UNIVERSIDADE ESTADUAL DE CAMPINAS
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RENEWABLE ENERGY TRANSITION: AN AGENT-BASED APPROACH TO EVALUATE GREEN INVESTMENTS THROUGH REAL OPTIONS ANALYSIS

TRANSIÇÃO ENERGÉTICA: UMA ABORDAGEM BASEADA EM AGENTES PARA AVALIAR INVESTIMENTO VERDE ATRAVÉS DA ANÁLISE DE OPÇÕES REAIS

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Supervisor: Prof. Doutor Marcelo de Carvalho Pereira

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*

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RESUMO

Esta tese explora a dinâmica econômica e as possibilidades de financiamento de energia verde. O objetivo principal é investigar a adoção da análise de opções reais (ROA) e seus efeitos sobre o financiamento de energia verde em um sistema econômico complexo, utilizando como referência um estudo de caso brasileiro. A metodologia ROA é proposta a fim de que sejam analisados os impactos de sua adoção como critério para a avaliação financeira de projetos de energia verde. Esta metodologia provou ser eficiente em tornar os projetos de energia verde financeiramente mais atraentes. Para alcançar maior robustez prática, teórica e estatística foi necessário incorporar tal método em a um ambiente complexo que considera tanto a dinâmica econômica quanto climática. Nesse sentido, o Capítulo 2 resume um importante processo de busca pelo melhor modelo econômico existente compatível com a aplicação da metodologia ROA-aumentada. Este capítulo exigiu um extenso mapeamento para modelos econômicos de equilíbrio geral, rede ou sistema complexo e baseados em agentes. Além disso, o Capítulo 2 fornece um mapeando nunca feito condensando em um único trabalho modelos de crescimento econômico e modelos de crescimento econômico com elementos ambientais e climáticos que usam a teoria de equilíbrio geral e teoria da complexidade. O Capítulo 3 contribui para expandir o modelo legado "Schumpeter Meeting Keynes" (K+S), incluindo a extensão "Distópica" (DSK), para oferecer uma configuração adequada para avaliar os efeitos da adoção da análise de opções reais (ROA) ao avaliar projetos de investimento em energia verde. Em comparação com as versões existentes do K+S, adicionamos: (i) um setor de energia totalmente competitivo, com várias empresas privadas produtoras de energia competindo em um mercado parcialmente regulado, incluindo leilões de energia; (ii) uma alternativa de financiamento de projetos de longo prazo fornecida pelos bancos para o investimento de produtores de energia em novas usinas de energia verde; e (iii) um subsistema climático aprimorado ("caixa climática"), considerando o ciclo completo de CO2. A partir desse último capítulo é que foi possível a incorporação da metodologia ROA-aumentada à um sistema dinâmico econômico e ambiental com uma representação de um setor de energia mais realista. Os resultados mostraram que o avanço na compreensão das condições em que a análise das opções reais pode tornar o financiamento de projetos SNPV/RO mais apelativo para um maior número de agentes económicos pode ter verdadeiros e positivos impactos no que tange a transição energética. A análise macroeconómica indica que, em termos de inovação, emissões de CO2, eficiência térmica e transição energética (com uma maior proporção de centrais de energia verde do que poluentes no final), os cenários de financiamento de projetos SNPV/RO e NPV têm impactos positivos em comparação com o cenário de crédito regular.

ABSTRACT

This thesis explores the economic dynamics and possibilities of financing green energy. The main objective is to investigate the adoption of real options analysis (ROA) and its effects on green energy financing in a complex economic system, using a Brazilian case study as a reference. The ROA methodology proposes analyzing the impacts of adopting it as a criterion for the financial evaluation of green energy projects. This methodology has proven efficient in making green energy projects more financially attractive. It was necessary to incorporate this method into a complex environment considering economic and climate dynamics to achieve greater practical, theoretical, and statistical robustness. In this sense, Chapter 2 summarizes an important process of searching for the best existing economic model compatible with applying the ROA-enhanced methodology. This chapter required extensive mapping to general equilibrium, network or complex system, and agent-based economic models. In addition, Chapter 2 provides a mapping never done before by condensing into a single work economic growth models and economic growth models with environmental and climate elements that use general equilibrium theory and complexity theory. Chapter 3 contributes to expanding the legacy "Schumpeter Meeting Keynes" (K+S) model, including the "Dystopian" (DSK) extension, to provide a suitable setting for assessing the effects of adopting real options analysis (ROA) when evaluating green energy investment projects. Compared to the existing versions of K+S, we added: (i) a fully competitive energy sector, with several private energy-producing companies competing in a partially regulated market, including energy auctions; (ii) a long-term project financing alternative provided by banks for energy producers' investment in new green energy plants; and (iii) an improved climate subsystem ("climate box"), considering the complete CO2 cycle. From this last chapter, it was possible to incorporate the ROA-enhanced methodology into a dynamic economic and environmental system with a more realistic representation of the energy sector. The results showed that progress in understanding the conditions under which real options analysis can make the financing of SNPV/RO projects more appealing to more economic agents can have real and positive impacts on the energy transition. Macroeconomic analysis indicates that regarding innovation, CO2 emissions, thermal efficiency, and energy transition (with a higher proportion of green energy plants than polluting ones), the SNPV/RO and NPV project financing scenarios have positive impacts compared to the regular credit scenario.

FIGURES

TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

ABM	Agent-based Model
ABMS	Agent-based Model Simulations
AB-SFC	Agent-based model Stock-Flow Consistency
AFD	Agence Française de Devéloppement
ANEEL	Agência Nacional de Energia Elétrica
BB	Banco do Brasil
BNDES	Banco Nacional de Desenvolvimento Econômico e Social
BT	Binomial Tree
CAPEX	Capital Expenditures
CER	Certified Emission Reduction
CGE	Computation of General Equilibrium
DSGE	Dynamic and Stochastic General Equilibrium
EA	Empirical Analysis
E-DSGE	Environmental Dynamic Stochastic General Equilibrium
EE	Electrical Energy
EPE	Empresa de Pesquisa Energética
ETL	Extract, Transform, Load
GT	Game Theory
IBGE	Instituto Brasileiro de Geografia e Estatística
MP	Probabilistic Model
NPV	Net Present Value
OPEX	Operational Expenditures
PD	Dynamic Programming
PDE	Partial Differential Equations
PK	Post-Keynesian
R&D	Research and Development
REE	Renewable Electric Energy
RO	Real Options
ROA	Real Option Analysis
SIM	Simulation
SNPV	Strategic Net Present Value
UNFCC	United Nations Framework Convention on Climate Change
WACC	Weighted Average Capital Cost

LIST OF SYMBOLS

Summary

Introduction

Sustainable economic development pushes the energy demand, and their funding delimits the speed of progress. Whether by the populational level increase or capitalism deepening, the human necessities establish a progressive energy demand trend. This way, the energy supply capacity determines the economic development in the modern world. Energy sources and their finance are obstacles to their consistent increase (Rezai, Taylor e Mechler, 2013).

On a global scale, most greenhouse gas emissions are caused by energy generation. This is because most of the total energy is produced using limited and restrictive dirty sources since their continuous exploitation negatively affects other economic fundamental structures. To mitigate this problem, the most effective solution would be to transition to a new energy generation paradigm based on renewable or green energy sources. However, transitioning to a new paradigm based on renewable energy sources comprises changes in social, political, financial, and institutional layers (Costantini e Crespi, 2013).

The renewable energy transition efforts in social, political, financial, and institutional economy layers have been reported more strongly in recent years as updates on multilateral agreements, political statements, fiscal and monetary incentives, and awareness-raising campaigns (Campiglio, 2016; Costantini e Crespi, 2013; Li e Sun, 2018; Rezai, Taylor e Mechler, 2013; Zhang *et al.*, 2021). These efforts are important to change the economic structure directed to a renewable energy system but may only be enough if designed to connect and reinforce each other.

Even though most green energy generation technology is already available, and its economic advantages make it highly desirable, several factors still hinder its widespread adoption (Li e Sun, 2018; Mohsin *et al.*, 2021). These factors include the uncertainty surrounding financial risks, the lack of sufficient social pressure, the ineffectiveness of political action, and the perpetuation of an exploitative economic structure that is unsustainable but is protected by those who hold significant economic and political power in various sectors of the economy.

As mentioned, a complete solution for the consistent economic increase in this scenario requires multiple and combined efforts to a new paradigm based on exploring renewable energy sources. This work proposes and investigates one of them, the impacts of a real options analysis for evaluating the financing of new green energy projects compared to other less sophisticated evaluation systems. The interaction between different economic sectors and a competitive energy market was simulated from an agent-based modeling. One of the emphases in this analysis was the individual decisions of the banks when there is an option value like an investment criterion and the possibility of exercising the exit option.

Although the historical use of general equilibrium theory for studying policy changes in economic systems, including economic systems that incorporate environmental elements, this research shows why using an agent-based model to evaluate the impact of this green finance model can be the best choice (Nordhaus, 2014). Using a less generalist model structure, the economic representation used here is based on post-Keynesian theory and the relation structure between the agents in this economy on complexity theory. The individual agent behavior, on the other hand, is modeled from the evolutionary neo-Schumpeterian economic theory.

Broadly, the post-Keynesian theory establishes the economic dynamic as demand-led with flexible prices. From the monetary perspective of this system, the post-Keynesian suggests that money is an instrument of trade and a capital asset (Davidson, 1972). In complexity theory, as will be seen, the economic system properties that individual parts cannot deduce(KIRMAN, [s.d.]). This means that although the agent on the system has single features and functions, they are also modular and must be combined with other agent features and functions to compose the system. The evolutionary neo-Schumpeterian economic theory completes the structure of the model, inputting to the agents the evolutionary and adaptative capacity and limited knowledge (but one that can be expanded). Besides, the last also establishes stable or sustainable economic growth as the result of innovative processes carried out by agents. The chance of innovative events and establishing a stable growth path is directly associated (albeit randomly) with the investment dedicated to research and development (Dosi, Fagiolo e Roventini, 2010).

The application of real options analysis with an instrument to evaluate new long-term credits was inspired by numerous energy, engineering, and finance literature studies – most of this research applied to Asian energy projects(Kim et al., 2017; Kim et al., 2014). Although a timeline of ten years of studies, none evaluates the real options analysis effect on a complete economic system integrated. However, all the studies suggest this method is the most useful in uncertain and volatile markets like green energy projects(Kim *et al.*, 2017).

Contemplating the main features that can describe the economic system dynamics and the green energy finance possibilities, the guiding question of this thesis concerns understanding if adopting real options analysis can make green energy finance more attractive for a greater number of financial agents considering complex economic systems. For this purpose, this work is structured to explore the real options analysis as an alternative criterion for green energy financing evaluation (chapter 1), the different models commonly used to assess the effects of one-off changes and changes over time on economic dynamics (chapter 2), and an introduction of a competitive energy sector with SNPV/RO project finance, on an endogenous and stock-flow consistent agent-based model with climate box (chapter 3). Combining this different but complementary analysis provides new insights into the effectiveness of real option analyses in financing green energy. It opens new discussions about the interaction between finance systems, economic policy, and energy transition.

More specifically, Chapter 1 explores the scenario of a global energy transition, the financial uncertainty related to green energy generation projects evaluation, the elaboration and finance evaluation process of these projects, and proposes the use of real option value as a criterion by finance agents in the financing process decision. Estimating real option value uses the Brazilian energy market and worker market data on price, wage, capital utilization, and work productivity. The consequences of these new criteria were investigated and discussed in a Brazilian electrical plant as a case study.

Chapter 2 debates the existing theories and models dedicated to studying the increase in economic analysis, the increase in economic theories and models with an environmental approach, and the advance of these models. This part explores the basis of traditional models like computational general equilibrium, dynamic and stochastic general equilibrium, and agent-based economic models. This discussion shows that Agent-based models can be used to incorporate better and adjust the model presented in Chapter 1 to a complete analysis. That is the analysis of impacts that real option value adoption as an evaluation criterion for green energy projects not just project by project but in a complete economic system.

In the end, chapter 3 intends to analyze the conditions under which real options analysis can make green energy finance more attractive for many financial agents in a complex economic system. The agent-based model is based on a demand-led closed economy with four heterogeneous agents (Banks et al. and Energy firms), a climate box for absorbing and reflecting climatic factors and conditions, the government, and workers. The innovation process is the only way for the persistent economic increase that can be affected by climate change.

The model proposed in Chapter 3 differs from other agent-based models, especially in the competitive energy market (the heterogeneity energy firms subject to a competitive dynamic that defines their participation in the market and their exclusion), and by the new mechanisms for evaluating and granting credit to energy generating firms to build green energy generation plants. Incorporating these points required establishing an energy auction system whose dynamics are defined by the firm’s performance regarding energy generation capacity and energy price signalization. Also, the generation process should consider the construction of green energy plants, which change the dynamics of energy availability. Besides this, the energy firm must interact with the capital-good and consumption-good firms, workers, and banks, not just with energy suppliers or as a borrower but sometimes with a consumer of machinery or workforce. Unlike any other agent model, the bank needs to calculate the net present value of the green projects and the option value. In the amortization process, the bank must consider a grace period and decide whether to exercise the option to abandon the project.

Chapter I

Chapter 01 - Renewable electricity transition: A case for evaluating infrastructure investments through real options analysis in Brazil

1.1. Introduction

The world and the global economy are in constant transformation. In addition, with the persistent evolution of technology and increased available energy, the necessities of most parts of the energy generation process could be more sustainable. As the consolidation of this lifestyle advances, more greenhouse gases (GHGs) are emitted into the atmosphere (IEA, 2017). One reason for this result is the competitive cost of generating electricity using non-renewable energy, which still represents a barrier to the widespread diffusion of renewable energy in developing countries (IEA, 2018).

According to data from the International Energy Agency (IEA, 2018), the main energy source worldwide is oil, followed by coal, gas, hydro, nuclear, wind, biofuel, solar (photovoltaic and thermoelectric), waste, geothermal, and ocean. However, electricity production from non-renewable sources has declined recently (IEA, 2018). Some reasons for the recent improvement have been the new environmental policies and the increased efficiency of renewable electric energy (REE) options. However, these reductions are modest, requiring increasing efforts to establish sustainable alternatives to build medium- and long-term capacity to achieve climate targets in this decade (Elsawah *et al.*, 2020; IEA, 2018).

Despite the consensus that a quick energy transition is needed, the current levels of private funding for “green” energy are still insufficient (Barbrook-Johnson *et al.*, [s.d.]; IEA, 2017; Wüstenhagen e Menichetti, 2012), and it is unlikely that public investments alone will reach the levels, given the huge investments required (Fadly, 2019).

