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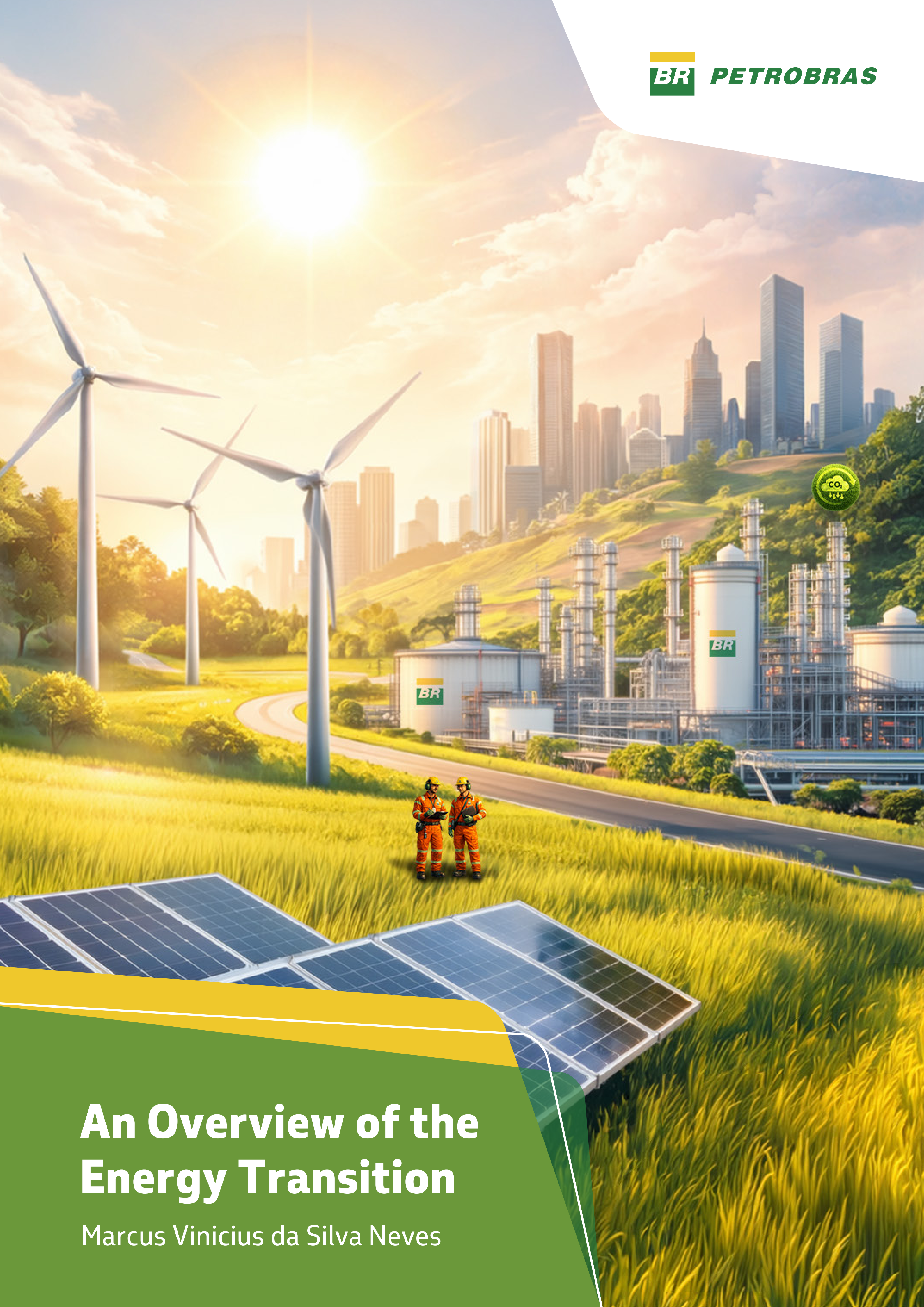

An Overview of the Energy Transition

Marcus Vinicius da Silva Neves

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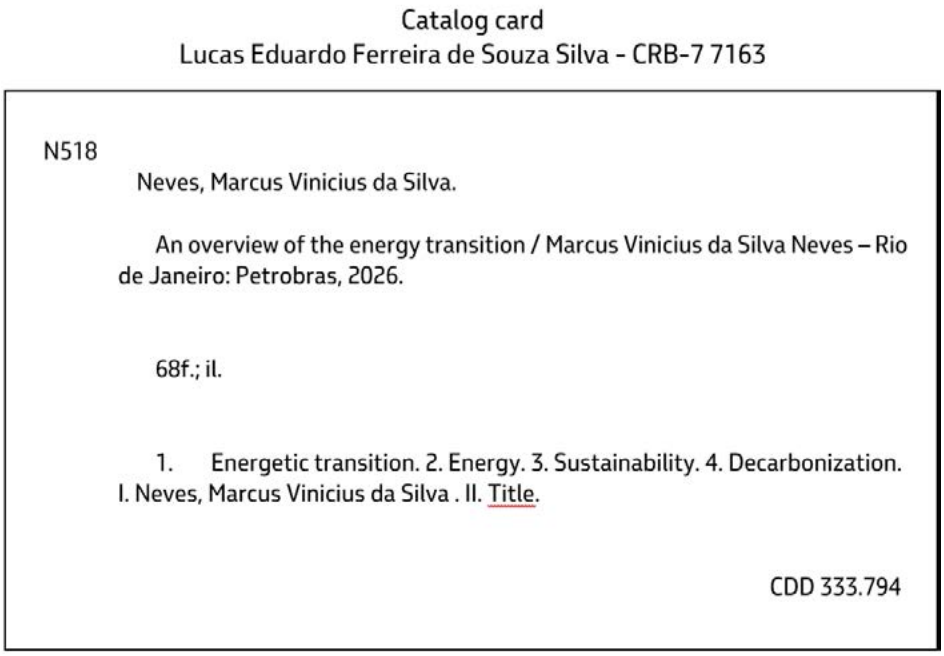

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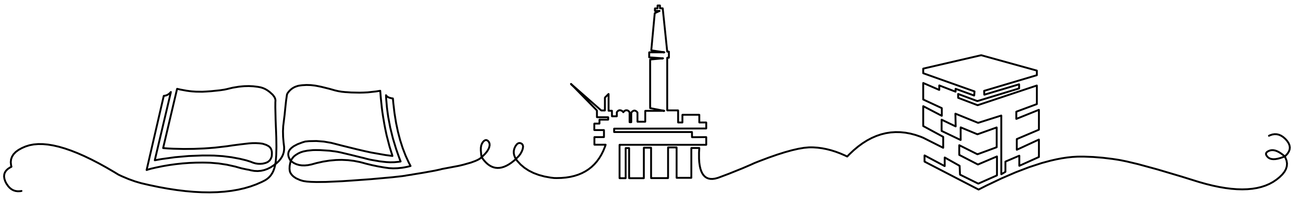

SUMMARY

Foreword

By Roberto Schaeffer and Alexandre Szklo, Full Professors, Federal University of Rio de Janeiro (UFRJ), Brazil

We live in an era marked by the confrontation of urgent needs and complex constraints. In our own work with integrated assessment models (IAMs) for climate mitigation, we often grapple with the concept of generalization—how can a system learn from the current reality of the energy and land use systems to navigate towards future, unseen possibilities? The ongoing global energy transition, the subject of this timely book by Marcus Neves, poses a similar challenge of generalization: how does humanity transition from a centuries-old paradigm of energy production and consumption, and its associated energy converters, to a potentially completely new operating state without causing the system to collapse?

The answer, as Neves eloquently argues in An Overview of the Energy Transition, is not found in simple "zero-or-one" responses. Public, and sometimes even "academic", discourse often reduces this major challenge to a duel between "dirty" fossil fuels and "clean" renewable energy sources. However, such simplifications rarely survive contact with our world reality. The energy system is a high-dimensional web of connections between energy flows and stocks, involving economics, geopolitics, social equity and thermodynamics, as well posed by Neves in his work, sometimes explicitly, sometimes implicitly. Perturbing one node of this network—such as rapidly phasing out high-density fossil fuels—may send shockwaves through the entire energy system structure.

What makes this book particularly valuable is its refusal to shy away from the thermodynamic rigor required to understand these shockwaves, which is very much a consequence of the academic background of the author. Neves anchors his analysis in the physical realities of Entropy and Exergy, concepts that are very dear to him, considering some of his previous academic works, including his doctoral dissertation. He reminds us that the economy is not a perpetual motion machine. It is a metabolic system that uses low-entropy resources and eliminates high-entropy waste. Or, quoting the classic text of Erwin Schrödinger from 1944 ("What is life?")... it is like a living organism, which "tends to approach the dangerous state of maximum entropy, which is of death. It can only keep aloof from it, i.e. alive, by continually drawing from its environment negative entropy."

By bringing the concept of Energy Return on Investment (EROI) into the debate, the author forces us to confront a difficult reality: we are attempting to move from high-EROI energy sources to historically lower-EROI sources. This "problem-driven" transition is fundamentally different from the "opportunity-driven" transitions of the past, where we moved from wood to coal, or from coal to oil (in the case of different energy carriers), or from horses to internal-combustion-engine vehicles, or from internal-combustion-engine vehicles to electric vehicles (in the case of different energy converters), largely because the new fuel, or the new converter, was thermodynamically superior. This is not the case of the ongoing global energy transition.

This is not a call for inaction, but a call for academic rigor. The book meticulously outlines the "technophobia" that clings to the past and the "technophilia" that sometimes acratically assumes technology will go around all physical limits, defying the conventional, natural, or perceived boundaries of human, technical, or environmental capacity. It proposes a trajectory that navigates the middle path—a path of "Sustainable Realism."

Neves draws on his extensive experience—spanning academic rigor at the Energy Planning Program of the Federal University of Rio de Janeiro, where he got his Ph.D., and practical leadership at Petrobras, where he has been working for more than two decades—to offer a roadmap that is both ambitious and well grounded. He explores the critical role of Carbon Capture and Storage (CCS) and Nature-Based Solutions (NbS) not as excuses to prolong the status quo, but as essential mechanisms to maintain the global energy system stability and economic viability while we build the infrastructure of the future, avoiding unnecessary and undesirable ruptures. Also, he highlights the often-overlooked possible bottlenecks of critical and strategic materials and geopolitical reshufflings that may arise from the new energy system that will likely emerge, if it is not emerging yet.

For readers approaching this subject from a technical background, the book offers a sufficiently robust framework that integrates Life Cycle Analysis (LCA) and systems thinking. For those coming from a more policy or social science perspective, it provides a convincing rational of why physical constraints matter for social justice. The sometimes-forgotten concept of the "Tunnel Effect"—allowing developing economies to leapfrog the fossil-carbon-intensive phase of development—is particularly evoking for those of us living in, or concerned with, the developing world.

Ultimately, this book serves as a bridge to connect where we stand now with the future we want to be. It associates the unquestionable laws of thermodynamics with the fluid, and sometimes unpredictable, dynamics of our human society. It endorses a portfolio approach—diversification over dogma—reminding us that our goal is not merely to modify the fuel mix per se, but to defossilize our global economy while preserving the energy services that make modern societies possible.

Marcus Neves goes beyond the provision of a summary of energy-system-related sources and technologies. He provides us with a framework that can help us all think about one of the greatest challenges of our time: the need for soft-landing the ongoing global energy transition. His book is a valuable companion for anyone—engineer, policymaker, or student—who wishes to understand not just where the energy transition is heading to, but also where it will take us and at what costs.

ACKNOWLEDGMENT

A challenge like this one-off writing a book on a subject with so many variables and uncertainties, is something impossible to be carried out completely individually. Several people contributed, each in their own way, to this goal. Thus, I record here my sincere thanks to some of these special people:

To the doctoral professors in the Energy Planning Program at COPPE/UFRJ for the information provided for academic training, materials provided and inspiring reflections, especially to my advisors Alexandre Salem Szklo and Roberto Schaeffer, as well as to professor Emílio Lebre La Rovere.

To Sonia and Jurandir Neves, my parents, for constantly showing me the path.

To my friend and coworker Antonio Felipe Flutt, who encouraged me to bring up the subject at company-wide internal training sessions.

To my wife Daniele Neves, who has courageously met each of our obstacles so far.

To Carol and Marquinhos Neves, my children, for being endlessly inspiring.

And once more, thanks to my son Marquinhos Neves and Melissa Walesko Payola Araujo for formatting, editing, and rewriting the content of the original manuscript in Portuguese.

