
Residue kg / Processed Biogas kg	10,00
Redidue kg / MJ produced electricity	194,40
Fuel Gas MJ/kg Processed Residue*	0,17
Fuel Gas MJ/MJ electricity	32,51
Exd MW	32,51

P5 – Thermoelectric unit	
Inputs	
Thermoelectric unit Energy Efficiency	52,40%
Fuel Gas kg/MJ produced electricity	19,44

Biogas Thermoelectric Plant	
Brayton Cycle	
Net Electric Power (MW):	331
Energy Penalty (MW)	0,00
Energy Penalty (%)	0,00
Utilization Factor (%)	0,85
Gas Mean EROI (Hall et al., 2014)	20
Expected useful life for the thermoelectric (years)	40
Ex_O (TJ)	354906,14
Exd (TJ)	34852,81
ExROI	10,18
ExK	1924,09
CAPEX (10^6 US$)	511,73
Exid	17600,02
Ex_{OP} (TJ)	4770,65
OPEX (10^6 US$)	1268,79
T_0 (K)	298
T_{Lb} (K)	521
Q_{Lb} (MW)	300,68
EQ_{Lb} (MW)	128,70
Ex_{Env} (TJ)	137992,77
Ex_{co_2} (TJ)	0,00

ExROEEI	**1,80**
Exergy Return on Environment and Energy Investment	

Premises – Sciubba, 2011:	**Present Value (21/12/2022)**
ee_L (MJ/wh)	
ee_K (MJ/US$)	3,76

Premises TOLMASQUIM, 2016:	**Present Value(21/12/2022)**
CAPEX (US$/kW)	1546,00
OPEX (US$/MWh)	12,87
Useful life (years)	40
Average Capacity Factor (%)	85

Legend:
GREET (2022)
IEA (2020)
Hall et al. (2014)
Calculated cell
Cardoso (2017)

APPENDIX F – NOMENCLATURE

$\dot{m}f_{id_i}$ – Mass flow of each fuel (i) used indirectly as support for the process under analysis.

$\dot{E}_F$ –Exergy flux from the Source of Energy from the Fuel (in this case, a mixture of fuel and air).

$E\dot{x}_O$ – Net Electric Power.

$\dot{m}f_{d_i}$ – Mass flow rate of each fuel (i) used directly to produce the process's main source of energy.

$\dot{m}_F$ – Mass fuel flow (in this case the air/fuel mixture).

ee_K – Equivalent primary exergy resource embodied in one monetary unit.

EQ_{Lb} – Thermal Exergy from energy effluents.

$\dot{W}$ – Gross electric power.

ex_{ch} – Specific chemical exergy.

CAPEX – Specific investment costs based on the enterprise's size.

CAPEX – Specific investment costs based on the enterprise's size.

CEII – CO_2 Emission Intensity Index.

Chemical Exergy – The part of exergy related to the chemical's potential to perform out useful work.

CO_2 – Carbon dioxide.

Decarbonization – The process of reducing or eliminating carbon dioxide (CO_2) emissions from energy sources, particularly in the electricity sector. It involves transitioning from high-carbon or fossil fuel-based energy generation to low-carbon or carbon-free alternatives (GRUBB *et al*., 2008).

ee_L – Equivalent primary energy resource embedded in one workhour.

E_{in} – Worldwide inflow of energy resources.

E_K – Exergy embodied in capital.

E_L – Exergy embodied in Labour.

Emergy – It is a unit of measurement used to quantify all of the energy (direct and indirect) consumed in a system. It offers a more thorough and sustainable understanding of industrial processes and interactions between natural and human systems (ODUM, 1973).

EROI – Energy Return On Investment.

Ex_{CO_2} – Requested exergy to Carbon Capture and Sequestration (CCS).

Ex_d – Direct Exergy.

Ex_{Env} – Exergy Equivalent of Environmental Impacts.

$Ex_{Env.g}$ – Exergy Equivalent of Environmental Impacts (gaseous effluents).

$Ex_{Env.l}$ – Exergy Equivalent of Environmental Impacts (liquid effluents).

$Ex_{Env.s}$ – Exergy Equivalent of Environmental Impacts (solid effluents).

Exergy – The exergy of a system can be defined as the amount of useful and theoretical work that it can obtain when it interacts with its environment (SZARGUT *et al*., 1988).

Exergy Analysis – Exergy analysis is a method that assesses and optimizes the energy effectiveness of systems and processes using the exergy concept. It is predicated on the division of energy into two parts: exergy, the useful portion capable of performing work, and anergy, the wasted portion not capable of performing work. It is possible to locate inefficient areas, suggest modifications, and assess the energy efficiency of various options by analyzing the exergy losses in a system. Exergy analysis, which takes into account not only the quantities of energy but also their quality and utility, offers a more thorough and accurate assessment of energy efficiency (SZARGUT *et al*., 1988).

ExEROI – Extended-exergy based energy return on investment method.

Ex_{id} – Indirect Exergy.

Ex_K – Capital Exergy.

Ex_O – Output Exergy.

Ex_{OP} – Operational Exergy.

ExROEEI – Exergy Return on Environment and Energy Investment (proposed method).

ExROI – Exergy Return On Investment.

ExRR – Exergy Return Rates.

LCV – Lower Calorific Value of the fuel used.

M2 – Monetary circulation in a society.

OPEX – Specific operational costs based on the size and complexity of the energy conversion facility.

P – Extract Primary Exergy.

Physical Exergy – The part of exergy related to the physical's potential to perform out useful work.

Q_H – Heat produced.

Q_{Lb} – Heat rejected to environment.

T_0 – Environment temperature.

T_{Lb} – Temperature of flue gases.

U – Produced Useful Exergy.

W_O – Output Net Power that leaves a process and is assessed as the portion referring to the society's ultimate use (MW).

α – Econometric coefficient.

β – Econometric coefficients.

ε – Exergy Efficiency.

η – Thermodynamic efficiency.