In Brazil, for instance, the situation is not an exception. Public banks such as the National Bank for Economic and Sustainable Development (BNDES) and the Bank of Brazil (BB) are the largest funders of renewable energy (BB, 2022; BNDES, [s.d.]), and another substantial part of in-vestments is made by international development banks such as the European Investment Bank (EIB) and the Agence Française de Développement (AFD). Investments made by the private sector are insufficient and reliant on public policies and incentives (Bloomberg, 2016; CEPAL, 2022). One of the current challenges is stimulating the implementation of REE plants with a good synergy between the private and public sectors. A critical issue is the adequate allocation of financial resources for REE investments, ensuring that the financing of transition projects from non-renewable electrical energy (NREE) to REE is workable.

One major bottleneck in private green energy finance is the need for REE investments (Nelson e Pierpont, 2013). The most common project evaluation practice is based on discounted cash flows based on current market expectations (net present value (NPV)). It considers funds required for capital and operational expenditures (CAPEX/OPEX). However, this project evaluation method must consider that the parties involved could change their strategies as the project develops. This means they must keep the committed resources dedicated to the project after the stipulated financing contract, even if the evolution of the expectations significantly changes the project valuation in due course. Given that green energy projects may require significant financial resources over long periods, such contractual rigidity may easily discourage private sector investment because of the significant uncertainty about some key expected values required by the NPV calculation. For instance, it can be trivially shown that energy prices exhibit significant volatility in the long run and do the expected project revenues and valuation. Considering the uncertainty in the variables employed in an NPV valuation, creditors require higher (internal) rates of return for the projects to be financed, potentially discarding projects that would prove perfectly viable with ex-post assessment.

This chapter proposes a system modeling application to support building evidence promoting Brazil's green transition agenda. The model's core component is adopting a financial evaluation method for renewable energy projects that incorporates the uncertainty of expected returns for the Brazilian economy. To model the agents' decisions, we assume that agents, financiers, and entrepreneurs behave strategically, relying on real options analysis (ROA). ROA complements the investment analysis performed using the Net Present Value (NPV) criteria by including the uncertainty of cash flows and exploring opportunities to change investment decisions in the analysis (Kim et al., 2017). One of the main contributions of this paper is to explore the importance of considering the value of such strategic opportunities when evaluating the NPV when the uncertainty associated with the expected values of critical variables is high, as with REE projects. We incorporate the uncertainty associated with variables such as wages and labor productivity in the ROA analysis as a complement to what has been discussed over the years by authors such as Kirkland (2007), Batista et al. (2011), Zavodov (2012), and Kim et al., (2017).

Specifically, Kjaerland (2007) showed that applying real options adequately explains Norway's aggregate investment in hydropower. Batista et al. (2011) showed that the expected value based on real options became superior to the traditional NPV approach by incorporating the possible strategic flexibilities in project development.

Zavodov (2012) discussed how applying real options, especially in hydropower projects, could be efficient in developing economies. Kim et al. (2017) proposed a framework for evaluating renewable energy investment based on real options. However, none considered the importance of variables such as wages and labor productivity. Volatility in the forecast of essential factors, such as wages, productivity, (imported) equipment prices, and exchange rates, has been historically high, particularly in developing countries.

The next section of the paper presents the literature review from the perspective of decision-making, project evaluation, and finance. The third section describes the proposed valuation model, and the fourth section applies the model to a hydropower plant in Brazil, including sensitivity analysis based on accurate data. Section five discusses the findings, and section six concludes the paper.

1.2. Literature review

1.2.1. Wider landscape for global energy transition

Increasing evidence indicates how changes in the physical and biological systems relate to increased greenhouse gas (GHG) emissions into the atmosphere. The increase in global average temperature has proven to be a significant factor in measuring such changes, as shown by more frequent extreme weather events in different regions of the world (IEA, 2020a). According to Loureiro (2019), the development of a global economy that favors the energy transition was marked by four events: (1) the enactment of the American environmental policy in 1969 (NEPA), (2) the United Nations conference in Stockholm in 1972, (3) the publication of the report “Our common future” in 1987, and (4) the United Nations conference in Rio de Janeiro in 1992 (Rio-92) (Loureiro, 2019).

To monitor the progress of the commitments made in Kyoto (UNFCC, 1997), a series of conferences were held until 2012. In 2015, at COP-21 (21st Conference of Parties), the “Paris Agreement” was approved, and it was determined that the increase in the planet’s average temperature should not exceed +2 °C above pre-industrial levels. However, it was only at COP-22 that rules were defined to enable the fulfillment of the Paris Agreement. The most recent conference, COP-27, in 2022 in Egypt, among other key points, suggested that the new climate target should be limited to +1.5 °C of global temperature increase compared to preindustrial levels. Although 1.5 °C may seem a non-significant increase in the global north, it may be categorical for the future existence of some coastal cities in the global south (WRI, 2021).

As IEA (2020a) highlights, the power generation sector sustains modern society by supplying energy but is responsible for most GHG emissions. Thus, there is enormous potential for climate change mitigation related to reducing GHG emissions associated with power generation. In 2020, power generation was responsible for 40% of CO2 emissions worldwide, making the focus on alternative technologies evident (IEA, 2021).

According to the United Nations Renewable Energy Observatory for Latin America and the Caribbean (UNIDO), among the options for renewable electricity energy (REE) generation, we have (1) hydropower, (2) geothermal, (3) wind, (4) ocean, (5) solar, and (6) biomass (OHCR, 2023). As the IEA (2017, 2018, 2022) report shows, the diversity of renewable sources in power generation has transformed the sector globally, and the advancement of REE generation sources has outpaced the growth in electricity demand (IEA, 2020a). Despite this, the investment in these projects remains primarily affected by uncertainty due to the impact of the agents' decisions, which can be linked to macroeconomic and microeconomic variables (Bangjun et al., 2022; Dokas et al., 2023).

1.2.2. Accounting for uncertainty in projects evaluations

From a macroeconomic perspective, uncertainty is primarily linked to the possibility of changes in regulatory policies that might alter the conditions of the REE generation market, affecting, for instance, variables such as interest, exchange rates, or employment levels (Jaafari, 2001). From a microeconomic viewpoint, uncertainty may be related to factors such as the scarcity of raw materials, technical difficulty, availability of skilled labor, and volatility of electricity demand, among others (Barbosa, 2016).

If the uncertainty is related to the possibility of regulatory changes affecting the interest and exchange rates, the agents involved can use the contract as a mitigating tool for this uncertainty. An economy's employment and disposable income level directly impact energy consumption but cannot be stipulated in a contract (Correia-Silva et al., 2016; DWIH, 2022). In this case, agents’ decisions and strategies end up being guided by long-term expectations about the behaviors of these variables. As Carvalho (2014) pointed out, these expectations must be supported by past and current performance estimates.

Regarding the availability of raw materials, uncertainty in REE generation projects is also associated with climate change. Barbosa (2016) shows that the raw materials of REE come from natural cycles that are currently abundant, although distributed in different proportions globally. Despite this, these sources of electricity are subject to the conditions of nature. Thus, a change in climate patterns could affect the production of REE for an extended period, with direct implications for the price of REE.

The price of electrical energy (EE) (usually charged per unit of energy in kilowatts per hour-kWh) includes the costs incurred in the generation and distribution process to consumers and includes charges and taxes. In addition, given the essentiality of EE, its full-time availability is also included in the price. In this sense, the scarcity of raw materials and any technical difficulty that generates uncertainty about the project's expected result affect the energy price (ANEEL, [s.d.]).

In general, we can summarize the uncertainties in the project development in two groups: (1) the uncertainty arising from the risks directly associated with the project performance and (2) the uncertainty arising from the risks linked with the country's business environment (Aguiar, 2010). In the first group, Araújo de (2006) distinguished the construction, operation, and financial risks, i.e., construction delay or abandonment or unexpected cost increase, choice of inappropriate technology, environmental risk, wrong estimates, lack of inputs, consumer market, inadequate product price, significantly high-interest rates, and exchange rate risk. Specific economic, political, social, and geographical characteristics are associated with the second group. For example, regulatory, institutional changes, tariff adjustments, tax changes, sudden changes in monetary, fiscal, or exchange rate policies, uncontrolled public deficit, or private debt (Araújo, de, 2006).

As a result, the development of project financing must maintain a certain level of certainty. This is because even when using approaches such as Project Finance, a financing modality directed to implement large infrastructure projects, the existence of distinct stages in the project's development spreads the uncertainty on several factors or agents. In this paper (see Section 3), we are considering uncertainty from the perspective of both groups, highlighting the possibility of oscillations in variables such as energy prices or tariffs, wages, utilization, and labor productivity.

1.2.3. The implementation stages of renewable energy projects

Schematically, the implementation of an REE project can be summarized in three stages, as shown in Figure 1: the first stage consists of the design and evaluation of the project, i.e., the elaboration of the Base Project; the second stage contemplates the execution of the Base Project, e.g., the construction of the power plant; the third stage refers to the operationalization of the plant.

In the first stage, there must be a study about the location and the community that will be served by the project (Neves et al., 2014). Electricity demand patterns differ based on geographical location and cultural habits. In addition, the community's economic structure should be evaluated because the profile of existing economic activities (such as farming, industry, tourism, and services) can affect the efficient production of energy (Neves, Silva, e Connors, 2014). When characterizing the power generation system, it is important to distinguish between autonomous and grid-connected systems. Autonomous systems should be able to respond to demand peaks independently and indifferently from grid-connected systems (Steinke et al., 2013). In summary, the first stage in preparing an REE project consists of a detailed definition of the electricity demand and the available generation possibilities and an assessment of the negative impacts caused by the plant in the targeted region (Mercure and Salas, 2012).

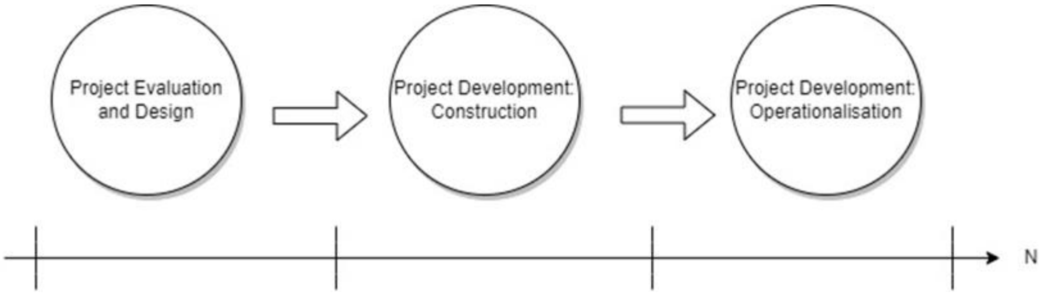

Figure 1 Summary of EER project implementation steps
Source: Own Elaboration

The second stage of the project, the construction of the REE plant, represents the most significant expenditure for project implementation. For this reason, in many hydroelectric projects, the viability of the plant construction is evaluated through the Gibrat ratio (Bezerra et al., 2011). In this case, the smaller the ratio between the length of the dam and the energy production capacity, the greater the feasibility. At this stage, the environmental impacts arising from the plant's construction, whether related to fauna or flora, must be mitigated.

The responsible organization in the country usually supervises the last stage (operationalization). In Brazil, the federal agency responsible for the coordination and control of the operation of power generation plants is the National Interconnected System (SIN), and the planning of the operation of isolated systems under the supervision and regulation of the National Agency of Electric Energy (ANEEL), is the National Electric System Operator (ONS) (ONS, 2021).

Although essential, SIN, ANEEL, or ONS still need to decide which projects will be financed. As mentioned, their scope of action is to coordinate, supervise, and regulate, respectively. As explained in the following section, the evaluation is an economical process.

1.2.4. Economic evaluation of REE generation projects via ROA

Historically, infrastructural investment in Brazil has relied mainly on public sources of capital (Ferreira and Malliagros, 1999). Even if precise figures are not available, there is evidence that the role of private creditors in renewable energy finance is mainly as a mediator of public institutions' programs, such as National Bank for Economic and Sustainable Development (BNDES) Fundo Clima or Finem "indirect support" modality or BNDES Garantia and FGI credit guarantee instruments (BNDES, 2022, [s.d.]).

The Brazilian regulatory framework may justify the risk aversion of public entities (like BNDES) in requiring substantial credit guarantees from candidate projects (BNDES, 2022). However, such constraints may not apply to private creditors when supplying funds. Understanding the regulatory conditions that can influence the behavior of (actual) private finance of renewable energy and increasing their support for the green transition are vital issues to be addressed by policy analysts and decision-makers. Supporting a regulatory framework that enables new financing agents and models is crucial for a successful green transition in developing countries where investment credit has been historically scarce and expensive, such as Brazil (BNDES, [s.d.]).

The process valuation of a project includes identifying and quantifying the benefits and harms attributable to its implementation over a given period. In scholarly works, numerous techniques have been suggested to determine or define workable factors. (Bordeaux-Rego, 2015). Among the commonly used methods are discounted cash flow, net present value (NPV), and, more recently, the real option analysis. Real option analysis (ROA) has been increasingly used in evaluating renewable energy projects (Lee et al., 2013; Lee, 2011; Lee e Shih, 2010), and it can be seen as a complementary part of the traditional evaluation process.

Unlike usual financial options, where the underlying assets are liquid (easily traded), real options are applied to real assets such as investment projects. The key idea is that the parties involved (i.e., creditor and developer) may change their decisions about the financing and development of a project after it started without incurring a breach of contract or litigation (Mun, 2012). There are distinct types of Real Options, as Gazheli et al. (2018) highlight:

- Postpone the possibility of waiting to invest in the project. More information on future market and production conditions is required to make an irreversible investment.
- Abandon the opportunity to abandon the project and return any residual value.
- Alter flexibility to change the project by altering the form of production, given future market and production conditions.

When receiving finance requests, and where the economic environment or the future context is uncertain, the creditor may wish to wait a certain period before deciding whether to invest in a renewable energy project. In such a case, the deferral option offers the chance to participate in such projects at some point in the future. The change option, on the other hand, would enable the agents to switch to technologies or business models that prove to be more profitable over time. Alternatively, if a project offers different ramifications, such as wind, solar, or hydro, the investing agent can acquire the right to switch between technologies according to the market feasibility.

The exit option provides both agents (creditor and developer) the right, but not the obligation, to leave the project before the fixed term, i.e., if for any reason the project's financial performance is affected negatively, both the creditor and the developer may (within an agreed period) opt to exit the credit operation, therefore, allowing opportunities to change investment decisions. As a result, the creditor may abstain from the obligation to finance other stages previously established in the contract, and both agents must agree on the period(s) in which they can exit. Furthermore, the exit option does not exempt the developer from paying the borrowed amount. Therefore, the exit option provides an alternative instrument for reducing the risk taken by the creditor.

To clarify the difference between real and financial options, the following situation is proposed: Suppose that the Brazilian company (Petrobrás, 2024), a company that deals with commodities, expects oil prices to fall in the future; it can buy oil put options and manage exposure to the risk of fluctuations in oil prices. In these cases, the strategy used by Petrobras is to guarantee the right to sell oil at a higher strike price if oil prices decrease by financial option. On the other hand, an oil company, such as Petrobras, may decide to invest in exploring an oil reserve. However, exploration is usually a multi-stage process, and the company can give up at any stage. For example, after the first exploration phase, the company may discover that the reserve is smaller than expected or that oil prices have fallen. In this case, the company can relinquish the project, thus avoiding further investment and possible losses. Unlike financial options with standardized contracts traded on stock exchanges or over-the-counter markets, real options are flexible and specific to each company and situation.