With the utmost love,

Marcus Neves

ABOUT THE AUTOR

Marcus Vinicius da Silva Neves is a Mechanical Engineer graduated from the Federal Center of Technological Education of Rio de Janeiro (CEFET/RJ, 2001) and Hochschule München, Germany (2001). He holds a postgraduate degree in Oil and Gas Equipment Engineering from PETROBRAS (2003), a master's degree in mechanical engineering from COPPE/UFRJ (2008) and completed his doctorate in Energy Planning at COPPE/UFRJ in 2024. Marcus is also a Certified Energy Manager accredited by the Association of Energy Engineers (AEE).

With approximately 23 years of experience at PETROBRAS, Marcus has held key positions in energy efficiency, maintenance engineering, operational safety, and reliability engineering. His significant contributions include developing PETROBRAS's first corporate guidelines and standards for energy efficiency, methodologies for offshore platform life extension, and processes for Exploration and Production (E&P) maintenance.

Marcus has served in leadership roles as Offshore Installation Manager (OIM) and Maintenance Engineering Manager, guiding large multidisciplinary teams in challenging operational contexts. Currently, he is the Manager of Schools at Petrobras University, overseeing training in Equipment and Processing Engineering. He actively contributed to academia as a postgraduate collaborator professor at Fluminense Federal University (UFF), Rio de Janeiro Federal University (UFRJ), and the Catholic University of Petropolis (UCP), among others.

Marcus has authored technical publications focusing on energy efficiency, including books published by Interciência (Eficiência Energética na Produção de Petróleo e em Centrais Termelétricas - 2018) and Springer (Energy Efficiency in Oil Production – 2024 and Offshore Operations Engineering: A Useful Guide for the Offshore Worker - 2025), and some articles in prominent scientific journals.

'The book also serves as a guide for articles that go deeper into subjects that are part of the Energy Transition universe.'

PEER REVIEW - REVIEWER'S NOTE

Reading this book was an intellectually stimulating and insightful experience. Marcus achieves something rare here: he manages to articulate, in an accessible and didactic way, the technical, economic, and social foundations of the energy transition — one of the greatest challenges of our time. The author uses some of the best available references and brings them together with insights developed throughout his academic and professional journey, particularly during his doctoral research.

The result is a clear and well-structured text that combines conceptual depth with a fluid and engaging narrative. Throughout the chapters, readers will find consistent discussions on the role of energy in modern society, the physical and economic limits of the transition, and the urgency of rethinking our production systems through the lens of sustainability.

One of the book's main strengths lies in its ability to balance technical rigor with accessibility. Even when addressing complex topics — such as entropy, exergy, or scenario modeling — Marcus provides intuitive explanations that bring readers closer to key concepts in thermodynamics and energy planning.

Another highlight is the section dedicated to transition scenarios, which invites readers to reflect on the multiple futures ahead as the world faces the imperative of decarbonizing its economy. The conceptual update and dialogue with recent frameworks, such as the Shared Socioeconomic Pathways (SSPs), make the text particularly relevant and contemporary.

This is a book that fulfills an essential role: translating the debate on energy transition into an accessible, informative, and inspiring work. It reflects not only Marcus's technical mastery but also his ability to communicate complex ideas with clarity and meaning. A remarkable contribution that deserves to be read and discussed.

Reviewer - Fábio Teixeira Ferreira da Silva

ABOUT THE REVIEWER

Fábio Teixeira Ferreira da Silva holds a D.Sc and a Master's degree in Energy Planning from Coppe/UFRJ, where he is currently an Assistant Professor at the Energy Planning Program (PPE) in the area of Energy Transition and Sustainability. He is a Chemical Engineer from Fluminense Federal University (UFF) and completed an academic exchange year at Hochschule Ruhr-West (HRW), Germany, where he studied Industrial Engineering – Energy Systems. He also works as a researcher at Cenergia Lab.

His research focuses on the modeling and assessment of decarbonization pathways, energy transition policies, and carbon dioxide removal (CDR) technologies such as biochar, BECCS, and enhanced weathering. He has led and collaborated on multiple applied research projects and technical consultancies with the public, private, and non-profit sectors, addressing topics such as climate policy design, renewable energy integration, and industrial decarbonization. Notably, he served as Technical Coordinator of the Pernambuco Decarbonization Plan (Plano Clima Pernambuco) for GIZ/UNEP and has contributed to several national and international initiatives related to long-term low-emission development strategies.

Fábio has extensive experience in biotechnology, renewable energy systems, biorefineries, and carbon capture, transport, and storage technologies, with a strong interest in the techno-economic modeling of low-carbon technologies and integrated energy-land-use systems. He has authored and co-authored several peer-reviewed publications in these areas, contributing to international literature on sustainable energy transitions. He also acts as a peer reviewer for numerous high-impact international journals, including Applied Energy, Nature Communications, and Environmental Research Letters, among others.

PETROBRAS UNIVERSITY TOTAL SUPPORT TO THIS PUBLICATION

The energy transition is one of the defining challenges of our time. It is not merely a technological shift, but a profound transformation that intersects engineering, economics, environmental stewardship, social equity, and geopolitics. Addressing such a complex challenge requires more than rapid answers or simplified narratives; it requires rigorous knowledge, critical thinking, and the ability to connect physical realities with strategic decision making. It is precisely in this context that An Overview of the Energy Transition makes a valuable and timely contribution.

Petrobras has accumulated, over decades of operation and innovation, a unique body of technical and organizational knowledge. This knowledge is the result of the experience, creativity, and commitment of its people, developed at the interface between theory and practice, academia and industry. Petrobras University plays a central role in preserving, structuring, and disseminating this intellectual capital, ensuring that it continues to generate value for the company, for professionals in the energy sector, and for society as a whole.

This book exemplifies that mission. Drawing on solid academic foundations and extensive professional experience, the author offers a balanced and intellectually honest view of the current energy transition. Rather than treating the transition as a simplistic substitution of fuels, the book frames it as a systemic challenge: one that must reconcile decarbonization with energy security, affordability, and social justice, while respecting the physical limits imposed by thermodynamics. By integrating concepts such as Energy Return on Investment (EROI), exergy, life cycle analysis, and scenario thinking, the work equips readers with analytical tools that are essential for navigating the uncertainties ahead.

In this sense, this work will certainly contribute directly to Petrobras University learning solutions. Especially, contributing effectively to one of our thirteen academies: the Decarbonization and Energy Transition (DET) Academy. One of DET Academy's core objectives is to foster critical mass within the company on energy transition topics, enabling informed decision making and strategic leadership in a rapidly evolving energy landscape. This book stands as a robust reference to support that objective, strengthening both individual capability development and collective organizational learning.

The publication of this volume under PELD (Programa de Editoração de Livros Didáticos), our Textbook Publishing Program, reflects Petrobras University's commitment to structured knowledge management. PELD was created to recognize and value the technical expertise developed within

Petrobras, transforming it into high quality educational material that supports training, continuous learning, and dialogue with the broader academic and professional communities. Through this program, internal knowledge is not only preserved but also shared, challenged, and expanded.

For Petrobras, this book reinforces a culture of technical excellence and critical reflection, supporting the development of professionals capable of engaging with the energy transition in a responsible and informed manner. For readers beyond the company, it offers an accessible yet rigorous entry point into one of the most complex debates of the 21st century, encouraging a portfolio based, realistic, and socially conscious approach to decarbonization.

Petrobras University is proud to support the publication of An Overview of the Energy Transition. We believe it will serve as a lasting reference for engineers, policymakers, researchers, and students who seek not only to understand where the energy system is heading, but also to reflect on how today's choices will shape a sustainable and equitable future.

Robson Campos Leite
Petrobras University
General Manager

1- Introduction

The book **An Overview of the Energy Transition** dares to present a broad panorama of the aspects related to what is arguably the greatest challenge humanity has ever faced. At the same time, it carries the humbleness of recognizing that it is impossible to cover every question or anticipate all possible outcomes in a problem shaped by countless variables and unpredictable combinations. Rather than striving for exhaustiveness, the book seeks to provide a useful and accessible guide, combining key concepts and references to leading authors and publications. It is intended for professionals, students, and interested readers who wish to deepen their understanding of energy transition through concise analyses supported by reliable sources.

The chapters are organized to progressively build this overview. Section 2 discusses why the current transition is fundamentally different from all others in human history. Section 3 expands on this by presenting the unique paradigm of today's energy transition, presenting the concepts of exergy and EROI. Section 4 explores the connection between energy, economy and society, grounding the analysis in thermodynamic and ecological principles. Section 5 turns to history and projections, tracing how energy use has evolved and what scenarios lie ahead. Section 6 highlights the environmental impacts of human activities, especially the dynamics of pollution. Section 7 introduces the vision of the Great Transition Initiative, examining alternative global scenarios. Section 8 focuses on the opportunities and challenges facing oil in the context of deep decarbonization, including the limitations of EROI as a metric. Section 9 brings the discussion to the forefront of contemporary debates by addressing the systemic need to decarbonize the economy, integrating issues of energy justice, critical minerals, hydrogen, CCS and nature-based solutions. Finally, Section 10 offers concluding reflections, emphasizing the complexity of the transition and the need for integrated, equitable strategies.

Taken together, these sections are designed to provide a coherent guide to the key dimensions of the energy transition, while also serving as an entry point to the broader literature for readers who wish to explore specific topics in greater depth.

GOOD READING!

2 - Why is the current transition different?

Because environmental concerns about the use of fossil fuels and their effect on climate change, rather than technological or economic motives, are driving the present energy transition, it differs from previous ones. Electricity and fossil fuels have helped the contemporary world flourish, yet only a small portion of the world's population completely or considerably benefits from them, and the gap between rich and poor countries has not greatly shrunk (Smil 2004). A crucial step towards reaching climate stability is a structural shift towards a low-carbon economy, which is becoming more and more apparent on Earth (Foxon et al. 2008; Grubb et al. 2008).

The current energy transition is strongly tied to the objective of reducing GHG emissions from fossil fuels in the world energy system, or the so-called "decarbonization of the economy". Fossil fuels will likely continue to play a substantial role in the global energy system for some time to come, therefore the task is tremendous (Sovacool 2015). It is important to emphasize that the global scale environmental challenge, rather than technological or economic performance advantages of the energy systems, is the main driver of the current energy revolution.

All the advancements that have had significant personal and social effects, including freeing hundreds of millions of people from physically demanding employment, increased health and life expectancy, widespread reading adoption, and wider access to material goods. Only 15% of the world's population, however, truly or significantly benefits from these advantages. The enormous energy revolutions of the past century have also raised living standards worldwide. Yet, the disparity between rich and poor countries has not considerably shrunk. For instance, more than 40% of total commercial primary energy use in 2000 was accounted for by the richest 10% of the global population (Smil 2004).

While environmental concerns are driving the present energy transition, it also has significant effects on global politics and socioeconomic advancement. The need to eliminate energy poverty and give everyone access to clean, cheap energy is a crucial component of the transition. The Sustainable Development Goals (SDGs) and the reduction of global greenhouse gas emissions must both be attained by 2030, according to the International Energy Agency (IEA 2021).

Geopolitics and the world's energy markets will be significantly impacted by the shift to a low-carbon economy. Moving away from fossil fuels would have significant economic and social repercussions, particularly for nations that are strongly dependent on oil and gas exports, according to the International Monetary Fund (IMF 2020). Traditional energy companies may struggle to preserve market share and influence as renewable energy sources grow more competitive and new technologies are developed. At the same time, the transition may open up new possibilities for nations and businesses that are well-positioned to benefit from the dynamic energy market. One central dimension of this geopolitical reconfiguration lies in the rising demand for critical minerals; such as lithium, cobalt, and rare earth elements; whose extraction and supply chains will increasingly shape the pace and fairness of the energy transition. This issue is addressed in Section 9.6, which discusses hydrogen, critical minerals and storage economics in greater detail.

To achieve climate stability, a structural shift to a low-carbon economy is essential (Intergovernmental Panel on Climate Change — 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 and Cleveland 1981). However, other studies (Fouquet and 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 and 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 CO2 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 and 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 notion 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 and 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.

The necessity for massive investments in new infrastructure and technology is one of the major obstacles facing the energy transition. The Shared Socio-Economic Pathways (SSP), developed by the Intergovernmental Panel on Climate Change (IPCC), highlight the necessity of significant changes in energy systems, including the creation of new energy sources and storage technologies, enhancements to energy efficiency, and the expansion of low-cost systems of carbon transport (Riahi et al. 2017). While these investments are essential to achieve the targets of the SDG and the Paris Agreement, they also necessitate substantial financial resources and political efforts, as well.

Some experts are urging a more comprehensive strategy for the energy transition that takes into account social, economic, and environmental factors in order to address these issues. This strategy, often known as "energy justice," emphasizes the demand for a fair distribution of transitional costs and benefits and acknowledges the significance of local communities and their expertise in forming energy systems (Sovacool et al. 2020). It might be feasible to create a more egalitarian and sustainable energy future by engaging a wider diversity of perspectives and values into decision-making about energy.

The idea of the "circular economy"[1] as a means of lowering waste and emissions is one factor to be considered in the present energy transition. The circular economy paradigm advocates preserving the useful life of materials and resources, minimizing waste and pollution through material recycling and reuse, and reducing carbon intensity across economic sectors. With the idea of retrieving low-carbon energy carriers from waste heat and integrating carbon capture technologies, this strategy is gaining popularity in the energy sector (Ellen MacArthur Foundation 2021).

Furthermore, the transition can also be analyzed in terms of two pathologies associated with technology. The first pathology, technophobia, can be seen as the resistance to the energy transition from the part of some stakeholders. The unquestioning acceptance of renewable energy sources reveals the second, technophilia. Technophobia is seen when energy industry stakeholders oppose the switch to renewable energy sources out of concern for how it will affect their company. This is especially true for fossil fuel companies, which may exert tremendous political and economic influence. They may advocate against laws that support renewable energy sources or disseminate false information about their efficacy. On the other hand, the technophilia picture can be seen when renewable energy sources are assumed to be the perfect solution to all energy-related issues without taking into account any potential drawbacks. As a result, compli-

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[1] The term "circular economy" refers to an economic model that seeks to minimize waste and keep resources in use for as long as possible. In the energy sector, this means reusing materials (such as metals from batteries), recovering waste heat from industrial processes, and integrating technologies like carbon capture to reduce greenhouse gas emissions. The goal is not only to recycle products, but to close energy and material loops in ways that reduce carbon intensity and improve efficiency across the whole system.

cated energy concerns may become oversimplified, and the efficacy of renewable energy sources may be overestimated. However, if these technologies involve extensive land conversion, they may have detrimental effects on biodiversity, land use, and food security.

Electric cars provide yet another illustration of the structure of technophilia. Although electric vehicles are marketed as a more environmentally friendly alternative to conventional combustion engine vehicles, their production has a substantial negative impact on the environment. Lithium-ion battery production for electric automobiles, for instance, uses a lot of energy and water and can produce a lot of greenhouse gas emissions. Additionally, the recycling of electric vehicle batteries is still in its infancy, and there are worries about the possible environmental effects of disposing spent batteries on a wide scale. In conclusion, the energy transition analysis can be used to detect both technophobia and technophilia. While switching to lower-GHG sources is essential for combating climate change, it is also necessary to account for any potential drawbacks of renewable energy sources and make sure the switch is handled responsibly and sustainably (Sovacool 2014).

Another thing to think about is how energy storage technology can help with the energy shift. In order to balance energy supply and demand, stabilize grids, and enable the integration of sporadic renewable energy sources, energy storage technologies like batteries, pumped hydroelectric storage, and hydrogen fuel cells are becoming more and more crucial (IEA 2021).

While it is undeniably vital to reduce greenhouse gas emissions, the present energy shift may not be the most efficient or fair way to do so. Critics claim that the potential for cleaner and more effective use of conventional energy sources is overlooked in the focus on renewable energy sources and the eradication of fossil fuels.

For instance, natural gas has been presented as a “bridge fuel” to a low-carbon future because it emits less carbon dioxide than coal or oil. In addition, recent advances in carbon capture and storage technology may enable the continued use of fossil fuels with reduced emissions.

Analysts also point out that the current energy transition disproportionately affects low-income countries and communities. Developing nations may lack the financial and technological resources to switch to renewable energy sources and may rely heavily on traditional fuels for economic growth. Furthermore, moving away from fossil fuels could exacerbate existing energy poverty by raising energy costs and reducing access to reliable electricity.

Some experts propose a more inclusive and gradual strategy that takes into account the particular requirements and difficulties of many nations and communities, as opposed to a quick shift away from traditional energy sources. In addition to initiatives to increase energy efficiency and broaden access to power, this may incorporate a combination of renewable energy, natural gas, and carbon capture and storage.

Similar to this, Cronin et al. (2021) propose a transdisciplinary research agenda to include justice in the shift to a low-carbon economy in keeping with the objective of limiting global warming to 1.5°C. The authors contend that the energy transition must take into account the social and political ramifications involved and cannot be seen as a purely technological or commercial issue. The suggested study program covers issues including the fair allocation of transitional benefits and costs, the democratic participation of impacted communities, the consideration of gender and racial perspectives, the compatibility with human rights, and global climate justice. The authors stress the significance of a transdisciplinary approach that incorporates interaction between several fields of study and involvement of various social groups impacted by the transition. A fair and sustainable energy transition that considers the difficulties and complexities of this process is the goal of the suggested research program.

The article also discusses how the transition may result in a new type of carbon colonization, where wealthy nations and multinational corporations exploit resources in developing nations to meet their own emission reduction targets without taking local communities and the environment into account. In order to prevent this from happening, the article makes the case that it is essential to address climate justice and make sure the transition is fair and inclusive.

As we can see, this is an extremely complex problem with a great number of variables, and there is no easy way to solve it. Instead, to determine the best course for any nation or region, a thorough modelling of local circumstances is required. The need for rare metal mining to power the economy's growing electrification, which could lead to geopolitical conflicts, the concentration of new energy conversion technologies in wealthy nations or organizations, which could lead to even greater disparities between the socioeconomic conditions of developed and developing nations, and other factors are undoubtedly not addressed or fully described in this publication. As a result, we caution the reader to never believe anything magical when it comes to a straightforward approach to issues related to the energy transition.

At this point, it is important to warn about two key points that can bring difficulties to the energy transition: Critical-Mineral Bottlenecks and the Rise of Green Hydrogen Meeting net-zero targets will require an unprecedented build-out of batteries, wind turbines, solar panels, electric vehicles, and grid hardware—all of which depend on critical minerals such as lithium, nickel, cobalt, rare-earth elements, and copper. These supply chains are highly concentrated geographically, environmentally intensive, and vulnerable to price shocks, creating new geopolitical fault lines even as they enable decarbonization.

In parallel, green hydrogen—produced from water electrolysis powered by renewables—is emerging as a flexible energy carrier for hard-to-abate sectors (steel, fertilizers, long-haul transport, maritime bunkering). Scaling it up, however, requires massive additions of zero-carbon electricity, dedicated storage and pipeline networks, and internationally harmonized certification of "green" molecules.

A credible transition pathway must therefore couple rapid renewable deployment with:

- responsible mining standards, recycling, and circular-design strategies to ease mineral-supply constraints;

- coordinated innovation and investment to lower green-hydrogen costs and build global markets for its derivatives (ammonia, methanol, e-fuels).

Without such integrated planning, mineral bottlenecks could slow technology roll-out, and the hydrogen economy could remain niche—jeopardizing both climate goals and equitable development.

Want to know more?

Here are some articles worth reading:

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3 - 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 understood. 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[2] 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 and 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 CO2 emissions is a recent major challenge that drives the energy transition (Fouquet and 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 and 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).

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[2] Exergy represents the maximum useful work that can be extracted from a system as it moves towards equilibrium with its environment. Unlike energy, which is always conserved, exergy measures "energy quality": some forms (like electricity) can be fully converted into work, while others (like low-temperature heat) cannot.

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 and 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 and Pearson 2012).

In conclusion, the current energy transition is distinct in its urgency, given 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, such 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.

Let’s summarize the last two sections? Why is the current transition different? And the current energy transition: a different paradigm.

So, why is the Present Energy Transition Unique?

The transition now under way is problem-driven, climate-constrained, and equity-minded—three attributes that set it apart from earlier, opportunity-driven energy revolutions.

- Problem-driven: for the first time, the prime motivation is not the search for cheaper or denser fuel but the imperative to cut greenhouse-gas emissions rapidly enough to avoid dangerous climate change.
- Climate-constrained: high-carbon, high-density fossil fuels must give way to low- or zero-carbon alternatives even when the latter deliver lower energy density or less favorable short-term economics.
- Equity-minded: the transition must expand access to modern energy for the billions still below basic consumption thresholds while not only phasing out the fossil fuels that powered past industrialization but also actively reducing their overall use. As York and Bell (2019) emphasize,

simply adding new renewable energy sources does not guarantee a real transition unless there is an actual decline in fossil fuel consumption rather than just growing overall energy supply.Meeting all three goals simultaneously means redesigning energy systems—not merely swapping fuels. Infrastructure must handle variable renewable electricity, new value chains for hydrogen and critical minerals, and a circular-economy approach to materials. These coupled technological and social challenges make the current transition qualitatively different from the shifts from wood to coal or from coal to oil, which unfolded over many decades without an external carbon budget or a global justice mandate.

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4 - Energy, Economy and Society

The flow of energy from the sun to its use on Earth is a process of increasing entropy[3] . The sun takes low entropy energy from nuclear fusion and converts it to higher entropy energy in the form of visible light. Life on Earth then takes this higher entropy energy and converts it into even higher entropy energy, like infrared photons. Therefore, the mission of life can be seen as a continuation of the mission of the stars in the universe.

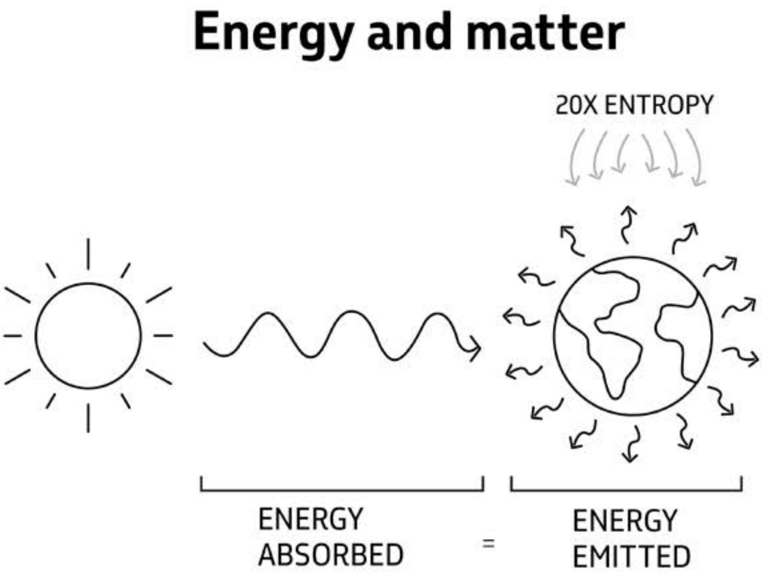

Figure 1 – Energy from the Sun Absorbed x Emitted by the Earth

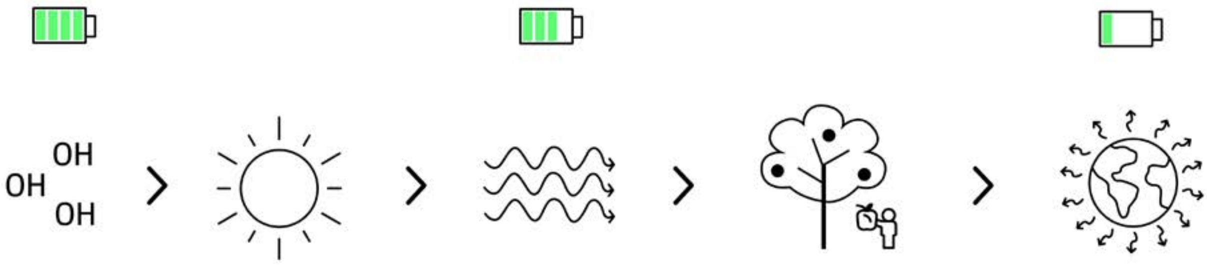

Figure 2 – Flow of Energy from the Sun to the Conversions on Earth

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[3] Entropy is a thermodynamic property that describes the degree of disorder in a system. Higher entropy means greater dispersal of energy, reducing the ability to convert that energy into useful work.

Want to know more?

Bejan A, Zane JP (2013) Design in Nature: How the Constructal Law Governs Evolution in Biology, Physics, Technology, and Social Organizations. Anchor Books.

Current economic models, on the other hand, do not take into consideration the irreversibility of thermodynamic processes or the reduction in the stock of matter and energy with low entropy. The second law of thermodynamics states that any process of production results in a change from an order with a lower entropy to an order with a bigger entropy. The field of economics, in contrast, is predicated on profit and unbridled expansion, disregarding the environment's capacity to sustain such flows without eventually collapsing. Georgescu-Roegen (1971) argues that in order for economic research to advance, it needs to consider the constraints posed by the environment and identify boundaries for theories of economic growth that predict limitless expansion. The unrestricted exploitation of natural resources and the aggravated contamination of the environment must be reduced, and it is essential that new approaches be developed to accomplish this. This necessitates the intervention of political and social agents, such as corporations, governments, and society, to modify their pattern of interaction with the surrounding environment. The gravity of the environmental crisis and the finite nature of the resources with low entropy needs to be brought to the attention of society.