The valuation of real options in investment projects can be computed using different methods, as shown in Table 1. According to Marques, Bastian-Pinto, and Brandão (2020), the binomial lattice method emulates the option valuation method presented by Black e Scholes (1973), and, as it does not require tractable statistical models, it allows for far greater flexibility on the option formats that can be valued.

Table 1 Real Option analysis methodologies applied to renewable energy projects (in chronological order of completion)

Authors	**Country**	**Type ER**	**Method**
(Hoff, Margolis & Herig, 2003)	California	Photovoltaic	BT
(Zhang *et al.*, 2005)	Non-Regional	Hydraulics	SIM
(Kjaerland, 2007)	Norway	Hydraulics	PDE
(Kumbaroğlu, Madlener and Demirel, 2008)	Turkey	Wind	PDE
(Lee, 2011)	Taiwan	Wind	BT
(Yang *et al.*, 2010)	China	Wind	SIM
(Batista *et al.*, 2011)	Brazil	Hydraulics	SIM
(Lee e Shih, 2010)	Taiwan	Wind	EA
(Zavodov, 2012)	China	Hydraulics	EA
(Reuter *et al.*, 2012)	England	Wind	PDE
(Boomsma, Meade, and Fleten, 2012)	R. Nordic	Wind	AMMO
(Lee *et al.*, 2013)	Indonesia	Hydraulics	GT + SIM
(Kroniger and Madlener, 2014)	England	Wind	PDE + SIM
(Kim, Lee, and Park, 2014)	Korea	Wind	BT
(Abadie and Chamorro, 2014)	UK	Wind	PDEPDE
(Weibel and Madlener, 2015)	England	Wind (onshore and offshore)	AMMQ
(Jeon Lee and Shin, 2015)	Korea	Photovoltaic	MP
(Zhang *et al.*, 2005)	China	Photovoltaic	PDE
(Kim *et al.*, 2017)	Korea	Hydraulics	PDE
(Agaton and Karl, 2018)	Philippines	ER	PDE + AMMQ
(Gazheli and Bergh, Van Den, 2018)	Non-Regional	Solar and Wind	PDE

Legend: PDE = Partial Differential Equations; BT = Binomial Tree; SIM = Simulation; PD = Dynamic Programming; EA = Empirical Analysis; AMMQ = Monte Carlo Least Squares Approach; GT = Game Theory; MP = Probabilistic Model. Source: Own Elaboration

The application of the binomial tree method comprises two stages. The first comprises the project valuation and the application of Equations (1) and (2). The second stage comprises valuing the project option and applying Equations (3) and (4).

To construct the binomial valuation tree for a project whose investment S_0 at the initial point of valuation (n = 0), we start a binary tree (two branches starting from each node) with the root node at n = 0. At each n subsequent period, the value S_n of each node, relative to the value of the option to defer the investment decision from 0 to n, is unfolded into two new nodes, relative to the time point n + 1. N represents the total number of decision moments considered in the calculation. Decision moments do not represent linear units of time (t) but only a sequence n = 0,1, …, N relative to each moment in which the agents may make or value a decision on the investment.

The value of the project in each of the two new nodes of the tree is obtained by multiplying the value of the previous node $S_{\{n-1\}}$ by the risk factors ϕ_u e ϕ_d. Figure 2 presents the binomial tree for a three-step decision process ($\mathrm{N} = 3$). The value SI at node I, for example, can be got by the product $S_0\phi_u\phi_d^2$ the value at node I, which, for example, can be got by the product got by the ABEI path or by the numerically equivalent ACEI or ACFI paths. The paths represent the various possibilities of project development, given the uncertainty. The products represent how the additional information is incorporated into the project valuation. Thus, each node represents the future values of the project and is positioned at a constant logarithmic distance. This means that a discrete process and state can approximate the stochastic value of the project in continuous time and state.

After constructing the binomial tree of project valuation, the options valuation tree of the model can be developed. Kim, Lee, and Park (2014) applied the backward induction method. This method proposes that the values of the last and intermediate nodes of the option valuation tree are obtained by subtracting the difference between the values in the project valuation tree and the initial investment.

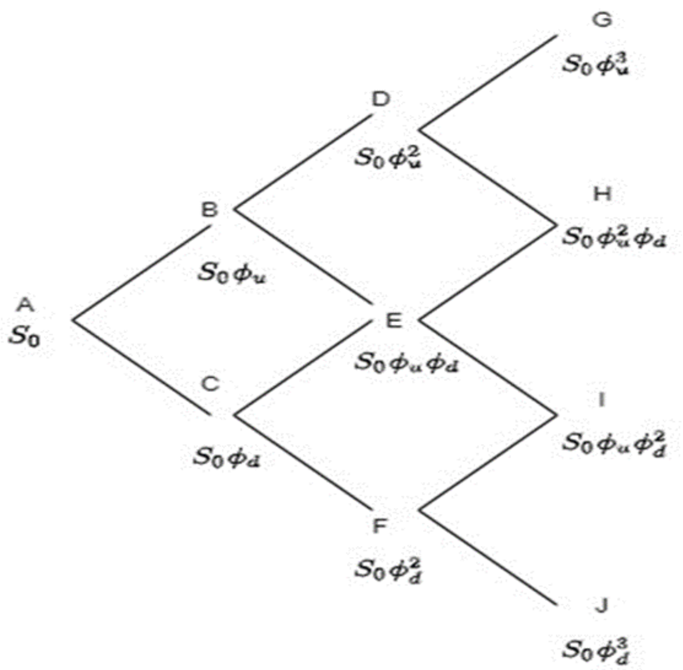

Figure 2 Example of the binomial tree of project valuation with three decision steps
Source: Own Elaboration

To calculate the value of each option OV_n recursively, we discount from the value of subsequent nodes $OV_{n+1}^{u,d}$ the risk-free rate r weighted by the risk-neutral probability q.

Figure 3 presents the binomial option valuation lattice for a three-step decision process $(\mathrm{N} = 3)$.

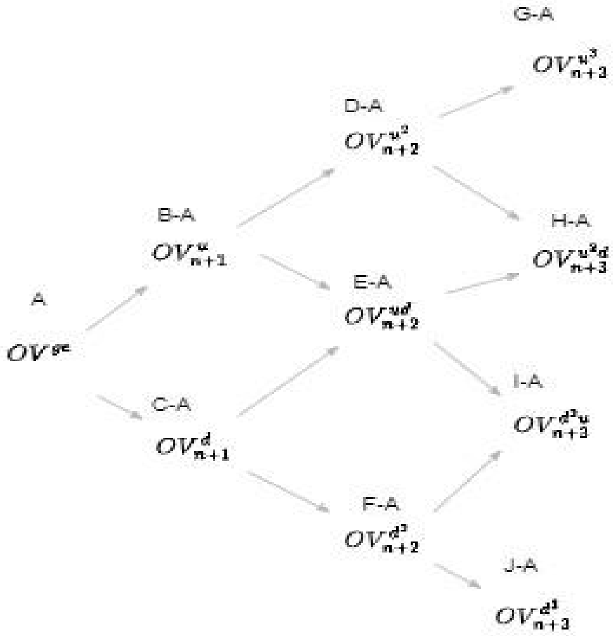

Figure 3 Options Valuation Tree
Source: Own Elaboration

The decision tree model gives the investor an overview of the investment, highlighting alternatives and option values and reducing project risks. According to Castro Rodrigues and Rozenfeld ([s.d.]), this method is used mainly when asset values cannot be determined analytically. When no “closed” mathematical formulas describe the researched phenomenon, other models are required, such as the binomial lattice and Monte Carlo simulation.

1.2.5. Discounted cash flow and strategic net present value

The project's discounted cash flow (DCF) is obtained from the sum of the difference between income and expenses in each period, duly adjusted by the time value of money (interest rate). The DCF consists of projecting the project’s future results, adjusted for a single period. The discount rate applied is the weighted average cost of capital (WACC), according to Fernandez (2010), and reflects the project’s capital cost structure.

Strategic net present value (SNPV) is an adaptation of the discounted cash flow method and the concept of net present value (NPV) to the context of decisions that can be postponed. The SNPV includes the option value of abandoning or modifying the project after its start in the analysis (Kim et al., 2017).

According to Silva and Fontes (2005), in calculating NPV, flows are intrinsically fixed since all decisions are taken simultaneously in $\mathrm{n} = \mathrm{t} = 0$ and are defined as the difference between the present values of revenues and expenses throughout the project.

As Abdelhady (2021) explains, NPV is an indicator of the economic viability of a project. A positive NPV indicates that the project is viable during analysis, considering the information available thus far.

When considering the option value (of deciding in the future), as presented above, agents incorporate the value of potential future decisions into the analysis. This could mitigate losses in the unfortunate scenario where the project does not develop as expected. According to Kim et al. (2017), using SNPV as a project evaluation method is a superior alternative to NPV for projects with uncertainty in their main variables, as is the case of REE. For example, REE projects have a volatile cash flow due to the uncertainty in future market conditions that imply considerable risk, for which the possibility of abandonment has a real value that needs to be considered in the project evaluation.

The logic for comparison of financing decision-making can be illustrated with the following example. Looking at the interaction between agents, a financier, and an entrepreneur, the investment in REE can be schematically separated into three moments. In the first stage ($\mathrm{n} = 0$), the technical–economic design of the REE plant is conducted, and its development schedule is determined. At this moment, the entrepreneur must use their resources to complete the necessary documentation. If the investment is made on a project finance (PF) basis, the expected performance of the project is the primary information the financier needs. Therefore, the projected cash flows need to be thoroughly examined (Steffen, 2018) and the NPV computed.

In the second step ($\mathrm{n} = 1$), the key performance variables are identified and assessed for uncertainty, and the project's true value can be calculated using the SNPV. If the project is not feasible ($SNPV$ negative), both agents abandon the project. In case of continuity, the financier provides the necessary resources for the entrepreneur to start the plant's construction.

In a third moment ($\mathrm{n} = 2$) after construction and before the power plant starts operating, agents can again evaluate the decision to proceed with the project based on updated information and less uncertainty.

Figure 4 presents the project stages from the entrepreneur’s perspective. Although the entrepreneur performs the first action, i.e., to present the project for financing, it is only after a (possible) proposal from the financier for the interest rate and the resulting evaluation of the SNPV that the first decision moment occurs (n = 1): to start the project development, building the plant, or to reject the proposal and abandon the project. In the second step (n = 2), after the construction of the plant, if market conditions make the pre-agreed performance of the project unfeasible, the entrepreneur may choose to abandon the project, taking back any residual values or proceed with the operation of the REE plant.

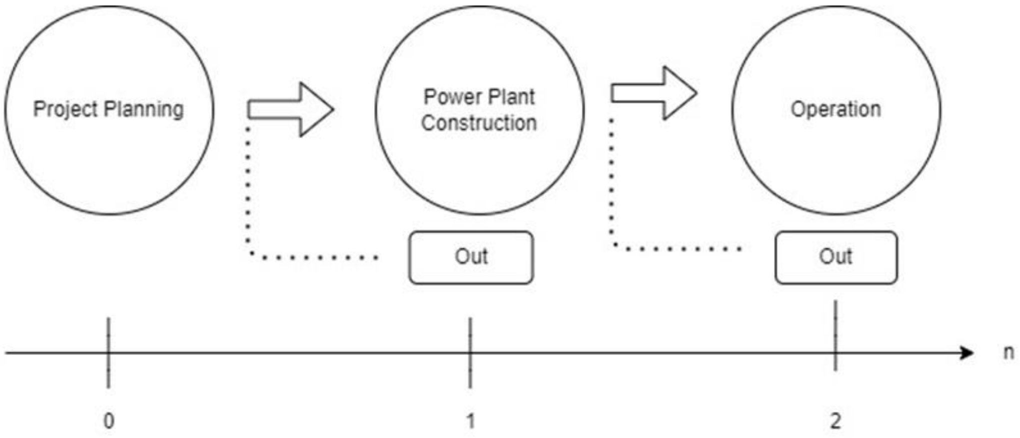

Figure 4 Project stages (entrepreneur)
Source: Own Elaboration

After analyzing the project, the financier's first decision $(n = 1)$ is to offer or not the financing. After that, the lender will finance the capital expenditure (capex) if the entrepreneur accepts the financing. The second decision $(n = 2)$ of the lender, after construction, is to continue (or not) with the financing of the operational expenditure (OPEX), as shown in Figure 5. For both agents, as shown in Figures 4 and 5, the abandonment option may include recovering part of the invested amount by liquidating the remaining assets.

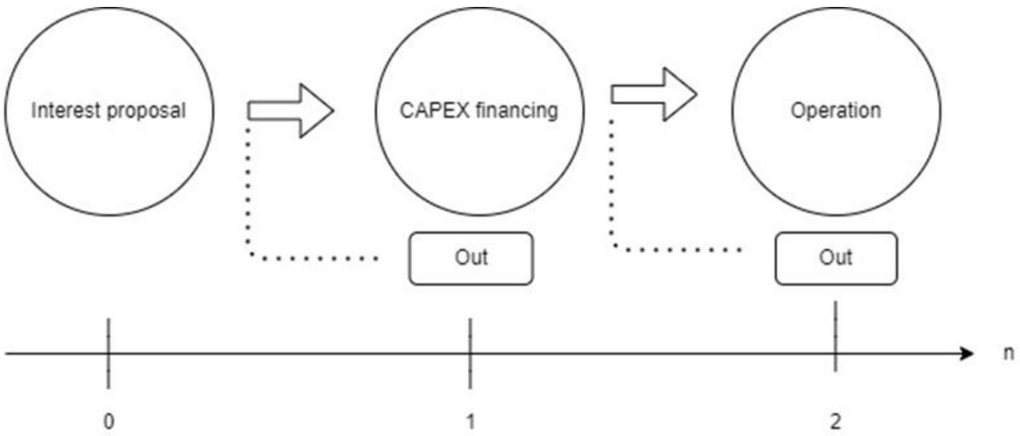

Figure 5 Project stages (bank)
Source: Own Elaboration

Generically, Figure 6 presents an example of the relationship between the project's cash flow and the agents' decisions. The depreciation of the financed value will only occur when the plant is already operating, as usual in Project Finance (FP). Nevertheless, the investment should occur at the start of the project, with the amount corresponding to CAPEX. During project execution, if both parties decide to continue the project, the resources destined for OPEX should still be spent. Access to tranches of funding occurs according to the achievement of pre-agreed performance levels (key performance indicators or KPIs) (George, 2019).