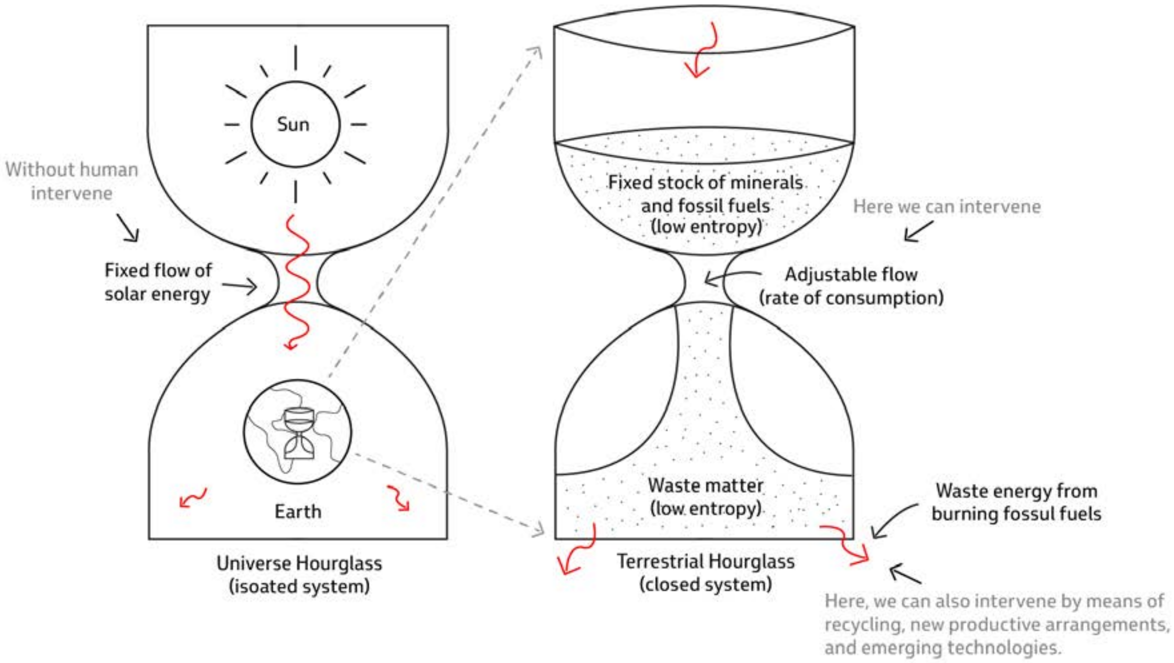


Figure 3 – Sun x Earth Open System and Control Volume of Matter and Energy on Earth

Did you like it? Here is an interesting read: Georgescu-Roegen N (1971) The entropy law and the economic process. Harvard University Press, Cambridge

The short-term rationale of economic activities divorced from ecology and the development of socially manufactured wants lead to an increase in strain on non-renewable, renewable, and "free" resources, which leads to the destruction of the ecological balance by man. This predicament was made worse by the Industrial Revolution, which fueled the growing market and wealth accumulation. As a result, nations like the United States, which only have 7.5% of the world's population, use 37% of the energy produced globally and a third of the nonrenewable resources globally each year. The primary cause of the current ecological disaster has been the unrestrained chase of immediate profit without taking into account the long-term effects on the ecosystem.

Learn more at:

Leff E, Orth LME (2015) Saber ambiental: sustentabilidade, racionalidade, complexidade, poder. Vozes, Petrópolis

and

Lago A, Pádua JA (1984) O que é Ecologia. Brasiliense, São Paulo

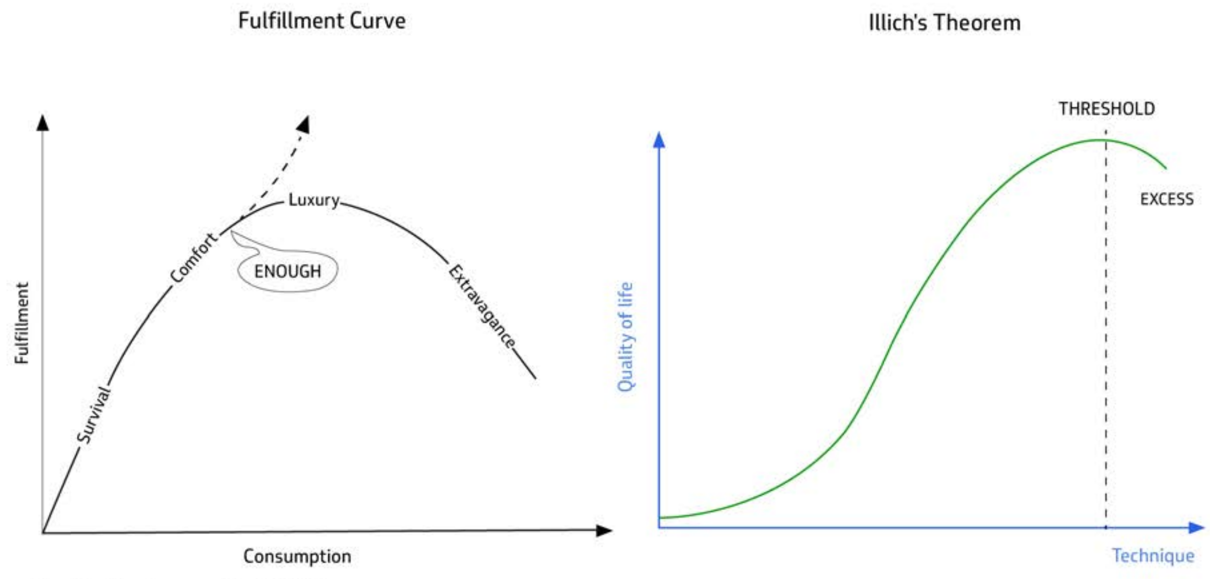
The disparities in annual energy use per person around the globe are striking and concerning. While more than 3 billion people worldwide consume less than 50 Giga Joule per year (per capita), particularly the poorest areas, other countries, like the United Kingdom and the United States, have extremely high consumption rates of more than 135 GJ per year. When taking into account that poorer people typically have fewer efficient energy converters, which raises inequality in terms of available useful energy, this discrepancy is made much more pronounced. Achieving global energy sustainability will be quite difficult given the disparity in energy distribution across the globe.

Interested? Look:

Smil V (2020) World History and Energy. Westview Press, Boulder

To illustrate the connection between the intensification of production and consumption and the decline in system efficiency, Ivan Illich, one of the key critics of industrial society, developed the idea of counterproductivity. Illich (1973) contends that productivity gains above a certain threshold have a negative impact on societal gains, rendering the system ineffective.

An illustration of the inflection point of the quality of life curve, where rising technology and production become counterproductive, is used to explain Illich's counterproductivity theorem.



Based on Dominguez and Robin (1992)

Figure 4 – Satisfaction Curve and Illich's Theorem

Illich applies this concept to demonstrate how expanding different facets of modern society—including healthcare, transportation, and education—beyond a certain point, no longer generates substantial social advantages. According to education theory, for instance, learning does not improve if a particular amount of information is reached. Individual transportation does not promote quality of life when a growth in automobiles causes traffic and pollution, just as excessive medication might be counterproductive in the desire for a quality living. It is possible to tie the ecosystem evolution curve, which also has a growth limit, to Illich's counterproductivity curve. Both curves demonstrate that raising inputs or technology can be advantageous up to a certain point, but that efficiency declines and becomes counterproductive beyond that point. This contrast is crucial for comprehending how society and the environment interact because it demonstrates how rising production and consumption can result in ecosystem degradation.

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5 - HISTORY AND PROJECTIONS

This section is based on the U.S. Annual Energy Outlook 2023 from Energy Information Administration (EIA) and in the Renewables 2023 from the International Energy Agency (IEA).

Since the Industrial Revolution, civilization has been more and more reliant on non-renewable energy sources like coal, oil, and natural gas to power economic expansion and raise standard of living, with negative effects on the environment and public health. The development of cleaner, more effective technologies, such wind, solar, and biomass energy, started in the 1970s.

Despite these developments, one of the primary contributors to global warming is the energy sector's emissions of greenhouse gases, particularly carbon dioxide (CO2). The energy sector's CO2 emissions increased by more than 300 times between 1900 and 2020, primarily as a result of rising energy consumption brought on by population expansion, industrialization, and urbanization.

Fossil fuels like oil, coal, and natural gas replaced earlier energy sources like firewood and charcoal to become the primary energy sources in the globe during the 20th century. Since burning these fossil fuels produces significant volumes of greenhouse gases, this change in the energy matrix has sped up the emission of CO2. The energy sector's CO2 emissions are still rising at the beginning of the 21st century, but renewable energy sources are also beginning to gain ground.

One of the biggest environmental issues in the world today is the CO2 emissions from the energy sector. There are global initiatives promoting the adoption of renewable energy sources and the enhancement of energy efficiency, even if the transition to a more sustainable energy matrix is still a problem. To meet this challenge and provide a more sustainable future for future generations, collaboration is required.

Renewable energy sources are expected to expand by an average of 12% over the next ten years, according to projections. Yet, overall global energy consumption is still rising, especially in developing nations. In order to fulfil the growing demand without lowering the standard of living for future generations, it is crucial that businesses in the energy sector invest in more efficient technologies and renewable energy sources.

Depending on regional circumstances and governmental energy policy, there is energy growth everywhere in the world. With the swift economic growth of China and India as a highlight, the Asia region is recognized as a leader in energy growth. However, other regions of the world, including Latin America and Africa, are also seeing an increase in energy demand. It is also emphasized that there is a growing interest in renewable energy sources, which means that the expansion of energy is not necessarily linked to an increase in the consumption of fossil fuels.

Consequently, the shift to a more sustainable energy matrix is becoming a more pressing worldwide issue. Many nations are reconsidering their reliance on fossil fuels and considering cleaner, renewable options as a result of the need to cut greenhouse gas emissions and minimize the effects of climate change.

It is a difficult and complicated task involving several entities, including governments, businesses, civil society, and consumers. To make it possible, funds must be allocated to the study and creation of cleaner and more effective technologies. Public policies that stimulate the use of renewable energy sources and the advancement of energy efficiency must also be supported.

Renewable energy sources include solar, wind, hydropower, geothermal, and biomass are some of the most promising. Due to declining production costs and incentive policies implemented by several nations, the use of solar and wind energy in particular has increased dramatically in recent years. In many regions of the world, hydropower is still a significant source of renewable energy, even though it usually has negative environmental and socioeconomic impacts.

The interaction between society and energy consumption is a crucial factor to consider in addition to technical and financial concerns. The amount of energy consumed, and the number of natural resources used can be greatly influenced by how people use it. For waste reduction and the adoption of more sustainable behaviors, increasing consumption awareness among the populace is crucial. Regarding the future of energy consumption, there are still a lot of unknowns, like the evolution of demand, the evolution of source prices, the accessibility of cleaner and more efficient technologies, among others. When deciding on future energy and environmental policy, it is essential to research these uncertainties.

Below are references for those who wish to delve deeper into history and projections of energy consumption and production:

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US Energy Information Administration (2023) Annual Energy Outlook. https://www.eia.gov/outlooks/aeo/. Accessed 6 Oct 2025

6 - IMPACTS OF HUMAN ACTIVITIES

One of the most detrimental effects of human activity on the environment is pollution. This needs to be considered when there is discussion about energy transition because the implications are directly related to energy conversion technology.

Modern high-energy civilization is a major contributor to environmental pollution and ecosystem degradation and may even be endangering the preservation of a biosphere that is habitable. The average annual per capita gross supply of commercial energy has more than quadrupled from just 14 GJ to nearly 60 GJ, despite the world's population nearly quadrupling from 1.6 billion in 1900 to 6.1 billion in 2000. In Japan, the use of energy per person has more than quadrupled to just over 170 GJ/year, while in China, where fossil fuel use per person was exceptionally low in 1900, it increased 13 times between 1950 and 2000, from just over 2 to 30 GJ/year. In the United States, energy use per person has more than tripled to about 340 GJ/year (Smil 2004).

Basically, opulence and misery are two separate causes that contribute to pollution.

The "pollution of misery" is mostly produced by organic waste and garbage and is brought on by a lack of sanitary conditions, as well as poor living and working situations.

Modern manufacturing processes and the urban tertiary industry are to blame for the "pollution of opulence". Chemical surplus and garbage amassed from elite consumption and waste are its main agents.

Additionally, pollution has an impact on biodiversity, human health, and the quality of the air, water, and soil. Human-caused emissions of harmful gases can seriously harm one's health, including respiratory, cardiovascular, and cancer conditions. There are several levels of water pollution, ranging from simple nutrient overload to deadly chemical waste pollution. On the other hand, trash from the use of agricultural chemicals, as well as trash from large cities polluting vast areas, especially vacant lots and garbage dumps, as well as activities like ore extraction, processing, and smelting, are the main causes of soil contamination. Radioactive elements discharged into the environment because of nuclear power plant accidents, nuclear bomb tests, radioactive contamination in the waters nearby power plants, and uranium mining operations, in addition to "atomic waste," are the main causes of radioactive pollution. Given that many harmful substances can seep into groundwater, this contamination degrades soil quality and has an impact on human health. The use of clean, renewable energy sources, proper waste disposal, and stricter inspection and management of industrial and agricultural activities are all required preventive steps to reduce pollution.

Table 1 – Relationship between Environmental Problems, Sources and Affected Public

Environmental Problem	Main Source of the Problem	Main Affected Group
Urban air pollution	Energy (industry and transport)	Urban population
Indoor air pollution	Energy (cooking)	Rural poor
Acid rain	Energy (fossil fuel combustion)	Everyone
Ozone layer depletion	Industry	Everyone
Greenhouse warming and climate change	Energy (fossil fuel combustion)	Everyone
Freshwater availability and quality	Population growth, agriculture	Everyone
Coastal and marine degradation	Transport and Energy	Everyone
Deforestation and desertification	Population growth, agriculture, and energy	Rural poor
Toxic, chemical, and hazardous waste	Industry and Nuclear Energy	Everyone

Source: Prepared by the author (2024).

Want more information? Here are some references:

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7 - GREAT TRANSITIONS

This section is based entirely on articles from the Great Transition organization in: https://greattransition.org.

7.1 CURRENT ISSUES

Sustainable energy is defined as energy systems, technologies, and resources that can meet long-term human needs, including economic and development needs, in a way that also protects the integrity of fundamental natural systems, expands access to basic energy services to the more than 2 billion people who do not currently have access to them, and reduces security risks and potential geopolitical risks. A set of public policies and commercial activities that promote the adoption of renewable energy sources and more efficient technologies are necessary to achieve this shift. In order to make new technologies more accessible and competitive compared to fossil fuels, it is also vital to invest in their research and development.

Since there are still billions of people without access to electricity worldwide, which jeopardizes the economic and social development of the areas where they live, it is important to take these issues into account in order to support the energy transition. Therefore, it is necessary to look for solutions that provide sustainable and inclusive universal access to energy. The energy revolution also raises concerns about geopolitics and energy security. Because certain nations' reliance on fossil fuels can lead to vulnerabilities and international conflicts, matrix diversity is crucial for ensuring the security of the world's energy supply.

The paths to transition, however, involve other socioeconomic and environmental aspects, including:

- Regionalized, diversified, and self-sufficient economy, focused on the basic needs of the population, promoting the integration of the city with the countryside, and built from efficient, cheap, and non-polluting techniques, based on renewable energy sources.
- Political decentralization, increasing municipal and regional political autonomy.
- Use of alternative, soft and ecologically balanced technologies. Techniques of organic agriculture, natural medicine, eco-architecture, among others.
- The adoption of environmental protection measures to guarantee the future decentralized society's ecological survival.
- The preservation of natural ecosystems through the establishment of reserves and natural parks (at the moment, these areas make up less than 2% of Brazil's total area). To protect springs, slopes, etc., a system of mini-reserves would be established.
- A moratorium on hunting wildlife and protection of wildlife. All endangered species reproduction.

- Rationalization of the use of mineral reserves. It is fundamental to convert production to prioritize the use of renewable and abundant sources of matter and energy.
- Extreme industrial pollution control. Filtering emissions that cause pollution in the near future. Conversion to technologies with lower environmental impact in the medium term. One illustration is the closed-loop reuse of water by industry.
- The management of sewage and automobile pollution.
- Reuse of glass, metal, paper, and other discarded and used materials.
- Product quality control, which promotes the manufacturing of long-lasting, reusable, repairable things that consume the least amount of energy and natural resources.
- Radical improvement of the environment in large towns.
- Incentive to forestry, with a distinction between ecological reforestation and reforestation for the timber sector.

We need to fundamentally alter our society and ideals. Therefore, the cultural issue is crucial to the ecological mission. We could work less and live better if we changed the way we live and produce. Live a more fulfilling, equitable, compassionate, and peaceful existence with nature.

7.2 Branch Points: Global Scenarios and Human Choice

The International Institute for Applied Systems Analysis (HASA) has compiled a paper titled "Branch Points: Global Scenarios and Human Choice," (Gallopín et al. 1997) in which different possibilities for the future of the world are presented. These scenarios take into account human actions and the potential outcomes that may result from these decisions. In each of the possible worlds, what are the expected outcomes?

To frame the role of scenarios in understanding energy transitions, it is important to clarify that scenarios are not forecasts but structured narratives of how the future could unfold depending on socioeconomic choices, technological developments, and policy directions. They provide a way to explore uncertainties, highlight risks, and compare long-term pathways under consistent assumptions.

Scenario 1: CONVENTIONAL WORLDS

The "conventional worlds" are scenarios that anticipate an energy future that will not significantly differ from the one that exists today. In these worlds, reliance on fossil fuels will continue to be prevalent, and the shift towards renewable sources will be restricted. This scenario has the potential to have major repercussions for the ecosystem, including but not limited to an increase in the average temperature of the planet, the melting of polar ice, and rising sea levels.

The increased need for energy in developing countries, combined with rising prices of fossil fuels, could lead to greater economic and social inequality. This would be a big socioeconomic consequence as well. In addition, geopolitical instability brought on by countries competing for limited energy resources can bring to conflict and tension between nations.

It is essential to emphasize the fact that opting for the scenario of a "conventional world" is not a necessary prerequisite for making the shift to a more sustainable economic model; there are other possibilities available. To put these options into action, however, calls for fundamental shifts in both politics and the global economy, as well as a commitment on the part of governments, enterprises, and individuals to make the shift to an economic system that recognizes and honors the limits imposed by individuals and the earth.

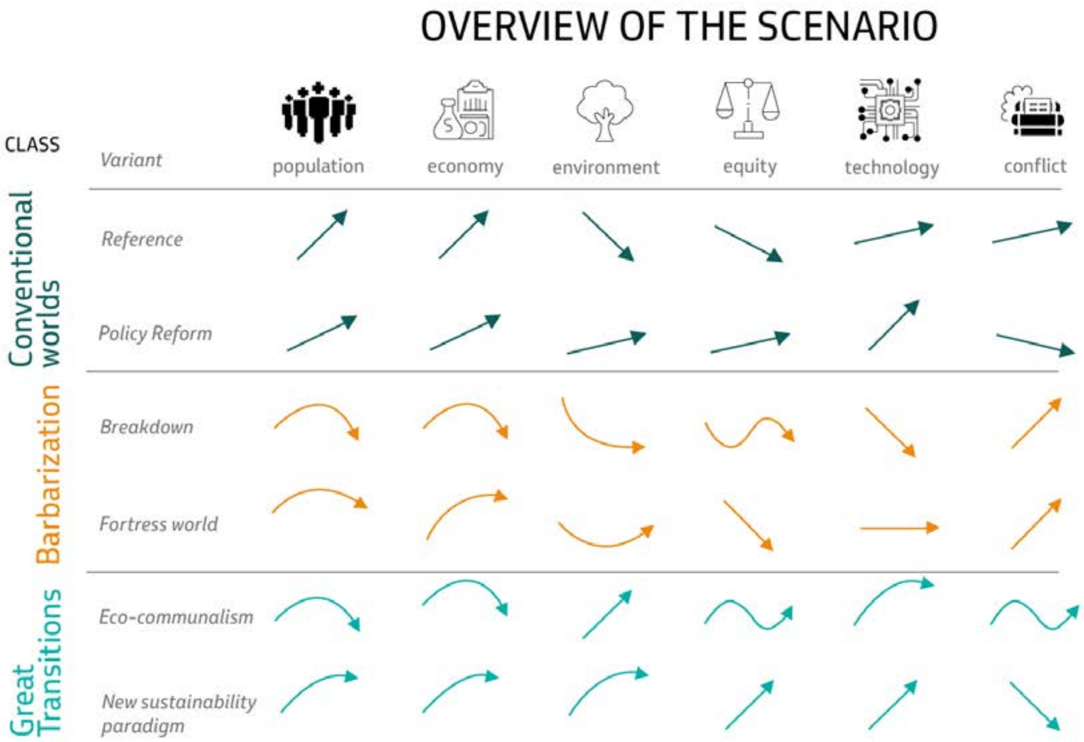

Figure 5 – Overview of Transition Scenarios

Scenario 2: BARBARIAN

In the “barbarism” scenario, mankind would be faced with a global breakdown, which would include a number of military wars, political and economic instability, as well as an increase in the severity of natural and climate calamities. In this hypothetical future, technology is insufficient to alleviate society’s issues, and the environment in which people live becomes increasingly chaotic and harmful.

Barbarism can be caused by several different things, including a lack of global collaboration, the emergence of fanatical nationalism, ethnic, religious, or political disputes, and rising social and economic inequality, to name just a few of these potential causes.

This is a troubling possibility that must be avoided at all costs. In order to accomplish this goal, it is vital for both society as a whole and governments to undergo a mental and emotional transformation. To avoid a future marked by barbarism, it is essential to work towards global collaboration, sustainable development, the promotion of social and economic equality, and the protection of the environment. In addition, technology and innovation can be employed in a responsible and strategic manner to address global concerns and encourage the development of sustainable practices.

Scenario 3: GREAT TRANSITION

The Great Transition scenario is the goal that needs to be accomplished, and it represents a vision of a more just, sustainable, and wealthy future for the entire world. It is centered on three primary pillars: economic transformation towards a green and solidarity economy, social equality to eradicate poverty and exclusion, and global governance to coordinate worldwide activities on issues such as climate change and human rights. These three pillars are the foundation of the initiative. This scenario envisions a future in which societies embrace the ideals of collaboration, social justice, and sustainability, so fostering a new way of life that is centered on the individual well-being of the group as well as the protection of the environment.

It is predicated on the requirement for forward-thinking solutions to the problem of sustainability, which may involve new socioeconomic arrangements as well as fundamental shifts in the values held by society. However, this is not a straightforward task and calls for concerted actions on the part of all relevant parties, including governments, businesses, and non-governmental organizations in addition to the public people. Though, these shifts could bring about enormous benefits, such as a reduction in emissions of greenhouse gases, an improvement in the quality of both the air and the water, and the promotion of sustainable economic development.

A concerted effort on a worldwide scale and a resolute dedication to meeting the difficulties we confront as a society are required to realize the potential of the Great Transition. It is absolutely necessary for us to keep cooperating with one another in order to advance sustainable solutions and develop a future that is safer and healthier for everyone.

It is necessary to recognize the driving forces in order to comprehend the possibilities and limitations of the ongoing global transition and to assist in guiding collective efforts towards a future that is more just and sustainable. Following the path that is given by the scenario can only be accomplished by doing so. They are the primary forces propelling societal transformation in the direction of a more equitable and environmentally responsible future. The creation of new social movements, such as fights for human rights and gender equality, the proliferation of new technologies that are clean and renewable, changes in public policy, and a greater awareness of the global ecological problem are some of these developments. These societal mobilizing forces are essential to the process of transition because they encourage society as a whole to take collective action in support of substantial societal shifts.

Social insecurity, which is already ingrained in our way of life, constitutes one of the most significant challenges. Criminal and terrorist organizations are behaving in a manner that is ever more aggressive, professional, and well-planned. One more thing that cannot be predicted with absolute precision is how the energy transition will affect different towns and how the job market will operate. The shift away from dirty energy sources could result in the demise of businesses and a loss of employment opportunities in industries that are dependent on the production and consumption of fossil fuels. For this reason, it is imperative to provide social protection and professional requalification systems for the workers who may be affected.

The necessity to handle environmental concerns such as degrading ecosystems, changing climates, and polluting the environment is an additional significant influence. It is essential to implement efficient public policies in order to curb emissions of greenhouse gases and advance efforts to preserve the planet's biodiversity. In addition to this, it is critical that incentives be developed to encourage businesses and customers to adopt more environmentally friendly behaviors.

The shift to a new paradigm may include substantial cultural adjustments, including the prioritization of different sets of values and patterns of behavior. It is vital to encourage educational campaigns and awareness initiatives so that people realize the long-term effects of their actions and the significance that the minor changes adopted will make in both their day-to-day lives and the future of the world. This will allow people to make better decisions that will benefit both the planet and themselves.