According to Yescombe (2002), project finance has two main phases: construction and operation. As exemplified in Figure 6, after the financing is agreed upon, the entrepreneur has several periods dedicated to constructing the plant. At the end of this period, both agents must decide to abandon and continue the project. Once the decision to continue is taken, the REE plant has an expected number of helpful life periods.

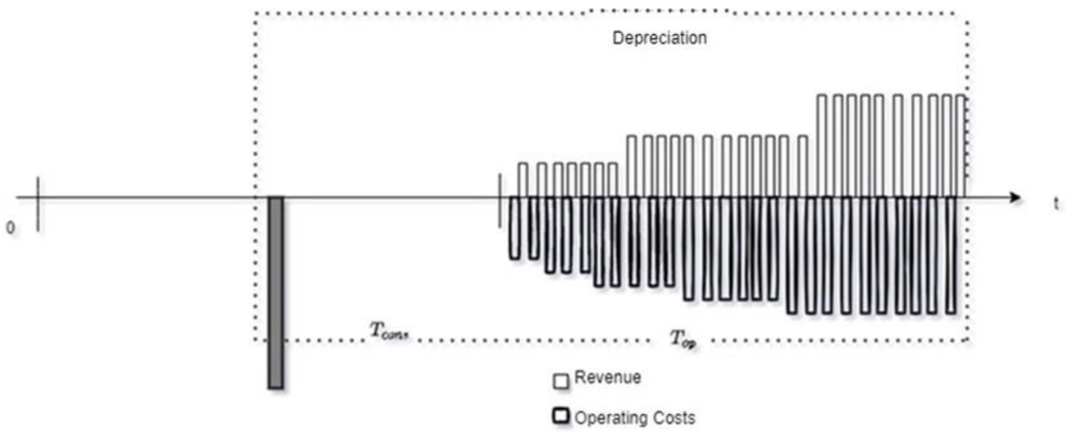

Figure 6 Example of a simplified cash flow
Source: Own Elaboration

1.3. Proposed Model Synthesis

Given the context and the project evaluation method presented in the previous sections, this section synthesizes the real options (RO) model in REE projects. The application of RO requires: (1) the initial definition of a moderate scenario used to apply the valuation method of an estimate the option value of the project; (2) a binomial lattice model applied to renewable electrical energy REE; and (3) the use of discounted cash flow (DCF) or net present value (NPV).

1.3.1. Model Purpose

This model presents solutions to the public and private funding shortage for green electricity. We focus on the potential for applying exit options for renewable energy projects in developing countries, such as Brazil. The RO approach has been applied in various countries' wind, solar, and hydroenergy projects (see Table 1). However, we have no information about the application of RO with Brazil, likely because of the absence of an instrument in the standard credit models proposed by (BNDES [s.d.]). Here, we apply the real options analysis framework proposed by Kim et al. (2017) and briefly discuss the potential of exit options to boost REE financing. We focus on Brazil, where almost seven thousand publicly funded infrastructure projects (with a total contract value of R$9.32 billion) were suspended between 2012 and 2021 (among those, there were renewable energy projects that were paused in the project's mid-execution, probably for insufficient funding, or changes in expected outcomes). This highlights the need to review how projects are evaluated and approved (CNM, 2022).

Considering the increased uncertainty in a developing country, a deeper exploration of the RO alternative can enable financing a group of projects that otherwise would not be viable. The great potential is to use these variables as parameters to understand the volatility of the project and define the cost of this volatility through the option value.

Our contribution is to propose a simple model to evaluate projects by considering variables that can reflect on the NPV performance of an infrastructure project and the country's business environment. We focus on four variables: wages, labor productivity, capital utilization, and service tariff. As a result, we incorporate volatility arising from the labor market and the consumer energy supply-and-demand market in the valuation model. While higher labor productivity can reduce costs and make the project NPV more effective, higher wage growth than labor productivity may offset the positive outcome of efficiency. We use wages and labor productivity to exemplify typical sources of project volatility and define the implicit 'cost' of this volatility through an exit option value. For completeness, we also consider two additional variables, service (energy) tariffs and capital utilization (service/energy demand), in our model, as we expect that the higher these variables are, the higher the supply and the higher the volatility of the project.

The projected cash flow is estimated and first evaluated as standard project evaluation and analysis practices. Equations (1) and (2) represent the cash flow of a simplified REE project, i.e., the cash inflows and outflows throughout its execution, considering discrete time t = 0,1,2 … T. The only input considered is the operational revenue by period, i.e., the value obtained when executing the project. As for the cash outflows, we have the investment (CAPEX) in the plant's construction and the operational cost (OPEX), referring to the expenses in its operation.

In this model, operating revenue S_t^e, in each period t is determined by three variables: the tariff (price) per unit of energy sold p_t^e in each period t and the plant's installed capacity K_{t-1}^e in each period t-1 , and its level of utilization u_t^e in each period t, according to Equation (1). Among the three variables, only the installed capacity is fixed. The tariff p_t^e and utilization u_t^e are defined based on supply and demand in the electricity market.

$$S_t^e = p_t^e \, K_{t-1}^e u_t^e \tag{1}$$

The operating cost (OPEX) a C_t^e in each period t is determined from the average wage w_t labor productivity(A_t^e), and the installed capacity K_{t-1}^e (see Equation (2)). The operating cost C_t^e does not vary with the level of utilization u_t^e of the plant, and c_t^e expresses the unit fixed cost per unit of installed capacity. For simplicity, we consider the unit variable cost to be zero. The average wage w_t follows the dynamics of the labor market. Labor productivity A_t^e, on the other hand, is initially estimated ($\tilde{A}^e$) but it becomes known (and kept constant) at the beginning of the project's operation.

$$C_t^e = c_t^e \mathrm{K}_t^e \qquad c_t^e = \frac{w_t}{\tilde{A}^e}$$

2

It is essential to note that developing an energy plant assessment of future conditions involves uncertainty. Thus, we assume four cash flow variables as uncertain: the tariff (price) p_t^e the utilization of the plant u_t^e plant utilization, workers' salaries $w_t$and the plant's productivity A_t^e. The uncertainty amplifies the investment risk for both the financier and the entrepreneur. That is why, as Salles de (2004) explains, the financial risk should always be evaluated, and, as Porter (2004) proposes, this can be performed by adopting future scenario exploration. Ribeiro, Correia, and Carvalho (1997) highlight Godet's method among the different scenario analysis approaches. Godet's method is characterized by morphological analysis of variables and the most critical future-bearing facts. As shown in Table 2, the expected scenarios may be presented in a matrix format, thus presenting the intrinsic risks of every variable in our model. From this technique (i.e., the three-point estimation technique), three scenarios are proposed for every variable: the best, the worst, and the moderate (Vizireanu & Preda, 2013). The historical moving average of the variables usually represents a moderate scenario. The extreme and symmetric scenarios are defined based on the parameters (δ_p), (δ_w), (δ_u), and (δ_A), which indicate the expected amplitudes of uncertainty.

Table 2: Scenarios of evaluation of the expected values of variables with uncertainty in the renewable electrical energy plant project

Variables	Scenarios		
	Best	Moderate	Worst
Tariff	$(1+\delta_p)\tilde{p}^e$	$\tilde{p}^e$	$(1-\delta_p)\tilde{p}^e$
Salary	$(1-\delta_w)\tilde{w}^e$	$\tilde{w}^e$	$(1+\delta_w)\tilde{w}^e$
Use	$(1+\delta_u)\tilde{u}^e$	$\tilde{u}^e$	$(1-\delta_u)\tilde{u}^e$
Productivity	$(1+\delta_A)\tilde{A}^e$	$\tilde{A}^e$	$(1-\delta_A)\tilde{A}^e$

Source: Own Elaboration

Once estimated, the cash flow makes it possible to determine the present value of the investment through NPV analysis. Equation (8) presents the expected NPV of our project model, assuming that the payment for construction is executed only on the project's completion:

$$NPV^{ge} = -\frac{K^e\, c^e}{(1+r)^{T_{con}}} + \sum_{t=T_{con}+1}^{T_{con}+T_{op}} \frac{\Pi_t}{(1+r_{deb})^t}$$

3

In short, the NPV shows the operating result of the enterprise and the difference between operating revenues and costs in the period t. In Equation (3), the variable T_{con} represents the duration of construction, and T_{op} is the plant's operational life. K^e is the installed capacity, and c^e is the expected unit cost. The variable r expresses the risk-free interest rate. In contrast, r whereas r_{deb} is the contracted interest rate for the project (WACC).

To estimate the project's profitability volatility, we must first evaluate it under extreme conditions. Equation (4) represents the present value of operating income under the best-case scenario, whereas Equation (5) represents the present value under the worst-case scenario. The first term in the numerator of both equations consists of the highest (lowest) expected revenue, i.e., the multiplication of the average expected prices and utilization in the best (worst) case scenario. The second term in the numerator consists of the projection of the lowest (highest) average expected cost, i.e., the lowest (highest) wage and the highest (lowest) productivity.

$$\Pi_t^M = \sum_{t=1}^{T_{op}} \frac{(1+\delta_p)\tilde{p}^e \cdot (1+\delta_u)\tilde{u}^e \cdot K^e - \frac{(1-\delta_w)\widetilde{w}^e}{(1+\delta_A)\tilde{A}_t^e} \cdot K^e}{(1+r_{deb})^t}$$

4

$$\Pi_t^P = \sum_{t=1}^{T_{op}} \frac{(1-\delta_p)\tilde{p}^e \cdot (1-\delta_u)\tilde{u}^e \cdot K^e - \frac{(1+\delta_w)\widetilde{w}^e}{(1-\delta_A)\widetilde{A_t^e}} \cdot K^e}{(1+r_{deb})^t}$$

5

As previously mentioned, from the extreme expected operating results, and if the project's operating result has a log-normal distribution, we can obtain the expected variance σ^2 from Equation (6).

$$\sigma_t^2 = \frac{\log\left(\Pi_t^M - \Pi_t^P\right)}{\sqrt[4]{T_{op}}}$$

6

Considering the objectives of the agents (entrepreneur and financier) and the proposed evaluation methodology, we will propose an (extremely) simplified model of the agent's decision process. At the beginning of the project (m = t = 0), the entrepreneur proposes the project to the lender only if the condition of positive expected SNPV is met ($SNPV_0$ > 0) (Equation (11)) and based on the expectations of the interest rate $\tilde{r}_{deb}$ that the financier would practice Based on the assumption of a log-normal distribution of risks, the factors ϕ_u and ϕ_d are calculated according to the equations:

$$\phi_u = e^{\sigma \sqrt{\Delta t}}$$

7

$$\Phi_d = \frac{1}{\phi_u}$$

8

where the factor ϕ_u describes the positive variation in the asset value per period, and the factor ϕ_d the negative variation. From the risk-free interest rate r (or the interest rate $\tilde{r}_{deb}$), the risk-neutral probability q can be approximated by Equation (9).

$$q = \frac{e^{r\,\Delta t} - \phi_d}{\phi_u - \phi_d}$$

9

Thus, the option value is calculated using Equation (10). The variable OV_n^{ge} is the option value that is obtained recursively (Figure 3) by discounting the risk-free rate r weighted by the risk-neutral probability q from the value of subsequent nodes $V_{n+1}^{u,d}$:

$$OV_n^{ge} = e^{-r\,\Delta t}\,[q\,NPV_{n+1}^{u} + (1-q)NPV_{n+1}^{d}\,]$$

10

The strategic net present value $SNPV$ is determined as follows:

$$SNPV = NPV^{ge} + OV^{ge}$$

11

Where Net Present Value (NPV) is the difference between revenues, investments, and costs discounted by the WACC. OV_0^{ge} represents the value of the option to abandon the REE project.

In the following period (m = t = 1), the entrepreneur reassesses the Strategic net present value (SNPV) of the project's realization with the interest rate r_{deb} offered by the bank. They proceed with the construction of the plant if the value is positive ($SNPV$ > 0) under the current conditions of the energy and labor markets (Tariff, demand (usage), and wage values may have changed since period 0 altering the scenario). In this case, the bank provides the first part (tranche) of the financing to cover the capital costs.

In the next step (m = 2, t = T_{con} + 1), after the construction of the plant, the entrepreneur proceeds with the project if and only if the operating NPV is positive under current market conditions. It is worth noting that the initially agreed-upon rate (r_{deb}) may no longer be adequate for the bank under market conditions as interest rates vary.

1.3.2. Model Application to the Brazil Case of Itumbiara

The electricity sector in Brazil is divided into generation, transmission, distribution, and commercialization. Simplistically, generators produce energy, transmitters transport it from the point of generation to substations in large consumer plants, and distributors take it from there to citizens' homes and companies. The Brazilian energy sector is made up of public power companies and institutions (e.g., the National Agency for Electrical Energy (ANEEL), Eletrobrás, and the Energy Research Company (EPE)) and private initiatives that operate on different fronts, from generation to distribution, including the regulation of the sector. ANEEL is responsible for (i) implementing the federal government's policies and guidelines for the exploitation of electric power and hydraulic potentials and (ii) regulating the granted, permitted, and authorized services by issuing the necessary regulatory acts (ANEEL, 2022a; b). The purpose of the EPE is to provide research services to the Ministry of Mines and Energy (MME) to support the planning of the energy sector, covering electricity, oil, and natural gas and their derivatives and biofuels (EPE, 2000). ANEEL organizes and approves the energy auctions held to contract the purchase of electricity by delegation and following the guidelines of the Ministry of Mines and Energy (ANEEL, 2022a).

We consider the project for a plant such as the Itumbiara Hydroelectric Plant, the largest plant in the Furnas System (Brazilian hydroelectric power plant systems with facilities in the states of São Paulo, Minas Gerais, Rio de Janeiro, Espírito Santo, Paraná, Goiás, Mato Grosso, Mato Grosso do Sul, Pará, Tocantins, Rondônia, Rio Grande do Sul, Santa Catarina, Ceará, Bahia, and the Federal District). In terms of generation potential, the Itumbiara Power Plant is considerably smaller than the Itaipu Power Plant, one of the largest power plants in the world, being able to generate around 85% less than the Itaipu plant (GOV, 2019). The project's total investment (construction) is USD 187,589,100 and is expected to last 47 years. The first seven years were dedicated to construction, and the remaining 40 years were dedicated to operation (concession period). We consider the same periods in this simulation. Table 3 summarizes the expected values for the project (moderate scenario). There is no precise information on how long of time was needed for the planning and deduction of the project's finances. Therefore, this assessment assumes that the project finance has already been prepared and is ready for evaluation by the investing agent. The information regarding the necessary investment amount, as well as schedules and the other variables presented in Table 3, were obtained through official institutional channels, such as (ANEEL, 2022c, [s.d.]), (BB, 2022), (BNDES, 2022, [s.d.]), and (EPE, 2000).

Table 3 Example design data for a hydropower plant (moderate scenario/0, value in US dollars.

Description	Values
Installed generation capacity (K^e)	$2.3994 \times 10^6\ MWh$
Unit investment cost (c_i^e)	$187{,}589{,}100.00\ million\ USD$
Construction period (T_{con})	$7\ (years)$
Operating period (T_{op})	$40\ (years)$
Risk-free interest rate (r)	$4.5\ \%$
Interest rate contracted by the entrepreneur (r_{deb})	8%
Expected average unit operating cost ($\tilde{c}^e$)	$0.13\ USD - kWh$
Expected average electricity tariff ($\tilde{p}^e$)	$0.26\ USD - kWh$
Expected average salary ($\widetilde{w}^e$)	$0.89\ USD - kWh$
Expected average productivity ($\tilde{A}^e = \frac{\widetilde{w}^e}{\tilde{c}^e}$)	$6.84\ USD - kWht$
Expected average use ($\tilde{u}^e$)	53%

Legend: kWh = Kilowatt-hour; ht = working hours; Source: Prepared by the authors based on (ANEEL, 2022c, [s.d.]), (BB, 2022), (BNDES, 2022, [s.d.]), and (EPE, 2000).

The expense incurred in the planning phase does not cover the amount required for financing and needs to be considered for simplicity. To analyze the feasibility of the project, it is paramount that uncertainty ranges are identified, as per Table 4, and that projected cash flows are computed for the three scenarios (worst, best, and moderate).

Table 4 Evaluation scenarios for the average expected values of the varieties with uncertainty in the example plant design REE.

Variables	Scenarios		
	Best	Moderate	Worst
Tariff	$0.88\ USD - kWh$ (128%)	$0.69\ USD - kWh$ (100%)	$0.49\ USD - kWh$ (72%)
Salary	$0.74\ USD - kWh$ (84%)	$0.89\ USD - kWh$ (100%)	$1.03\ USD - kWh$ (72%)
Use	61% (115%)	53% (100%)	45% (85%)
Productivity	$7.63\ kWht$ (116%)	$6.84\ kWht$ (100%)	$5.74\ kWht$ (84%)

Source: Own Elaboration

From the three-point estimation technique, intervals were established for every variable. According to ANEEL (2022c, [s.d.]), Brazil's energy tariff between 2010 and 2021 had an average value of 0.69 USD/kWh, with an average variation of 28%. According to IBGE (2021), the salary (Brazilian minimum wage) had an average value of 0.89 USD/ht and a maximum variation of 16% between 2012 and 2021. Using physical capital in the moderate scenario was defined by the relation between the average of what was generated annually in electric power at the Itumbiara plant in recent years and the annual projection of the plant's total electric power generation capacity. The productivity in the moderate scenario was established in Table 3.

As previously explained, the operating profit in every period equals the operating revenue, less the operating cost. Considering that the Fiscal Year Income Statement (DRE) is not ready during project execution, the best possible estimate to calculate the periodic revenue is obtained through the calculation of the average expected revenue by subtracting Equation (2) from Equation (1), expressed in Equation 12.

$$\widetilde{\Pi_t} = \widetilde{S_t^e} - \widetilde{C_t^e} = \left(\widetilde{p_t^e} \cdot \widetilde{K^e} \cdot \widetilde{u_t^e}\right) - \left(\frac{\widetilde{w_t^e}}{\widetilde{A^e}}\right)\widetilde{K^e} \tag{12}$$

Evaluating the project development only by the NPV^{ge} (Equation (8)) and making use of the values proposed in the moderate scenario in Table 3, we get:

$$NPV^{ge} = \frac{-(2.3994 \times 10^6 \cdot\ 0.13)}{(1+0.045)^7} + \sum_{8}^{47} \frac{(0.69\ \cdot 2.3994 \times 10^6 \cdot 0.53) - \left(\left(\frac{0.89}{6.845}\right) \cdot 2.3994 \times 10^6\right)}{(1+0.08)^t}$$

Even with the simplifications, the result (452,382.11 USD) showed that the project would be feasible. However, suppose the decision to pursue the project (considering the value of the option to abandon the project) is made according to the NPV analysis. In that case, the situation becomes more attractive. From Equation (6), we have:

$$the\ \sigma_1^2 = \frac{\log\left(1.5027 \times 10^6 - (-450924.81)\right)}{\sqrt[4]{40}} = 6.29$$

Having got the project variance from Equations (1) and (2), we get ϕ_u = 1.87 e ϕ_d = 0.53 e q = 0.34. Considering an initial investment of USD 187,589,100.00, the project and option valuation lattices can be computed, as shown in Figure 7.

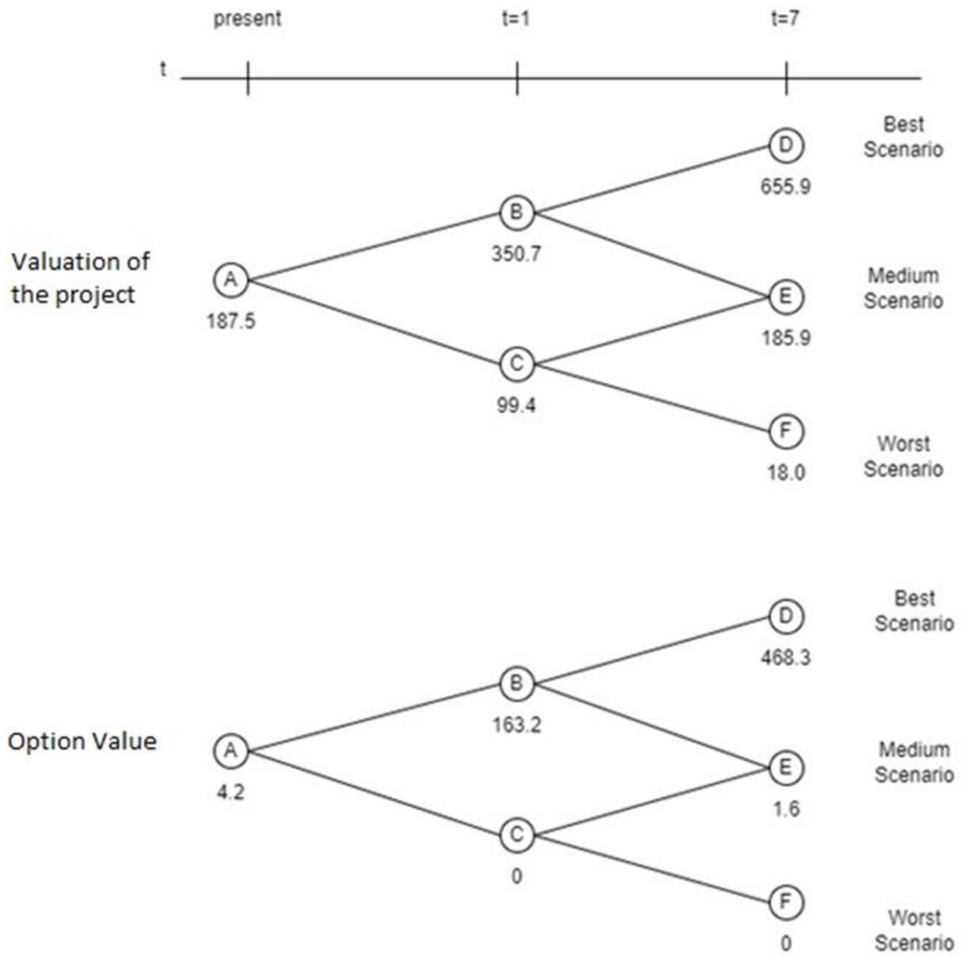

Figure 7 Project and option valuation lattices (USD million rounded values).
Source: Own Elaboration

Figure 7 presents the option value where a decision to proceed or abandon the project was not made at the start of the project (t = 0), as OV = 4.26 × 106 USD got from Equation (10), i.e., the probability of neutral risk was determined using Equation (9). q = 0.34. Thus, from Equation (11), we have $SNPV$ = 1.12 × 107, increasing the present value of the project by 61%.

1.3.3. Sensitivity Analysis

To perform the sensitivity analysis, the variables' initial investment, risk-free rate of return, interest rate contract by the entrepreneur, and plant operation time were kept constant. For the variables p^e, w^e, u^e and A^e, established as parameters, and their variations for the best and worst scenarios, we used the parameters as a uniform distribution. The time interval between decisions, i.e., Δt, was also established as a random result of a uniform distribution, where 2 < Δt < 10.

The model is simulated one hundred thousand times using Monte Carlo analysis. By the Law of Large Numbers, the expected value of a random variable can be approximated from an empirical average of independent samples of variables. In this sense, the more an experiment is repeated, the more precise the estimation of the probability of an event to occur (KROESE, 2013).

Figure 8 shows the calculated option values (in logarithm) about the estimated volatility. The size of the circles gets more prominent as the Δt increases, where Δt is the time interval between the agents' decisions to continue or discontinue the project. Red values are calculated when the probability q is less than 0.5, and blue values are calculated when the probability q is greater than or equal to 0.5. As the figure shows, most projects are likely to become more profitable below 0.5 within the ranges of our simulations. This suggests that a plant such as the Itumbiara Hydro plant has a lower probability of achieving economic viability using ex-ante analysis, even if the main driver for this assessment is exclusively connected to the historical volatility embedded in the main variables. In many cases, perfectly feasible projects are discarded because of valuation methodology constraints on dealing with the uncertainty associated with long-term projects using ex-post analysis.

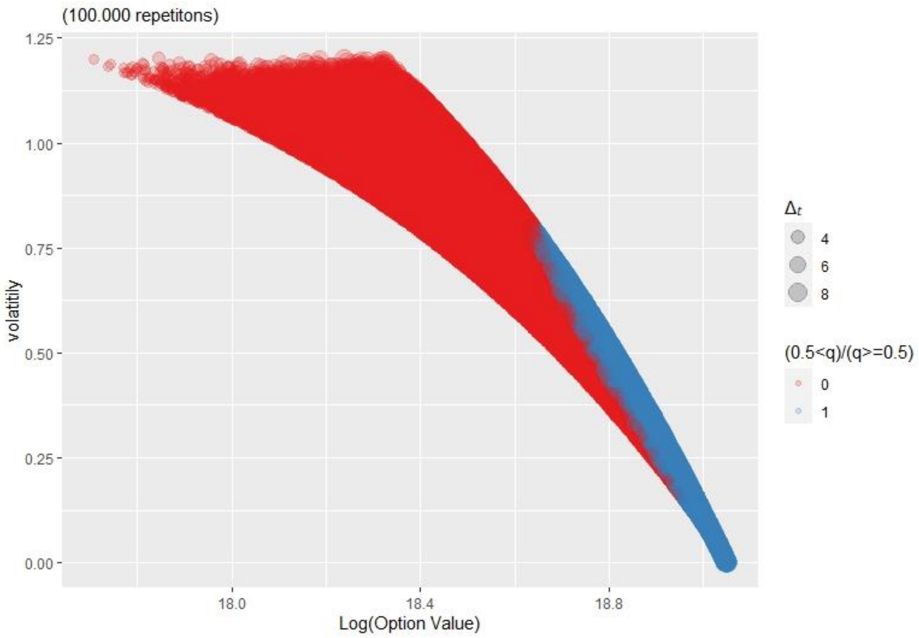

Figure 8 Expected Project Volatility and the Corresponding Option Value (USD million/100 M repetitions).
Source: Original results

Regarding the variable wage, Figure 9 compares the worst-case scenario (see the box plots at the top) with the best-case scenario (see the box plots at the bottom). As it is possible to see, the central lines indicate the median data between the two and the fact that there were no substantial differences, i.e., we see that there are no significant differences when we consider the probability q as the reference factor by looking at the median lines, although the scales are different. Similar behavior was observed for the productivity and capital utilization variables.

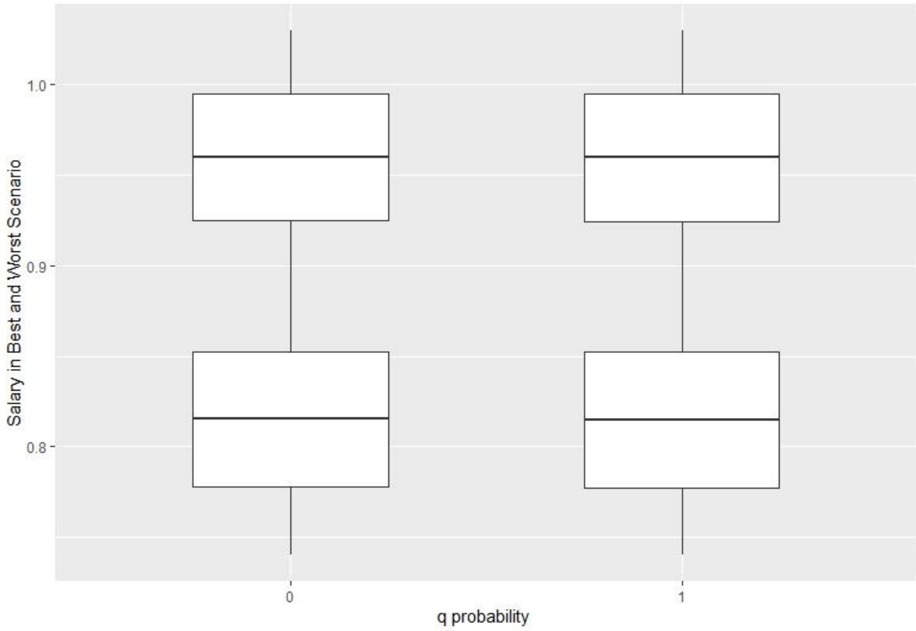

Figure 9 Probability q against salary in the best- and worst-case scenario.
Source: Original results

However, unlike the abovementioned variables, the energy tariff levels (price) in the worst-case scenario are higher when probability *q* is higher (see Figure 10). Figure 11, however, shows the opposite, i.e., more significant tariffs when probability q is smaller in the best scenario. In doing so, the energy tariff has a pro-cyclical behavior in the worst scenario and an anticyclical one in the best.