Alongside the classical scenarios of the Great Transition Initiative, which remain influential for articulating ethical and civilizational choices, climate research today also employs the Shared Socioeconomic Pathways (SSPs) developed under the IPCC framework. These SSPs offer structured narratives of possible global futures, serving as inputs to Integrated Assessment Models (IAMs) that link socioeconomic development with greenhouse gas trajectories.

The five SSPs are:

1. **SSP1 – Sustainability ("Taking the Green Road"):** a world oriented toward inclusive development, reduced inequality, and environmental stewardship, with low challenges for both mitigation and adaptation.
2. **SSP2 – Middle of the Road:** continuation of historical trends, with moderate progress on development and climate action, representing a "business-as-usual" pathway.
3. **SSP3 – Regional Rivalry ("A Rocky Road"):** a fragmented world dominated by nationalism, limited international cooperation, slow development, and high challenges for mitigation and adaptation.
4. **SSP4 – Inequality ("A Road Divided"):** stark disparities between a globally connected, high-tech elite and marginalized regions left behind, with uneven capacity to cope with climate risks.

5. **SSP5 – Fossil-Fueled Development (“Taking the Highway”):** rapid economic growth driven by continued reliance on fossil fuels, paired with strong technological and institutional capacity, but high mitigation challenges due to persistent carbon intensity.

By comparing the normative visions of the Great Transition Initiative with the structured pathways of the SSPs, readers gain a clearer sense of how scenario exercises range from value-driven transformations to quantitative modeling frameworks. Both sets of scenarios underscore that choices made today; about technology, governance, and equity; shape the long-term feasibility of deep decarbonization and sustainable development.

7.3 Great Transition - The Promise and Lure of the Times Ahead

The process of shifting towards a world that is more sustainable and equitable is one that is intricate and drawn out, comprising several stages and obstacles along the way. One of the most notable aspects of this process is the acceleration of history, which refers to the sensation that we are going through significant and speedy transitions in a relatively short amount of time. This is one of the most notable qualities of this process. This quickening can be seen in a few different aspects, including the advancement of technology, the rising interconnection of people all over the world, and the creation of new values and social movements.

In this setting, indicators of a transition to the future on a planetary scale are also beginning to show. These signs point to the beginning of a new age for humanity and for the world as a whole. They include a growing concern with environmental and social issues, the adoption of more sustainable and conscious practices by companies and governments, the emergence of new technologies and renewable energy sources, and the strengthening of social and political movements that defend justice and equality. All these signs point to a possible shift towards a more sustainable and conscious future.

However, the process of making the shift to a world that is more just and sustainable is not a straightforward or simple one. It requires confronting several obstacles, including the opposition of powerful and conservative sectors, a lack of leadership and global coordination, inequality and social exclusion, and a general lack of understanding and commitment on the part of society as a whole. In addition, it is required to deal with the inherent limitations of the planet, recognizing that the existing model of economic development is not sustainable and that we need to create new ways to both live and produce. It is necessary to deal with the natural limitations of the globe.

As a result, in order to make the shift to a future that is more sustainable and equitable, our beliefs, practices, and ways of thinking will need to undergo a significant transformation. It is vital to embrace a more integrated and systemic perspective of the world in order to recognize the interconnectedness between the various realms of existence and the requirement to care for the planet and its people. This view can be achieved by adopting an integrated and systemic view of the world. For society as a whole to comprehend the immediacy and significance of this transition process, it is essential to make investments in educational and awareness-raising programs.

CONSUMPTION & WELL-BEING:

In the context of the Great Transition, the concept of equity fairness is essential to the process of constructing a world that is more just and sustainable. In this sense, it is vital to understand the relationship between consumption and well-being since equity does not just refer to the equal distribution of resources; rather, it refers to the process of ensuring that all people have access to the resources necessary to live with dignity.

However, the way consumption is monitored and encouraged in today's culture can lead to considerable inequities, even though consumption is a vital indicator of one's level of happiness. In many wealthy countries, for instance, excessive consumption of food and luxury items is promoted, yet in other countries, many people struggle to get basic resources to exist. One reason for this disparity is economic development. In section 2, when Illich's idea of counter-productivity was presented, we did briefly touch on the topic of consuming.

In this sense, equality necessitates a significant shift in how society conceives of and approaches consumption. This involves a change in both the production and distribution of resources, as well as a modification to the criteria by which success is judged. To achieve equity, we need to move away from gauging success by the accumulation of things and material wealth and towards an economic system that places a premium on health, well-being, and quality of life.

In addition to this, equity necessitates making certain that everyone has access to the resources they require in order to fully engage in societal activities. This involves access to basic health services, education, transportation, and housing, in addition to access to economic and political chances. Moreover, this also includes access to political and economic opportunities.

Because of the potential for the energy transition to have a considerable impact on the allocation of resources and opportunities, equity is of utmost significance when it comes to the move away from fossil fuels. It is of the utmost importance to make certain that the most defenseless and oppressed populations are not cast aside during the period of transition, but rather that they are included in the development of equitable and long-term solutions.

AGENTS OF CHANGE AND UNCERTAINTY:

There are many different types of players who might be considered change agents in the context of moving towards a more sustainable future. These actors include individuals, organizations, enterprises, and governments. Market forces and policy reforms stand out as the two of these factors that are considered particularly important to the transformation process.

When it comes to making the shift towards a future that is more sustainable, market forces like firms and investors both have an important part to play. Companies can lower their ecological footprint and encourage other actors to embrace sustainable practices if they adopt sustainable business practices such as reducing energy consumption and adopting renewable energy sources. Other sustainable business practices include minimizing energy consumption. Investors can also use their financial power to influence corporate behavior, such as supporting the adoption of sustainable practices and discouraging the ones that are harmful to the environment by using their influence.

Reforms in public policy are also an essential force that can help modify the current trajectory towards a future that is more sustainable. The adoption of beneficial actions by businesses and individuals can be encouraged with the assistance of public policies such as tax incentives and subsidies for sustainable practices. In addition, the government's policies have the potential to foster innovation as well as the development of new technology.

However, it is essential to keep in mind that the process of change will not be simple or fast. Achieving a sustainable future involves considerable transformation in our institutions, economy, and cultures. The market forces and policy reforms are just two weapons that can be employed to accomplish this objective; nonetheless, coordination and cooperation between various players will be essential to the completion of a smooth transition.

In this context, one of the most significant unknowns is whether or not civil society will be able to come together in the pursuit of a common objective, or whether it will instead continue to be divided into a number of distinct groups and interests. There are hopeful indicators that civil society is coming together around global concerns such as the worldwide movement for climate justice and the recent worldwide mobilization to abolish racism and racial discrimination. Examples of these movements include the global movement for climate justice and the recent worldwide mobilization. In addition, the proliferation of social networks and other communication technology has made it possible for citizens to engage with one another and organize themselves around shared causes. However, our society is still plagued by a great deal of discord and inequality, which can make it challenging to find common ground and work towards a shared objective. As a result of the large number of economic and political interests at play during the transition, there is the potential for competition and fight for power.

It is essential for political leaders and organizations representing civil society to collaborate in order to overcome these divisions and develop a common understanding of what the future holds. This calls for an approach that is collaborative and inclusive, one that takes into account the many different points of view and interests that are involved in the change. We will not be able to overcome the unknown and construct a future that is more just and sustainable for everyone until that time comes.

TRANSITION DIMENSIONS:

The shift towards a world that is both more sustainable and just comprises multiple facets that are intertwined with one another and mutually reinforce one another. The first dimension is demographics, and the way people interact with one another. The rise of the population, as well as shifts in family structures and gender roles, all have an impact on the dynamics of society and the demand for natural resources. It is essential to implement policies that promote gender equality, sexual and reproductive education, and the decrease of excessive consumption to ensure a demographic transition that is both sustainable and successful.

Changing people's mentalities and constructing a new culture that places a high value on life, nature, and solidarity are also components of the knowledge and values dimension. It is imperative to encourage the development of an education process that is transformative, which encourages critical reflection and citizen action, and that creates people who are cognizant of their responsibilities. Additionally important to the change are technological advancements and ecological considerations. It is essential to look for long-term technical solutions that can cut down on the amount of energy and raw materials that are used in addition to lowering the amount of pollution and other negative effects on the environment.

Institutions pertaining to economics and governance will also need to go through considerable shifts in order to make the transition a reality. It is vital to rethink the forms of production and consumption, as well as to construct new economic models that embrace the social and environmental aspects. Some examples of such models include the circular economy and the solidarity economy. In addition, it is essential to improve global and regional governance in order to solve global concerns such as climate change, inequality, and social exclusion. These challenges must be addressed.

In this expedited process of change, all these aspects of the shift are connected to one another and mutually reinforce one another. Change will not be achieved until all aspects of society, including governments, corporations, civil society, academic institutions, and individual citizens, work together and actively participate in the process. The shift towards a world that is more sustainable and just is a significant obstacle, but it also presents a significant chance to construct a better future for everyone.

ENVIRONMENTAL RISKS AND DEVELOPMENT:

Environmental risks are becoming more obvious and are significant obstacles to the achievement of sustainable development. Industrialized nations, which have traditionally been responsible for a significant portion of the world's greenhouse gas emissions, now bear the duty of spearheading the shift to a low-carbon economy and looking for ways to mitigate the negative effects their economic activities have on the surrounding environment.

In turn, developing countries have a responsibility to search for a path to development that does not jeopardize the aims of global sustainability. They face the problem of balancing the needs of economic growth and poverty reduction with the need to protect the environment and combat climate change by investing in environmentally efficient technologies that are relevant to local social and environmental settings. This is a challenge that they encounter since they are faced with the need to protect the environment and battle climate change.

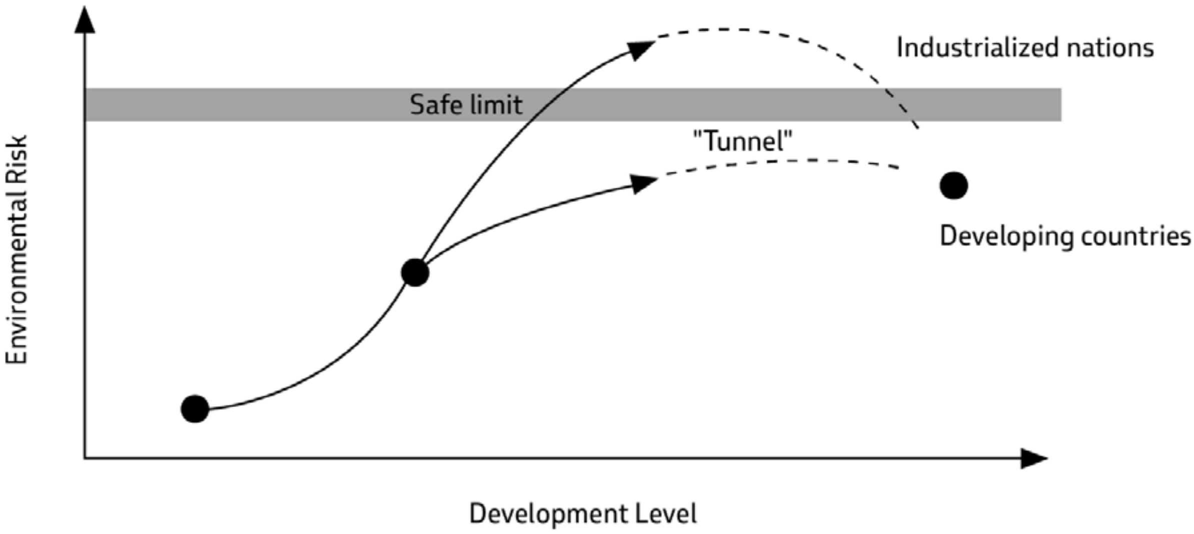

Figure 6 - Tunnel Effect for Development

The Tunnel Effect addresses some of the concepts that were discussed in the paragraphs that came before it. It shows that poor countries have the potential to reach the same degree of development as affluent countries, but they must do so in a way that is environmentally friendly. The growth of developed countries (industrialized, wealthy) came at the expense of a high energy consumption, which was caused by the utilization of fossil fuels and other non-renewable sources of energy, such as coal and oil, for example. Therefore, in order to expand further, industrialized countries decided to follow a development policy that was related with increased energy production. However, in order to forestall the escalation of the current environmental problem, particularly as it relates to climate change, they will need to make a concerted effort to cut their energy consumption. This can be accomplished by embracing innovative technologies that improve the efficiency of energy conversion and by drawing power from renewable sources. This process symbolizes the return of environmentally developed nations to a point where they can sustain themselves.