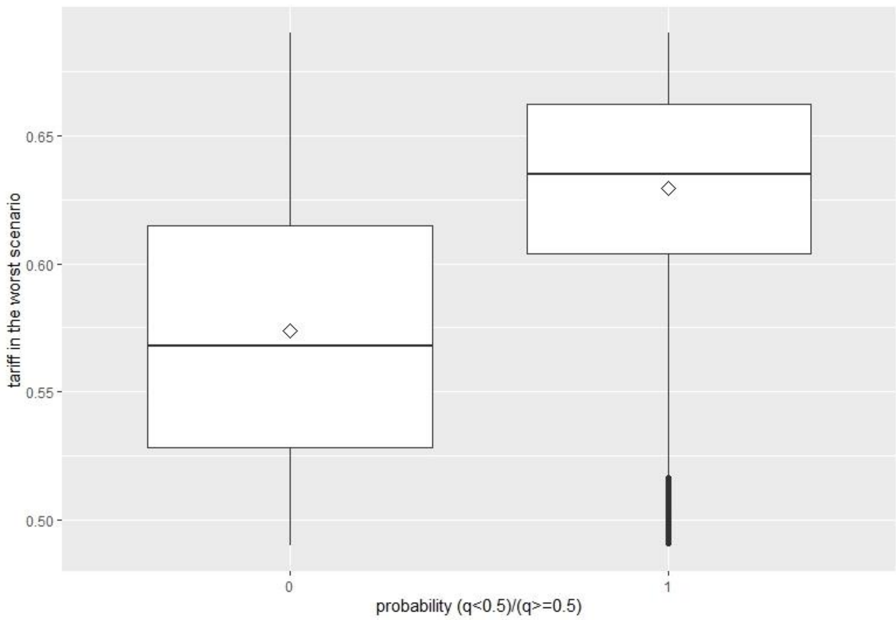

Figure 10 Probability q versus energy tariff in the worst scenario.
Source: Original results

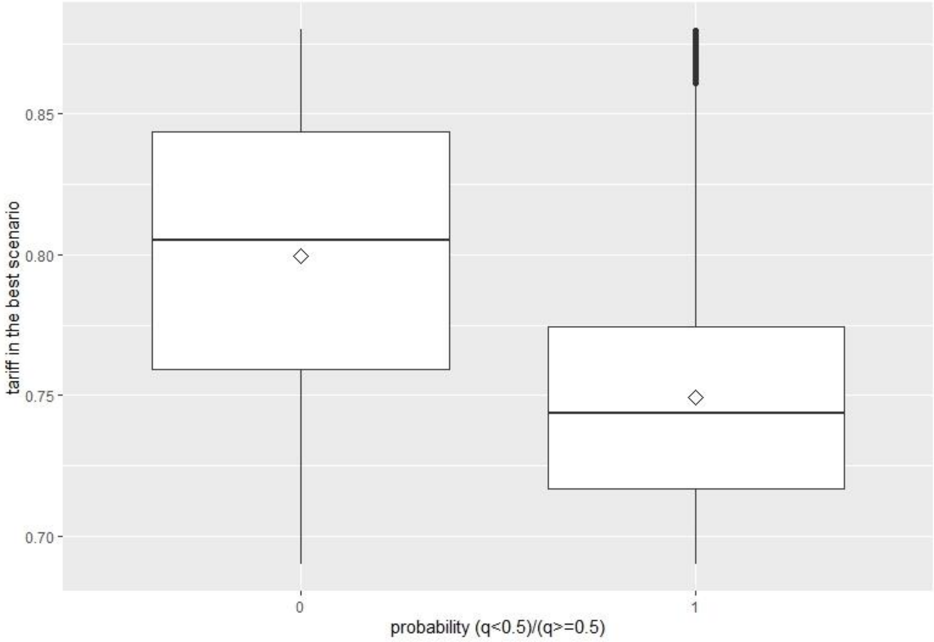

Figure 11 Probability q versus energy tariff in the best scenario.
Source: Original results

Finally, Figure 12 shows the distribution of calculated option values concerning probability *q*. Therefore, there is a certain point of intersection where the probability *q* becomes greater or lower than 0.5 and returns a similar option value. In this range, agents would obtain an equal option value even with a different market volatility.

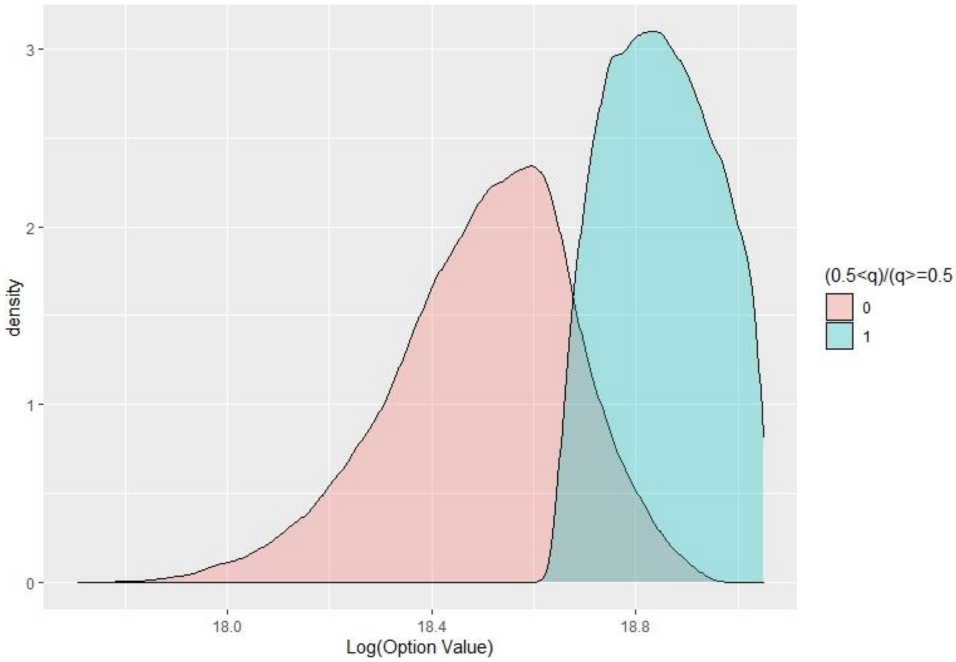

Figure 12 Calculated option value.
Source: Originals results

1.4. Discussion of Results

The experimental results proposed in this paper are consistent with the low levels of private investment in the infrastructure sector in Brazil and many developing countries. The documented higher volatility of domestic markets in these economies, plus the limited ability of the usual valuation methods—developed for advanced countries—to deal with such a level of uncertainty, seem to indicate that new approaches as the one proposed in this paper are needed to support a satisfactory level of engagement from private finance.

The model validation process showed that a project investment such as renewable electric power generation becomes more financially attractive when the real options analysis method is applied, as argued by Kjaerland (2007), i.e., despite the assumption of a positive NPV, the project shows greater profitability when considering the option value. However, these projects share different probabilities of success. Furthermore, this study complements the work (Zavodov, 2012) by showing how applying real options analysis, especially in hydroelectric projects, applies to developing economies such as Brazil.

Assuming that Brazil is a country that seeks to encourage the use of renewable energy sources, with targets for the use of these sources and fiscal incentives, the evaluation of energy projects such as Itumbiara from the RO perspective could be another factor encouraging greater private sector participation (CMS, 2023; IEA, 2020a; b). In other words, private companies are more likely to engage in renewable energy projects as we become more effective in financing. However, it is worth noting that this is an entirely speculative observation and requires further discussion. Comparing the results obtained with the results obtained by Kim et al. (2017) (that differ from what is proposed in this paper), who used the Certified emission reduction (CER) variable without considering wages and labor productivity in their study, the volatility of the project profitability was higher. For this reason, the probability q was much lower in the case study applied in this work than in the one obtained by (Kim *et al.*, 2017). Finally, considering that the power generation market is inserted in a complex system where other agents also seek access to finance for their projects, it becomes interesting to evaluate the results of this model in the context of complex economics and policy (see an example of a multisectoral model (Dosi *et al.*, 2022)).

1.5. Conclusions

This chapter evaluated an exit-option model applied to finance large projects, such as renewable electrical energy (REE) generation. The proposed model expands the existing real options analysis (ROA) literature by considering uncertainty associated with cost-side variables such as wages and labor productivity. It is a tool to evaluate the overall valuation volatility of large-scale projects, considering the value of strategic opportunities after they are started. This is particularly important in the case of REE projects, which are exposed to substantial uncertainty in the attempt to forecast many of the variables required for financial valuation. In this scenario, perfectly viable projects ex-post may be rejected ex-ante due to disregarding the real value of strategical options not included in traditional valuation models, such as the early abandonment of the project. This is particularly important if one wants to engage the private sector in financing REE projects in developing countries, where uncertainty about the future is always higher than in industrialized regions, under a scenario of urgent need for energy transition. The ROA methodology has been used in recent years as a complement to traditional project valuation approaches, and the current study is an expansion of the ROA to add some key variables (wages and labor productivity) to the analysis with a focus on developing countries. We expect our contribution to indicate possible alternatives to accelerate the transition to green energy.

To make our contribution more tangible, particularly for emerging countries, we applied the proposed ROA-augmented methodology to analyze an existing hydropower project in Brazil. Despite a primarily sustainable energy-generation matrix, the country still needs REE sources to supply the ever-growing demand for electricity. The model application to this case showed that the proposed methodology would have increased the ex-ante financial attractivity of the chosen project substantially. Considering new variables such as wages and labor productivity resulted in a significantly higher volatility of the project valuation, an important finding, especially for developing countries. The possibility of agents "neutralizing" the uncertainty by considering the value of future strategic options and obtaining a viable project valuation even under higher market volatility can be helpful as a highlighted early exit option.

Despite the adequacy shown by the model in the simple application proposed here, it still relies on simple assumptions with limited applicability for supporting policy decisions. From the perspective of supporting policymakers in using systems thinking and complexity, given the UN Conferences of Parties' (COP) events on climate change, we propose to incorporate the augmented-ROA conditions in an agent-based simulation model able to model both the overall macro dynamic and the specific processes occurring in the energy sector: in particular, the competition between renewable and carbon-based energy generation. Beyond COP28, we highlight that COP30 will be hosted exactly in Brazil, and further development of this line of research may prove fruitful to be proposed at those events.

In this sense, the next chapter presents the search, mapping, and conditioning of the most relevant existing economic growth models. It also classifies them according to their underlying theories and separates those that seek to take environmental or climatic elements into account. Finally, it presents the model most compatible with the analysis objectives.

Chapter 02 - Complex and systemic macroeconomics models and the incorporation of climate analysis

2.1. Introduction

Systemic economic models are known for considering also non-economic, like the behavior of humans, social institutions, technology, and the natural environment, to evaluate the efficiency of policies or the impact of specific events on the economic system (Fattahi et al., 2020). The interconnections between the agents and the existence of different non-economic factors characterize this system as complex and, in turn, require advanced methods and techniques to be analyzed (Ovando e Brouwer, 2019). Among the methods used to analyze policy efficiency or the specific impact of economic events in an environment formed by different agents and connections are the general equilibrium models, network or complex system models, and agent-based models (see more on Fan et al., 2022; Ghaith et al., 2021; Granco et al., 2019; Jafari, Safarzadeh and Azad-Farsani, 2022).

General equilibrium models are based on neoclassical economics theory and assume, as the name suggests, the existence of general equilibrium in the economic system. These models use mathematic equations and simulate the aggregate economic agent's environment from a rational maximizer representation of economic agents (MAS-COLELL, 2016). Such assumptions restrict their ability to model complex systems.

Alternatively, the network or complex system models objectively comprehend and analyze complex interactions and structures that emerge during the exchanges of economic agents. However, most existing methods in this category also present fragilities and limitations. In this methodology, the Extract, Transform, Load (ETL) process of complete and robust data analysis defines the network environment. Data reliability is critical to applying the methodology because the network structure is sensitive to the connections between the retreated economic agents.

In contrast to the other alternatives, agent-based modeling (ABM) does not initially require ETL-type data processing. In this methodology, agent interaction is also most relevant to modeling. However, the network structure is obtained by the agents and the modeled environment. Because of this, the ABM method is considered a promising instrument for simulating and investigating complex systems despite some challenges that have yet to be considered. An agent-based model requires specifying the individual's behavioral rules for each agent simulated and assessing their validity. Validation is possible when realistic, precise, and representative parameters are from the natural environments of agents(Fontana Magda; Terna Pietro, 2015). This is important because small parameter or rule variations can substantially change the model's results (Fagiolo e Roventini, 2012). Besides the three families of methods mentioned above, other complementary techniques can be employed when the indicated limitations are recognized as relevant to the analysis.

It is essential to highlight that incorporating complex system theory, as explained by Kirman ([s.d.]), allows the separation of the observed macroeconomic structure from the comprehension of individual decisions. This is because these economic interactions promote externalities that, differently from classic microeconomic theory, are essential to understanding the aggregated environment. As Guilmi and Carvalho (2017) explain about this approach, the interactions and feedback effects are fundamental to explaining the complex system. This is due to heterogeneous individuals connected and organized on a non-linear interaction network that produces feedback and divergence. Consequently, this feature allows for non-linear dynamic and unpredictable system evolution (KIRMAN, [s.d.]).

As expected, the logical and mathematical understanding of complex economic systems and their emergent proprieties is difficult for conventional analytical methods. Tesfatsion (2006) proposes agent-based modeling (ABM) to study such systems based on the detailed representation of the microeconomic environment using computational simulations (LEBARON E TESFATSION, 2008).

This chapter will systematically review some prominent economic growth models incorporating climate factors. Ultimately, they will contribute to the model proposed in the next chapter, which evaluates the efficiency of different finance processes for renewable energy projects and their macroeconomic effects. The systematic review differs from traditional literature reviews in that it adopts a replicable, scientific, and transparent process, i.e., a detailed methodology, which aims to minimize the limitations of research using exhaustive literature searches of published and unpublished studies and by providing an audit trail of the decisions and procedures carried out by the researcher (Xiao e Watson, 2019).

2.2. Computable general equilibrium (CGE) and dynamic stochastic general equilibrium models (DSGE)

The first computable general equilibrium model was developed in 1939 after the computer was “born” and required almost 56 (fifty-six) hours to run. Before that, the general equilibrium or Walrasiano equilibrium model was resolved from numeric resolution methods.

The input-output (IO) model proposed by Leontief (1986) was pointed out by Rose (1995) as the intellectual and practical nexus that connects the theories of Quesnay and Walras from a matrix of interactions with a similar purpose that relations of production IO, using computational algorithms of CGE models (see more Batey e Rose, 1990; Rose, 1995; Stone, 1966). The number of equations in this system depends on the number of sectors represented, and this way, as more sectors are represented, the more complex the model and the more difficult it is to obtain a unique solution.

According to Guilhoto (2011), in the IO model, the economic sectors are independent and are in equilibrium. In this sense, the change in demand for some products can modify the equilibrium sector state, and the “sum” of these changes can represent a new equilibrium level of the economy as a whole. The IO information combined with national accountability data characterizes the CGE insurgence, that is, models with more flexibility in which the price and quantity should be flexible (Truong, Van e Shimizu, 2017).

Regardless of the need for more consensus on introducing the monetary aspect of economies in the model, the CGE models are seen as an advance in closing the distance between the micro and macroeconomic theories(Guilhoto, 2011). Considering the alternatives to the numerical solution of these models, Guilhoto (2011) divided them into two groups: the numeric keys or linear solutions methods (see (Truong, Van e Shimizu, 2017) and the nonlinear ones (see (Adelman, 1978; Truong, Van e Shimizu, 2017).

However, a base structure is shared by most CGE models, as explained by Babatunde, Begum, and Said (2017). According to the authors, CGE models are composed of three representative components: (1) families, (2) firms, and (3) the government. The families demand goods and services and offer their workforce, the firms demand the workforce and provide goods and services, and the government demands taxes and tributes while providing public goods and services. Besides that, the authors highlight two flows: consumption and payment flow. As a complement, Holmoy (2016) highlights that such models present flexible relative prices while the absolute prices are indeterminate (absence of monetary illusion), as well as optimal supply and demand assuming a rational environment. Babatunde, Begum, Said (2017), and Holmoy (2016) agree that the central contrasting aspect of CGE models, whether linear or not, is the dynamic or static nature.

The static CGE model compares the initial and final equilibrium economy in the face of changes in economic policies (economic shock). In this sense, these models offer helpful information about what agents, sectors, or individuals should be more affected by these economic shocks. As presented by Christiano, Eichenbaum, and Trabandt (2018), the CGE static models are indicated to be efficient for evaluating economic policy effects in the long term. Generally, in these models, the higher level of sector desegregation makes the specific police’s impact on different sectors like agriculture, manufacturing, or services possible. The dynamic CGE models, on the other side, look to capture the business fluctuations and can more strongly evaluate the short-term impacts of the new policy implementation. These models (dynamic CGE models) are less disaggregated than static CGE models and consider the possibility of random variation or uncertainty. Dynamic CGE models are more known as dynamic stochastic general equilibrium models (DSGE).

Various questions can be analyzed using CGE or DSGE model applications. Figure 13 presents the result of the papers search done from criteria: (1) papers that have the words CGE and DSGE used as keywords; (2) papers with status equal published in academic journals any time until November of 2023 on the Scopus (2023) website; (4) ordering by relevance according to Scopus(2023); (5) papers written in English and (6) it was considered all research areas. The size of the words represents the frequency with which these words were used as keywords, according to the metadata collected.

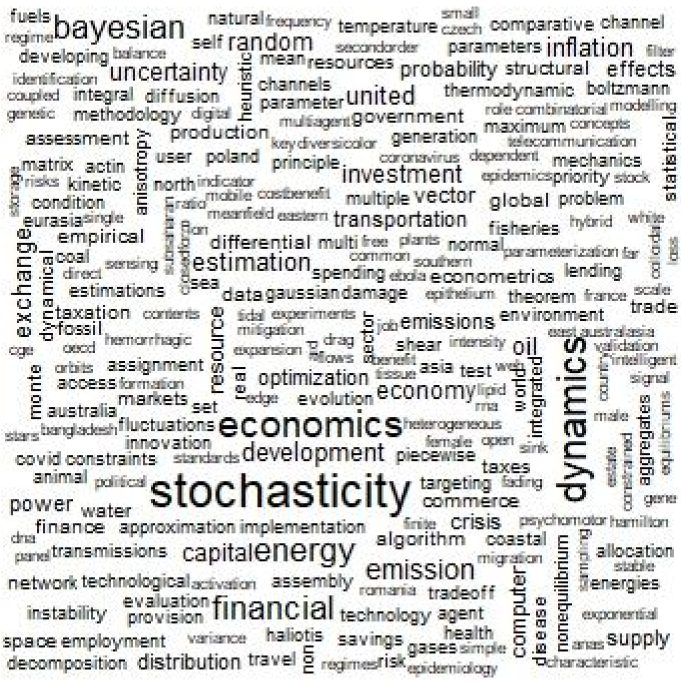

Figure 13 Frequency words cloud: keywords CGE and DSGE papers
Source: Originals results

The word cloud shown in Figure 1 is a graphical alternative for describing the metadata collected regarding keywords. As can be seen, the most frequently used keywords: (1) stochastic, (2) systems, (3) models, (4) politics, (5) economics, (6) environmental, (7) control, (8) dynamics, (9) monetary, (10) carbon, (11) macroeconomics, (12) financial, (13) energy and (14) numerical. These keywords represent the most recurrent themes in the literature researched. Much of the research is related to CGE and DSGE applications in areas like economic policies, macroeconomics, environment, energy, finance, and monetary markets (in other words, less frequently in Figure 13 but related to research areas) . In this sense, and converging to this work's objectives, we present and discuss the main contributions to the finance and energy markets from the perspective of the CGE and DSGE models.

2.2.1. CGE and DSGE models: Finance and energy markets

One classic example of DSGE is the real business cycle model developed by Kydland Prescott (1982) and Long Plosser (1983). According to Val (2001), these models, the real business cycle (RBC) theory origin, aimed to analyze and explain the dynamics of the North American economic business cycle during the 1970s and seem, with simplifications, to present precious insights to policymakers. The base CGE model structure can be easily seeded in Figure *14*.

Figure 14 Equilibrium conditions
Source: Own Elaboration

From the same metadata collected by the previous search and the source of Figure 13, the papers that also had the words “finance” and the expression “ monetary markets” as keywords were filtered. Table *5* presents the filtered result papers and their proposed ordering by year.

Table 5 CGE and DSGE are most relevant: Monetary and Finance markets.

Title	Propose/Model
The liquidity effect in a flexible-price monetary model (Chen, 2007)	Evaluate the financial liquidity from flexible prices and expansionist monetary policy. Changes in optimization problems to be solved by the government (inflation rate, interest rate changes).
The Great Depression in Belgium from a neoclassical perspective (Pensieroso, 2011)	Evaluate the impact of inflexible wages and monetary shocks on Belgic economies—changes in optimization problems to be solved by families.

Evaluating quantitative easing: A DSGE approach (Falagiarda, 2014)	Evaluate the impact of the insertion of budget constraints and fiscal policies, comparing China and the USA. Changes in optimization problems to be solved by the government (interest rate, public consumption, tax changes).
Policy Shocks and Macroeconomic Fluctuations in a Two-country Dynamic Stochastic General Equilibrium Model: Evidence from China (Ma, 2016)	Evaluate the impact of monetary policies on Croatia's economy. Almost all parameters were changed to present the Croatian economy with new economic policies (interest rate changes).
The empirical evaluation of monetary policy shock in a dynamic stochastic general equilibrium model with financial frictions: Case of Croatia (Palić, 2018)	Evaluate the impact of the Schumpeterian approach (the prices are changed to conform to the innovation process). Also, the effect of monetary shocks (inflation rate and interest rate changes).
A note on labor share, price markup, and monetary policy (Chu, 2020)	Evaluate the monetary shocks, markup participation in the workforce, and prices on the economy with durable and non-durable goods. Changes on optimization problems to be solved for the firms and by the government (output and interest rate).

Source: Original results

2.2.2. E-DSGE models: Carbon and Energy market

Among the metadados collected, a series of CGE and DSGE models are dedicated to evaluating the carbon and energy markets. As Chan (2020a; b) explains, incorporating environmental elements in a standard DSGE model reclassifies them as E-DSGE. In this sense, two papers stand out among the ones on the subject: the paper by Goulder et al. (1999) and Parry and Williams (1999). Both papers discuss the role of fiscal interactions and carbon emissions. Table *6* presents other relevant papers that use the general equilibrium theory to study the energy and carbon markets.

Table 6 The E-DSGE models: Carbon and Energy Market

Title	Objective/Model
Emissions targets and the real business cycle: Intensity targets versus caps or taxes (Fischer e Springborn, 2009)	Evaluate how control policies related to carbon emission affect economic performance, comparing the effects provoked by productivity shocks. Did insertions on different scenarios where the government and firms' optimization problems are adjusted (rates, taxes, bounded to carbon emissions by production).
How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks (Heutel, 2012)	Evaluate the supply technology shock answers and monetary shocks to carbon emissions. Include a damage function linked to all economic sectors.
(Nordhaus, 2014)	Integrates economic impacts and climate change. Consider financial increases, carbon emissions, mitigation policies, and associated costs.
Carbon emissions and business cycles (Khan *et al.*, 2019)	Evaluate the supply output and fiscal and monetary shock's answers to carbon emissions. Include a damage function related to carbon emission stock and adjust family, firms, and government optimization problems to be solved.
The impact of energy price uncertainty on macroeconomic variables (Punzi, 2019)	Investigate the economic implications of global energy price increase on economics' real variables. The authors adapted the optimization firm's problem for this.
On the impacts of anticipated carbon policies: A dynamic stochastic general equilibrium model approach (Chan, 2020a)	Evaluate the ideal time to increase carbon taxes and the carbon policies' impacts on environmental and macroeconomic perspectives. The authors did an adaptation on optimization of government problems for this.

The collaborative optimal carbon tax rate under economic and energy price shocks: A dynamic stochastic general equilibrium model approach (Chan, 2020b)	Compare the optimal carbon taxes between non-cooperative and cooperative environment fronts and economic shocks. The authors did an adaptation on the government optimization problem for this.

Source: Original results

Considering a research paper as standard in this area is not possible, only using Table *6* as a reference. Besides, considering the filters used (general equilibrium models, energy, and carbon market) in this process, it is possible to infer that most E-DSGE models (1) evaluate the impact of carbon emissions policies and (2) evaluate the performance of energy price policies or their evolution in the face of economic shocks. Nevertheless, according to Chan (2020a), using E-DSGE models is considered the standard method for analysis of the macroeconomic impact of environmental shocks.

2.3. Agent-based economic models (ABM)

An agent-based model can be defined as one in which the agents' decisions and interactions between them are modeled on the agent level. Tesfatsion (2006) explains that such an agent is autonomous, capable, reactive, and active. In other words, the agent operates like a system that is environmentally conditioned but capable of doing independent and flexible acts in search of his/her/its objectives. Combined with the economic context, this idea implies that the agent can interact with other agents and the environment to complete such objectives. The agent can be a consumer, a firm, a market, or an institution, and because of using the agent's interaction to explain the emergence of economic features, the agent-based economic models are considered micro-founded.

According to Caverzasi and Russo (2018), the micro-foundation implies that individual economic decisions are made to explain the aggregate results of one economy. These decisions are more accessible from agent-based models because flexible decisions consider agent heterogeneity in different dimensions. This way, a systematic review was done using the words "macroeconomics," "micro-founded," "ABM," and "agent-based" as criteria. Also, the results were limited to articles written in English published in a journal in its final version. The search found 86 documents; the five most cited papers in the last ten years that apply an agent-model theory and present a model are shown in Table 7.

Table 7 Most cited papers that propose an ABM model.

Authors/ Year	Models	Cite
(Assenza, Delli Gatti and Grazzini, 2015)	ABM with capital and credit (CC-MABM) to analyze the interaction between firms upstream and downstream firms and the financial conditions evolution.	97 times
(Riccetti, Russo and Gallegati, 2015)	ABM represents the adaptive nature of economic systems and the endogenous crises born.	82 times
(Caiani *et al.*, 2016)	AB-SFC (Agent-based model stock-flow consistency) to analyze the efficiency of ABM in policy application analyses.	178 times
(Nikiforos and Zezza, 2017)	AB-SFC expanded to include issues such as financialization and income distribution.	77 times
(Lamperti, F. *et al.*, 2018)	ABM analyses the problems induced by climate change effects on the economic system and the impact of economic solutions applied to them.	86 times

Source: Originals Results

The models listed in Table 7 highlight the versatility of applying ABM application. From a dynamic perspective, it is possible to associate an agent's and learning behavior with different stages in the economic cycle. Analyzing policies' efficiency or impacts using an ABM makes a deeper comprehension of the effects of these policies, for example, on workers, families, groups, and different sectors and categories. Figure 15 presents a thematic map based on co-word network analysis and clustering by keyword attribute (Cobo *et al.*, 2011). As is presented, the map expresses the relation between the theme's development degree and the theme's relevance degree.

The clusters are separated in Figure 15 by colors, and as much closer as a cluster, more related clusters are between them. The top right quadrant has more developed and strongly investigated themes in literature. The top left quadrant has themes that are strongly investigated but need to be developed. In the downright quadrant, there are themes in an emergency; in the left, themes are less developed and investigated.

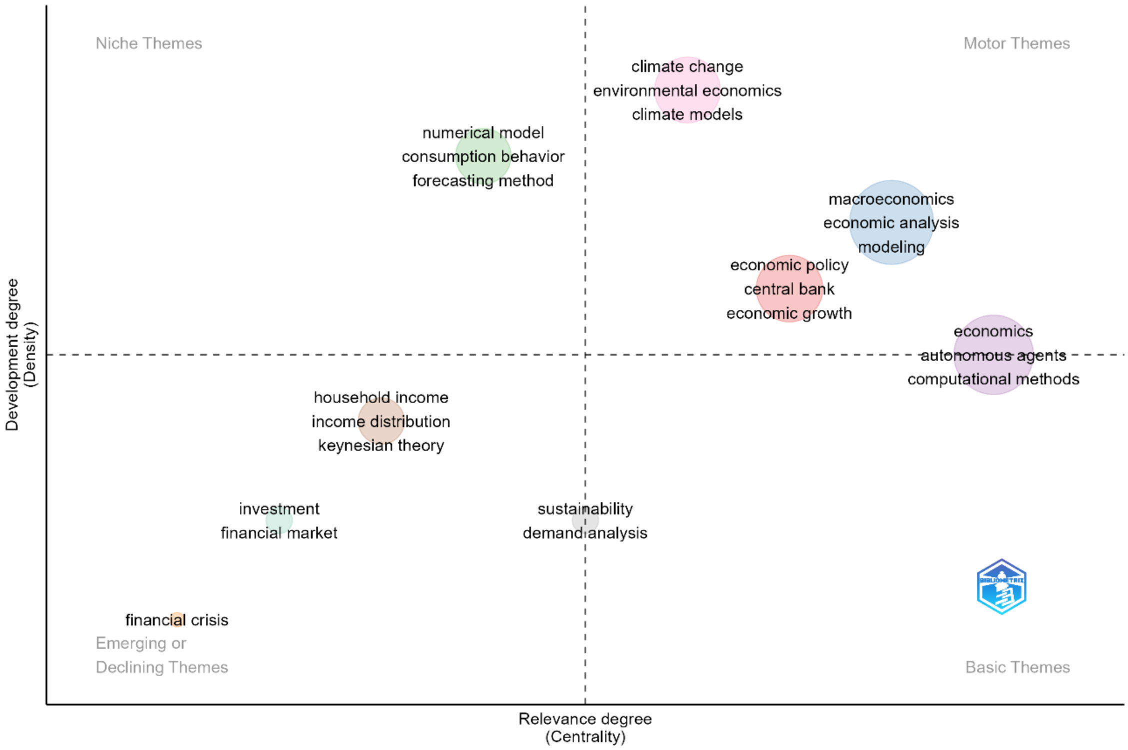

Figure 15 Thematic Map
Source: Original results.

The macroeconomics ABMs can yet show unintentional consequences or undesired results of agent interaction. This interaction, expected or not, defines the network structure and reflects how behaviors adapt to policy applications or the social and institutional rules modeled (Dosi e Roventini, 2019).

2.3.1. ABM models with climate elements

In the same way that macroeconomic models micro-founded with a focus on economic growth, policies, and distributive conflicts like the models presented in Table 5, the application of ABM to analyze energy transition and the impacts of climate change on the economic system has advanced in the last years. Table 8 presents the five most cited papers ordered by year.