It is not necessary for the growth of peripheral nations, also known as developing countries, to go through the peak of energy consumption, which would result in surpassing the acceptable levels of environmental impacts and causing threats to the environment. This is something that developed countries have already experienced. In this way, they are required to utilize new energy conversion technologies that are more efficient in addition to adopting, on a larger scale, energy sources that are considered renewable in order to reach a level of development comparable to that of the nations located in the north, but with an energy consumption structure that is structured based on renewable and non-fossil resources, navigating a “tunnel” to outline the new model for sustainable development, reducing environmental risks, especially shortening the effects of climate change.

Therefore, methods such as carbon sequestration, the utilization of renewable energies, and improved water management are required in order to lessen the negative effects that economic activity has on the surrounding ecosystem. Carbon sequestration, for instance, is a technique that can assist reduce emissions of greenhouse gases, and renewable energies, like solar and wind, are vital for the transition to an energy grid that is cleaner and more sustainable.

In addition, improved water management is needed to assure the availability of water resources for economic activities and for local communities, particularly in areas that are afflicted by water shortages. This is especially true in regions that have a limited supply of water.

A global commitment and cooperative efforts on an international scale are required to address environmental challenges and make progress towards sustainable development. The development of governmental policies that encourage technical innovation, investment in environmentally responsible infrastructure, and the adoption of more responsible economic practices are vital to the construction of a more prosperous and environmentally responsible future for all people.

Want to see the full articles? The references are as follows:

Gallopín G, Hammond A, Raskin P et al (1997) Branch Points: Global Scenarios and Human Choice. Stockholm Environment Institute, Stockholm. https://greattransition.org/archives/other/Branch%20Points.pdf. Accessed 18 Oct 2025

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8 - CHALLENGES AND OPPORTUNITIES FOR OIL IN THE CONTEXT OF DEEP DECARBONIZATION

The shift to cleaner forms of energy must happen as quickly as possible in order to reduce emissions of greenhouse gases. However, the viability of the available possibilities in terms of energy is something that needs to be analyzed so that the studies may be carried out based on trajectories that are able to meet human requirements in all their guises. Thus, the purpose of this study is to identify the opportunities and problems associated with the transition to a cleaner energy source, with a particular focus on the oil industry. These opportunities and challenges are broken down according to the environmental, economic, technological, and social dimensions. In particular, the paper titled "Net Zero by 2050 A Roadmap for the Global Energy Sector" that was published by the International Energy Agency (IEA) is evaluated. The findings suggest that oil will continue to play an important role, mainly in the transportation business, the petrochemical industry, and fundamental industry; nevertheless, adjustments to the low carbon scenario will be required. The significance of businesses in the oil and gas industry is also brought to light. Act in conjunction with national governments to increase energy access and the exchange of technological information while simultaneously lowering overall usage.

In light of this, we discuss the potential and difficulties that lie ahead for the oil industry as a result of the energy shift. The technological and environmental components both offer chances for the adoption of solutions that reduce greenhouse gas emissions. Some examples of these technologies include carbon sequestration and storage as well as the utilization of renewable energy sources.

Nevertheless, there will be a lot of obstacles to overcome, as carbon sequestration technologies are not quite where they need to be yet, and emissions will need to be cut down at every stage of the production chain. The diversity of energy sources, such as natural gas and renewable energies, can assist businesses in maintaining their relevance in a market that is undergoing transition from an economic and governance perspective. Nevertheless, the energy transition may provide a risk to the conventional economic model of the oil industry, and the push from investors and civil society for more environmentally responsible practices may present a difficulty for the corporate governance of corporations operating in the area. According to the IEA research that was referenced, there should be a major fall in the demand for oil and gas, with the use of fossil fuels being limited to the production of commodities in which carbon is an integral part of the product and to industries in which there are few possibilities for the reduction of emissions. The electrification of transport is an important strategy for lowering emissions. The use of fossil fuels should be discouraged by public policy, and new investments in oil and gas fields should be restricted, with the goal of concentrating supplies on producers with the lowest costs. In order to compensate for the declining profits from oil and gas, structural reforms and new sources of revenue are required.

8.1 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 takes into consideration a percentage of the total input components (Murphy et al. 2011).

- Numerous studies have analyzed the energy return for different sources (Bhandari et al. 2015; Gupta 2018; Gupta and Hall 2011; Hall et al. 2014; Wang et al. 2021). Two results are commonly found: (i) the EROI of fossil fuels, in general, is higher than that of renewable sources, and (ii) the EROI of fossil fuels has been decreasing over the years. However, although the EROI of fossil fuels is declining, most renewable energy alternatives have substantially lower EROI values. Thus, while there is a positive aspect of introducing renewable electricity as a high-quality energy vector, replacing fossil sources, there are some relevant challenges (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 from being 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).

Table 1 provides a more complete review than Figure 7, including additional data, sources, and considerations about the Energy Return on Investment (EROI) of various energy sources:

Energy Source / Technology	Average EROI	Commentary
Oil and Natural Gas	**20:1** (Hall et al. 2014) I **18:1** (Gagnon et al. 2009) I **10:1** *Only in USA (Guilford et al. 2011) I **20:1** - Oil and - NG **40:1** (Pahud and De Temmerman 2022) I **40:1** *Only in Norway (Grandell et al. 2011) I **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) I **2:1** (Murphy et al. 2011) I **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) I **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) I **6-12:1** (Weißbach et al. 2013) I **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) I **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) I **20:1** (Weißbach et al. 2013) I **95:1** (Pahud and De Temmerman 2022)	Coal has a high EROI but comes with significant environmental drawbacks, including high CO2 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).

Table 1 – EROI of different energy sources

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 CO2 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; International Organization for Standardization — 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).

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 and 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)[4] 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 and Van Den Bergh 2018; Lambert et al. 2014; Raugei 2019; Sers and Victor 2018). For instance, to quantify the conversion coefficients of various types of components, materials, and energy, the idea of Cumulative Exergy Consumption (CExC) has been proposed by integrating the exergy and life cycle views. If exergy is regarded as a flow, then CExC might represent the cost of exergy for a good or service (Rocco et al. 2014). Consequently, CExC 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 CExC 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.

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[4] Integrated Assessment Models (IAMs) are computational frameworks that link multiple economic sectors and domains—energy, economy, land use, climate, and public policy—into a single system to explore long-term scenarios. They are widely used by the IPCC, research institutions, universities and other international bodies to evaluate mitigation and adaptation pathways, providing insights into how technological, environmental, and socio-economic factors interact in the transition toward low-carbon futures.

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.

Want to see more?

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8.2 The Competitiveness of Oil

Energy Return on Investment (EROI) is a measure of the quality of various fuels, which calculates the ratio between the energy provided by a particular fuel to society and the energy invested in capturing and delivering that energy in its final or useful form, depending on the boundary of analysis. As Hall et al. (2014) point out, the EROI is expressed as an X:Y ratio, where investing one unit of energy Y results in X units of energy obtained. If the X:Y ratio is less than 1, there is no energy gain, meaning that there is an investment greater than the return obtained. So, the EROI plays a crucial role in assessing various energy systems. This principle calculates the ratio of energy derived from a specific source to the energy invested in its acquisition. The EROI serves as a guide to measure the energy efficiency of diverse sources and technologies and offers insights into their sustainability and economic viability.

As already mentioned, from the perspective of EROI, the current energy transition faces the challenge of intentionally replacing higher EROI sources with lower EROI sources (see Figure 7), which is precisely the opposite trend of previous energy revolutions (Smil 2011).

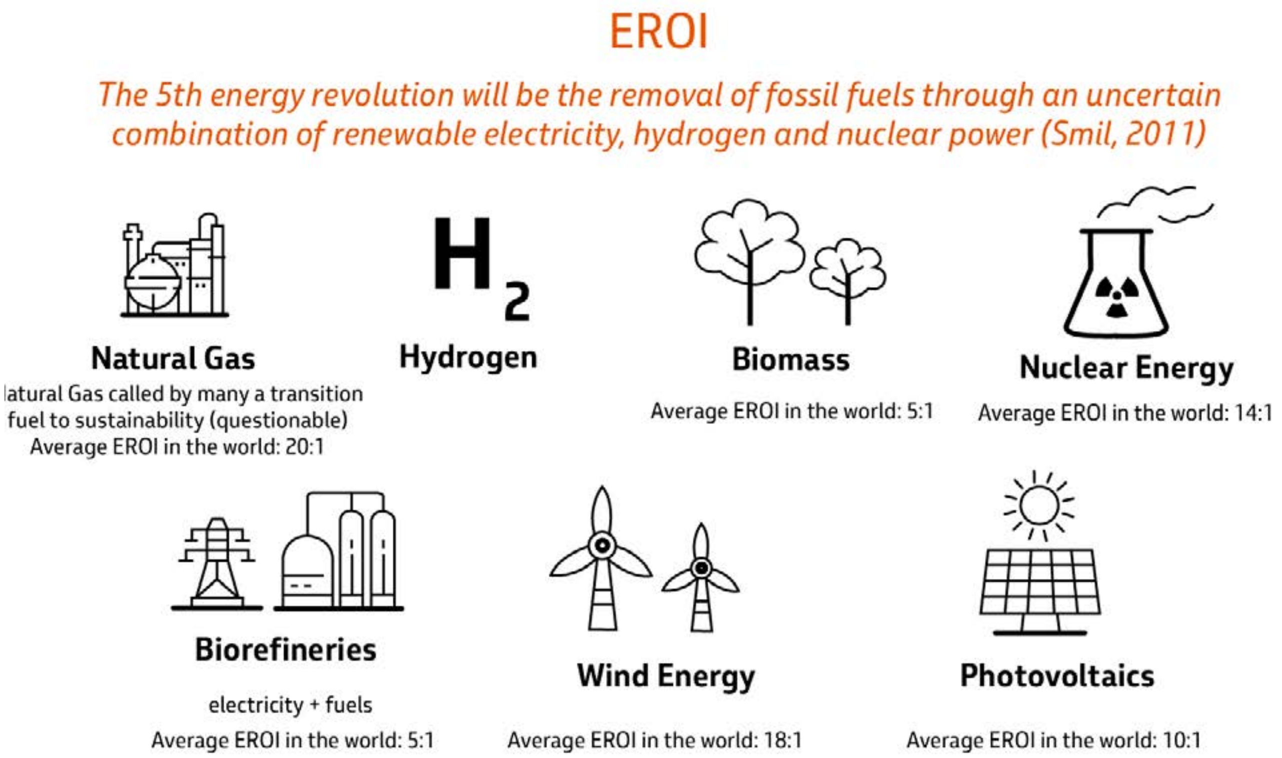

Figure 7 – Sources predicted by Smil (2011) for the Energy Transition

Petroleum currently leads the pack in EROI evaluations, with its high energy density and relative ease of extraction contributing to a significantly higher EROI than most renewable energy sources. As Hall et al. (2014) noted, petroleum's EROI ranges between 15:1 and 20:1, while solar and wind power typically fall between 5:1 and 10:1. This disparity means that for every unit of energy invested in oil production, we gain 15-20 units in return, as opposed to only 5-10 units from renewable sources.

The superior EROI of petroleum propels its competitive edge over most renewable energy sources. It is a highly concentrated energy source, cost-effective in extraction and transport, making it an attractive choice for various energy applications, from transportation to electricity generation.

Nonetheless, it is vital to recognize that the EROI of oil is not static. As petroleum reserves deplete, extracting the remaining reserves becomes more challenging and energy-intensive, consequently decreasing its EROI over time and potentially undermining its competitiveness against renewable sources.

Furthermore, we cannot overlook the environmental impact of oil extraction and combustion. Despite its EROI advantages, petroleum's negative externalities, including air and water pollution, greenhouse gas emissions, and ecosystem degradation, are substantial. Renewable energy sources, in contrast, have much lower environmental impacts, marking them as more sustainable and desirable options in the long run.

While the EROI is a valuable metric, it does not capture every aspect of the current energy transition, particularly the urgent need to reduce CO2 emissions. Cleveland et al. (1984) explain that the original application of EROI aimed at finding energy alternatives that could sustain economic growth while matching or exceeding oil's efficiency. Today's challenge lies in introducing energy alternatives that mitigate CO2 emissions, despite their typically lower EROI (Hall et al. 2014). Thus, the selection of technologies that balance efficiency, economic return, and environmental impact mitigation must consider both EROI and CO2 emissions.

Moreover, the traditional EROI evaluation approach, relying on calorific values to quantify direct and indirect energy input and output, has limitations. It only estimates the quantity of energy, disregarding energy quality, a crucial factor determining an energy source's societal utility. It also fails to provide a comprehensive view of the system's complexity, like labor, auxiliary services, and environmental inputs. To address these issues, physical approaches such as energy and exergy analysis have been developed. These account for both the quality and complexity of the system, and other physical approaches include ExROI, Return of Exergy on Investment in Exergy, and minimal exergy return rates required by society.

In this context, there is no "silver bullet" that can decarbonize the economy; rather, what is required is a systematic worldwide coordination of agents working towards a common objective (Löfgren and Rootzén 2021). There is a degree of inertia associated with this change brought on by the current economic and energy framework, which is optimized for operation using fossil fuels. Because it is difficult to replace fossil fuels in the transportation sector, steelworks, petrochemicals, and the cement sector, the focus in these sectors in the short term should be on increasing the energy efficiency of processes and applying CCUS (Carbon Capture, Utilization and Storage) technologies that are already available, while massive investments are made in research and development for alternative fuels for the long term. Specifically, petrochemicals show themselves as a prospective niche for moving the demand for oil, with the advantage of embedding carbon in the product that would be used to produce transition infrastructure. This could be a potential solution to the problem.

The mobilization of companies in the oil and gas sector to support the reduction of emissions that do not generate an increase in social well-being – for example, illegal deforestation – may allow for a longer use of petroleum derivatives, for example, allowing for increased safety energy in countries that are lacking in energy. This is because illegal deforestation does not generate an increase in social well-being. In addition, industrialized nations will have to take the initiative to cut their own consumption in order to designate a portion of their carbon budget for the purpose of narrowing the gap in the availability of energy sources. In the absence of this reduction, achieving climate goals and reducing energy poverty may become mutually exclusive objectives.

In conclusion, although oil's high EROI grants it considerable competitiveness over most renewable sources, we must consider the long-term sustainability and environmental impacts of our energy choices. As we transition towards a sustainable energy future, we need to continue investing in renewable energy technologies and mitigating our current energy systems' negative impacts. The challenge of transitioning from high EROI sources to lower EROI sources demands careful planning and infrastructure investment to effectively integrate renewable sources into our energy system.

Link to the full article:

Neves MVS, Aylmer RBV, Szklo AS (2022) Challenges and opportunities for oil in the context of the transition. Paper presented at the Rio Oil & Gas Expo and Conference, Rio de Janeiro, 26–29 September 2022. https://www.researchgate.net/publication/363917654_Transicao_energetica_oportunidades_e_desafios_para_o_petroleo_no_contexto_de_descarbonizacao_profunda. Accessed 11 Oct 2025

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9 - The Need to Decarbonize the Economy

The energy transition is not a duel of fuels; it is a race to eliminate carbon while preserving affordable, reliable energy services.

9.1 Framing the Real Challenge

Public debate often reduces the transition to a binary swap – oil for wind, coal for solar. Yet the climate imperative is broader: whole economies must deliver the same—or larger—volumes of useful energy with dramatically lower net-CO_2 emissions. The focus, therefore, is not on which primary energy appears in the mix, but on how fast every ton of CO_2 is prevented from reaching the atmosphere.

9.2 Why "Renewables" Are Not Truly Renewable (Yet)

- **Lifecycle dependence on fossils.** Solar modules, wind turbines, batteries and electrolyzers are manufactured in supply chains still powered mainly by coal, oil and gas. Global average grid electricity—over 60 % fossil-based—feeds the mines, smelters and gigafactories that enable "clean" hardware. Until those upstream processes decarbonize, no energy option is entirely fossil-free.
- **Materials intensity.** Per delivered megawatt-hour, wind and solar require orders of magnitude more steel, aluminum, copper and critical minerals than a gas turbine. These materials carry an embedded carbon footprint that is rarely counted in headline "zero-carbon" claims.

9.3 Energy Density, EROI, and the Cost Signal

Lower density and lower EROI do ***not*** make renewables undesirable; they do make them ***more expensive in net-energy terms***. See table 1.

A society that substitutes high-EROI fuels with lower-EROI options must either:

1. **Accept higher final-energy costs**,
2. I**nvest colossal volumes of additional capital and land** to offset the net-energy penalty, or
3. **Deploy complementary decarbonization tools** that preserve high-density fuels while neutralizing their emissions.

9.4 Equity, Affordability and Energy Justice

High-income economies can absorb cost premiums for cleaner energy; low- and middle-income countries often cannot. If decarbonization pathways ignore affordability, the transition risks deepening energy poverty, slowing industrialization and provoking social backlash. Energy justice therefore demands solutions that:

- **Keep marginal kWh prices within reach** of households and industry, and
- **Distribute new infrastructure and mineral supply chains fairly**, avoiding fresh "carbon colonization" of resource-rich but institutionally weak regions.

9.5 Keeping High-Density Fuels – but Capturing Their Carbon

Carbon Capture and Storage (CCS) and Carbon Capture, Utilization and Storage (CCUS) allow coal and gas plants, steel mills or steam crackers to operate with sharply reduced net emissions while still exploiting their favorable EROI.

- **Illustrative case** – a modern ultra-supercritical coal plant equipped with advanced post-combustion carbon capture technologies can significantly reduce its net carbon emissions, reaching levels comparable to renewable sources such as solar photovoltaic within fossil-dependent grids. Although implementing carbon capture inherently demands a meaningful portion of the plant's energy output, the overall net energy return on investment (EROI) could remain relatively high. This preserved energy return ensures that coal power with CCS can still play a valuable role in the energy mix, especially when considering the additional energy inputs required by renewable energy sources, including backup systems, storage, and supplementary grid infrastructure.
- **Gas combined-cycle equipped with CCS** can attain even more favorable energy efficiency and significantly lower carbon intensities. These plants provide reliable, dispatchable power that complements intermittent renewable sources, contributing positively to overall system stability and flexibility. The probable high residual energy return, combined with substantially reduced emissions, positions gas combined-cycle with CCS as a strategically valuable technology during the ongoing transition toward a low-carbon economy.
- **Nature-Based Solutions (NBS)** – such as reforestation, improved soil management, and ecosystem restoration—offer an important complementary pathway toward decarbonization. These strategies can effectively remove carbon dioxide from the atmosphere at relatively competitive costs compared to technological alternatives. By offsetting emissions in sectors that currently have limited viable alternatives, such as aviation and petrochemical industries, nature-based approaches allow for the strategic and continued use of fossil fuels in areas where their energy density and operational performance remain crucial. Consequently, NBS can meaningfully contribute to achieving economy-wide carbon neutrality while preserving the unique advantages of hydrocarbon-based energy sources where substitution is most challenging.

9.6 Complementary Vectors: Hydrogen, Critical Minerals and Storage Economics

- **Hydrogen** can decarbonize high-temperature industrial heat and long-distance transport, but its chain of conversions (electricity → H_2 → compression/liquefaction → end-use) halves the delivered EROI and drastically increases energy cost relative to direct electrification. Large-scale H_2 therefore makes sense chiefly where **no other low-carbon fuel works** (e.g., green steel, transoceanic shipping).

- **Critical minerals** (Li, Ni, Co, REEs, Pt-group metals) will scale dramatically under any renewables-and-hydrogen scenario. Their extraction is energy-intensive and geopolitically concentrated. Supply-chain bottlenecks could inflate costs faster than learning curves decrease them, threatening both affordability and schedule.
- **Storage** - Energy storage technologies play a crucial role in enabling grids with high shares of renewable energy. However, battery-based storage systems, while essential, currently lead to significant increases in overall energy system costs. Alternatives such as pumped hydro storage and geothermal storage can be more cost-effective, but their applicability depends heavily on geographic and site-specific conditions. As renewable penetration rises, system-level costs tend to grow due to the need for either additional storage capacity or oversized generation infrastructure. Balancing the integration of renewables with lower-cost, dispatchable generation options equipped with carbon capture technologies could thus be a strategic pathway to maintain overall system affordability and reliability.

9.7 Strategic Portfolio, Not Binary Substitution

A resilient, just and rapid decarbonization pathway therefore rests on **five simultaneous pillars**:

1. **Max-out energy efficiency** – the cheapest, fastest ton of avoided carbon.
2. **Scale variable renewables** where their low marginal cost and resource endowment justify the land and mineral inputs.
3. **Retain high-density fossil fuels** selectively, but e**liminate their net emissions** via CCS/CCUS, NBS etc.
4. **Deploy NBS at gigatons-scale** to balance remaining hard-to-abate sectors.
5. **Invest strategically in hydrogen, long-duration storage and critical-mineral recycling** only where life-cycle analysis proves them superior to other options.

9.8 Conclusion – Decarbonization First, Diversification Second

The core message is simple but often lost: **Decarbonization is the goal; changing fuels is merely one of several tools**. A portfolio that combines renewables and abated fossil energy maximizes net-energy delivered to society, minimizes transition costs and widens the envelope for energy justice. Success will not be judged by the share of wind-turbine blades or solar-panel acres, but by **how quickly the global ton of CO_2 per unit of useful energy falls** while keeping lights on, factories producing and households flourishing.

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10 - FINAL REMARKS

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.

Throughout the chapters, this book has argued that the defining feature of today's energy transition is the imperative of decarbonization. Unlike earlier energy shifts, the challenge is not simply one of replacing fuels or improving efficiency, but of reducing greenhouse-gas emissions fast enough to avoid dangerous climate change while preserving energy security and affordability. This dual pressure, climate urgency and socio-economic stability, makes the present transition qualitatively distinct.

The groundwork for understanding the role of Exergy and Energy Return on Investment (EROI) within the broader framework of the energy transition and the requirements of decarbonization has been developed throughout this book. The chapters collectively explored a set of guiding questions that shaped the discussion:

- 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?

Each of these questions was examined from different perspectives. Historical and conceptual analyses explained why today's transition is problem-driven, climate-constrained and equity-minded. Methodological chapters reflected on how exergy and refined approaches to EROI expand the assessment of sustainability. Other sections examined the links between energy, economy and society, the environmental consequences of human activity, and the opportunities and risks of different pathways—from renewable expansion and critical minerals to CCS, hydrogen, and the role of oil under deep decarbonization scenarios. Taken together, these reflections offer not definitive answers but a framework for thinking critically about the complexity of contemporary energy transitions and the tools available to navigate them.

Moreover, this book emphasizes the fact that energy density and net-energy availability (as quantified by EROI) significantly influence the economic viability and societal acceptance of new energy systems. Renewable energy sources, despite their benefits in reducing emissions, exhibit inherently lower energy densities and diminished EROI compared to fossil fuels. Consequently, transitioning entirely to renewables carries considerable economic implications, potentially exacerbating energy poverty and injustice. Therefore, maintaining energy justice demands carefully balanced portfolios, integrating low-carbon solutions alongside high-density fuels coupled with carbon-neutral technologies such as CCS and CCUS.

Carbon capture and sequestration technologies provide a viable route for achieving deep decarbonization without entirely abandoning fossil fuels. They permit continued use of high-density energy sources while drastically reducing their emissions footprint, thus preserving both economic efficiency and energy security. Similarly, indirect approaches such as Nature-Based Solutions (NBS) represent complementary pathways toward net-zero goals, leveraging natural carbon sinks at potentially lower marginal costs and broader societal co-benefits.

Hydrogen, especially the green variant, emerges as a potentially transformative energy vector, particularly suitable for sectors notoriously difficult to electrify or decarbonize directly, such as steel production, maritime transportation, and long-haul aviation. However, substantial thermodynamic inefficiencies, significant logistical challenges, and elevated production costs still limit its immediate large-scale applicability. Therefore, hydrogen development requires targeted, strategic investments, carefully evaluating its economic and energetic viability against alternative decarbonization strategies.

Another critical point highlighted is the under-discussed significance of critical minerals and material intensity in the energy transition. The exponential growth in the demand for rare earth metals, lithium, cobalt, copper, and nickel represents a potential bottleneck—both economically and geopolitically—that needs addressing through robust recycling infrastructures and diversified supply chains to secure an affordable and just transition.

Additionally, intermittent renewable sources such as wind and solar necessitate extensive investment in energy storage infrastructure, driving up overall system costs. Storage systems, particularly batteries, come with their own environmental and economic burdens, reinforcing the need for diversified energy solutions rather than singular technological substitutions.

Ultimately, achieving decarbonization will require more than merely substituting fuels. It calls for a fundamental rethinking of our energy infrastructure, including energy efficiency maximization, selective utilization of CCS-equipped fossil fuels, extensive deployment of renewables, strategic use of hydrogen, proactive management of critical minerals, and leveraging Nature-Based Solutions.

A genuinely successful energy transition thus emerges not from binary choices but from integrated, strategic approaches capable of balancing emissions reduction, energy availability, economic feasibility, and social equity. The pathway forward must recognize the interdependent roles of technology, economics, society, and the environment, ensuring that the transition does not sacrifice the very justice and accessibility it aims to uphold.

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