As it is possible to note, Table 8 has much research related to climate change and ABM application[1]; however, each has a different approach and focus. Some research has focused on analyzing more considerable climate change occurrences and their economic consequences. Others concentrate on a regional level or entrepreneur perspective. These differences imply different analysis criteria and the way they deal with uncertainty. Some of this research, for example, explores the system's tension and heterogeneity from different scenarios and mitigation strategies.

[1] There are other works not listed as (Ciarli e Safarzynska, 2020; D'Orazio e Valente, 2018) considered relevant for literature and discussion, the filter for search limited the list.

Table 8 Papers that use ABM and have climate elements.

Authors/ year	Models	Cite
(Robalino and Lempert, 2000)	ABM will examine the consumers' behavior and preferences related to carbon emissions.	29 times
(Hallegatte e Ghil, 2008)	ABM to simulate the impact of Hurricane Katrina on adaptative entry and regional.	94 times
(Gerst *et al.*, 2013)	ENGAGE ABM to analyze the economic innovation's dynamic and implications on carbon emissions.	95 times
(Bierkandt *et al.*, 2014)	Damage transfer ABM with conservation dynamics, evaluate the climate risk and the decisions related to them.	37 times
(Lamperti et al., 2018)	ABM analyses the problems induced by climate change effects on the economic system and the impact of economic solutions applied to them.	86 times

Source: Original results.

Lamperti, F. et al. (2018). ABM stands out from other models and presents an integrated model that combines a climate dynamic with economic system dynamics on a unique framework. This integration makes possible an extensive analysis of climate and economic system interaction and their implications.

2.3.2. The integrated ABM: Joining Climate and Economic System Dynamics

The Dosi, Fagiolo e Roventini (2010) model, the foundation presented in the next chapter, is a model where the authors combine the post-Keynesian (PK) theory and neo-Schumpeterian evolutionary theory. The PK theory, as explained by Guilmi and Carvalho (2017), is characterized as an alternative to the monetary theory presented by Freeman and Kydland (2000) and has six central conditions: (1) the consumption-goods market determines unemployment; (2) there is involuntary unemployment (results of practical demand inefficiency); (3) the investment defines the saved money level; (4) the money supply and demand affect the prices and the real variables in an economic system; (5) the money quantitative theory not is verified and, (6) the fundamental uncertainty interferes and defines the investment decisions. Besides that, the PK theory is also commonly applied in aggregated contexts that try to explain the behavior of the leading macroeconomic and aggregated economic indicators.

As a complex model, Dosi, Fagiolo, and Roventini (2010) use the ABM methodology to incorporate some of the realistic premises adopted by PK theory, introducing different behaviors and economic agent's features and converting the path dependence idea as an institutional structure (put in evidence as the individuals are linked with their trajectories).

Not by accident, the Dosi, Fagiolo e Roventini (2010) proposed model was expanded and was concentrated in the analysis of four agent classes: (1) consumer-good firms, (2) capital-goods firms, (3) consumers-workers, and (4) the government. They introduce a bank (Dosi *et al.*, 2015a), an energy producer, and a climate "box" in Lamperti et al. (2018).

It is essential to highlight that the model proposed by Dosi, Fagiolo, and Roventini (2010) describes the economic growth process while discussing three different questions. The first question is related to technological innovation and how this process affects macroeconomic variables like rent, wage, profit, prices, market share, and markup. The second question concerns the endogenous changes in the economic system demand due to investment (see more in Possas e Dweck, 2011). The third question concerns the long-term impacts of demand on the economic system (the main Keynesian argument).

In the model, Dosi, Fagiolo, and Roventini (2010) show the economy's growth as an endogenous process that is led by innovation activity and is driven by aggregate demand. Furthermore, the model uses heterogeneous agent representation with interactions based on the micro empirical evidence because this generates adequate behavioral rules (Appendix A). This perspective tries to answer the open-ended question in the literature about the long-term growth processes of the economic system.

The Dosi et al. (2013) model incorporates a generic financial sector that tries to explain the impact of financial fluctuation on real economic variables, income distribution, and the entry and exit firms' dynamics. Dosi et al. (2015) offer a more sophisticated organization of the heterogeneous banks that form the financial system, including the Central Bank (Appendix B). This increment helped the authors explore the economic fragilities in the face of bank crises and the impact of fiscal and monetary policies at the income inequality level.

Especially important for this work is the model proposed by Lamperti et al. (2018), the Dystopian Schumpeter Meeting Keynes (DSK) model, which uses a climate box to simplify the impact evaluation of the energy generation process on carbon emissions. Appendix C is dedicated to a detailed climate box proposed by Lamperti et al. (2018). The economic structure of the model, Figure *16* presents a generical summary of the model dynamics. In this model, the energy sector is separated from the other sectors. The energy sector comprises just one monopolistic power generator firm (green energy or not).

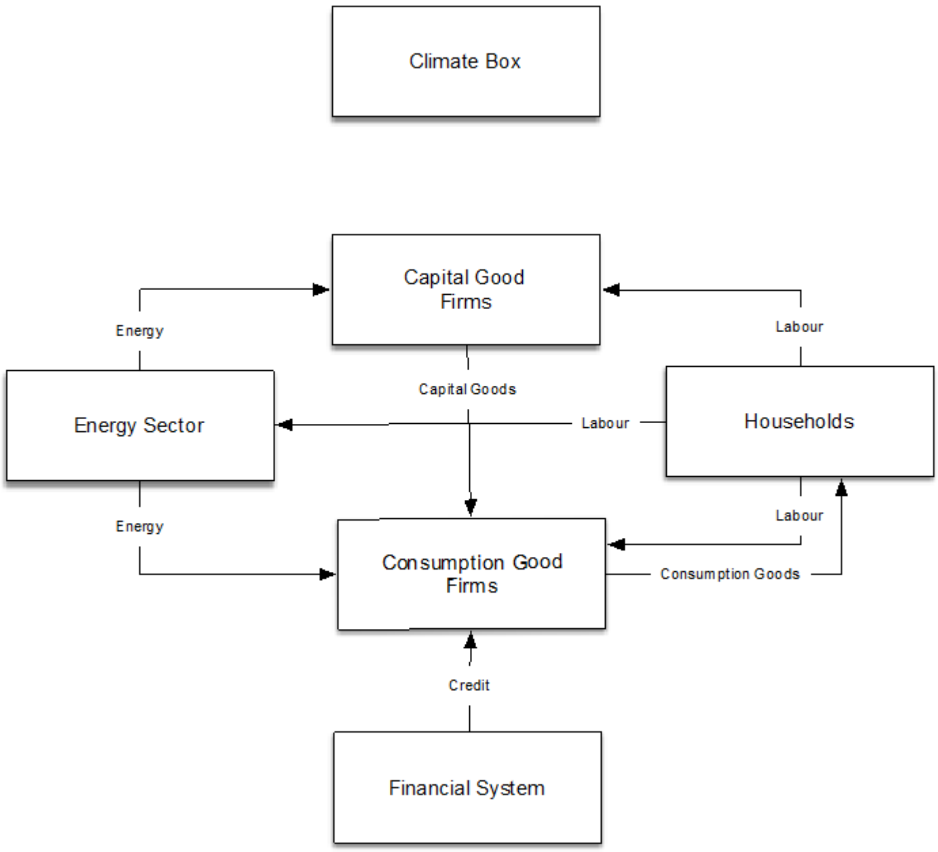

Figure 16 Economic structure DSK model.
Source:(Lamperti, F. *et al.*, 2018)

All productive activities in the model have some carbon emission level. These emissions are accounted for in the climate box and impact the economic system through climate shocks. The model also makes it possible to evaluate fiscal, innovation, industry, industrial, and monetary policy impacts on the climate and economic system.

2.4. Conclusion

This chapter presented and discussed the main methods used to evaluate the efficiency of different policies or the specific events' impact on the economic system from macroeconomic relations. Considering the importance of theories like general equilibrium and complex systems, the baseline concepts of general equilibrium and the agent-based models were presented.

This discussion concluded that the agent-based model is the most promising alternative when the research objective is to investigate the interactions observed among agents. In other words, applying ABM makes understanding macroeconomic phenomena possible from the individual contributions of the involved microeconomic agents. As its possible note by Figure *15* the theme related to investment and financial market is part of the emergence or declining themes, but if combined with themes like economic policy, economic growth, climate change and environmental economics themes the mainly object of this work (as all) has a large way for improvement.

Among the ABM macroeconomic climate models, Lamperti et al. (2018) is a good option for hosting the modeling ideas introduced in Chapter 1 into a complex climate economic system. The embedded climate box makes analyzing the carbon emission impact more tangible and the financial evaluation of green energy projects more effective. In this way, the next chapter presents our proposal for an energy-augmented K+S model, including a sophisticated energy sector and new instruments for banks to finance green investment projects.

Chapter 3

The Energy-augmented K+S Model

3.1. Introduction

The Energy-augmented K+S model sees workers as homogeneous agents, firms – producers of energy, capital, and consumption goods – and banks as heterogeneous agents. The firms that compose the consumption-good sector produce a unique and homogeneous product from two inputs: capital goods (machinery) and workforce. Capital goods are produced by (vertically integrated) firms that use labor as the only factor. Both inputs – capital and labor – have constant returns to scale. Workers are represented as homogeneous agents in this branch of the K+S model family; the number of workers firms defines the demand for work required to meet their production schedule.

In the K+S model, Dosi et al. (2015), the financial sector is formed by heterogeneous commercial banks that receive deposits and provide loans. Bank loans are directed to working capital – wages and cashflow management –and to finance capital investment and R&D in the energy and consumption sectors.

Furthermore, a central bank sets the basic interest rate besides holding banks' compulsory reserves and unsold government bonds. The central bank may also bail out banks with negative net worth. The government collects taxes on profits from all firms and banks, pays unemployment benefits, determines the minimum wage, and issues bonds to finance budgetary deficits.

Similarly, Dosi, Fagiolo, and Roventini (2010) state that firms' entry and exit processes are endogenous. This means that the firms are "expelled" from the market always because their market share is equal to zero or their net profit turns negative. The dynamic of entry and exit depends on the incumbent's number and financing conditions in the process. In this sense, they are considering that the firm's entry can be provided to bank financing or title emissions, increasing the net debt rate to ease the entry of new firms into the market.

Following Schumpeterian principles, as mentioned in the previous chapter, the innovation process is modeled as a stochastic process. In addition, innovation occurs in the capital goods sector and energy firms. The innovation in the energy sector is represented by the R&D search for producing improved generations of power plants irrespective of the applied technology – "green" (sustainable) or "dirty" (non-sustainable).

As in any investment project, energy producers must have access to the resources required to apply new technologies they may develop. In the model, technology is embodied in combinations of machines, which must be contracted from and paid to capital-good firms. The funds to acquire machines can be obtained from accumulated past profits or loans in the finance sector. In the previous versions of K+S, only short-term loans were available to finance capital. However, a new option is being introduced here: long-term project finance. Project finance is a usual form of credit to make large investment projects viable, considering scenarios where large initial expenditures have a long but low-risk payback period – like when building a power plant. To protect creditors from the substantial increase of the risk of default in such credit arrangements, project finance includes “safeguards” allowing for finance interruption in case of poor economic performance. In the current model version, the creditor bank is protected by the option to convert the loan into a short-term one if the expected viability (positive net present value) cannot be achieved after the plant construction.

Therefore, after the R&D process, the energy firm must consider using the currently achieved technologies to introduce green energy or a dirty energy plant. Introducing a green energy plant requires an initial investment, preferably by project finance. To this effect, the firm should apply to its customary bank, which holds a (separate) reserve specifically for financing green power plants.

Commercial banks have primordial functions like collecting deposits, providing loans upon request, and evaluating short or long-term credit applications. Among the heterogeneous commercial banks, firms establish (randomly) and maintain a fixed relationship with a single bank. The bank's capital and regulatory capital restrictions (of the Basel type) limit the credit supply.

The machinery commercialization between capital firms and the other firms stays as in previous versions of K+S; after price and productivity signaling, the buyers make their decisions. The machine prices are established using a fixed markup over workforce cost. Capital firms produce only by order. Conversely, consumption-good firms must form expectations about demand and produce accordingly. The quantity of goods that each firm obtains depends on (1) the stock and productivity of capital available to them, (2) the desired output level, and (3) the available inventories of unsold goods from past periods. In all cases, the acquisition of new machinery should be paid in anticipation.

According to the demand expectation, consumption-good firms update their machinery, and labor productivity changes accordingly. Besides that, the consumption-good prices are adjusted according to a variable markup rule, which balances profit and market share. Because of imperfect information, consumers do not change instantly to cheaper products.

The demand for the workforce in each sector depends on their demand or expected demand and labor productivity. If the workforce supply exceeds the demand, labor scarcity will be shared proportionally with individual firm demands. For simplicity, the banks and the government do not require a| workforce.

Workers use their wages on goods consumption; there is no capital acquisition or (planned) savings in this version of K+S. Workers do not request credit for consumption. In cases where the workers are also equity owners, which is not the baseline configuration of K+S, the government can be forced to bail out bankrupt workers.

The generated energy is distributed from the heterogeneous plant stock, and the generation energy process, as well as the machinery production or the consumption goods production, emits greenhouse gases (just CO2 in the model). These emissions affect the carbon concentration in the atmosphere and the temperature level, as modeled by the model climate box.

This chapter will be dedicated to presenting the ABM proposed to model the scheme described in the initial chapter of this thesis. Lamperti et al. (2018) proposed model was used as a baseline. Besides a competitive energy sector, new relations are established between the financial and energy sectors.

The results of this model in the different scenarios are obtained by applying Monte Carlo simulation, supported by the law of large numbers. According to the law of large numbers, the arithmetic means of the results of performing the same experiment repeatedly tends to get closer to the expected value as more attempts are made. In addition, the series obtained were evaluated using the Augmented Dickey-Fuller (ADF), Kwiatkowski-Phillips-Schmidt-Shin (KPSS), Brock, Dechert e Scheinkman (BDS), Kolmogorov-Smirnov (KS), Anderson-Darling (AD) e Shapiro-Wilk (SW) tests. The ADF, KPSS, BDS, KS, AD, and SW tests are essential statistical tools for validating the results obtained by Monte Carlo simulation. The ADF and KPSS tests are used to check for the presence of unit roots in time series, which is crucial for determining the stationarity of a series. The BDS test is used to detect the presence of non-linearity and chaos in a time series. The KS test is a non-parametric test that compares the empirical distribution of a sample with a theoretical distribution. In contrast, the AD test is a more powerful version of the KS test, giving more weight to the tails. Finally, the SW test is used to check the normality of the data(Hannan e Tuma, 1979).

However, not only the method but also the results obtained must be validated. These results must be compared with actual historical data to validate the results obtained by simulating the model in ABM[2]. If your model can reproduce trends and patterns observed in historical data, this is a good indication that the model is valid.

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[1] The code and initial parameters used are available in LSD software < www.labsimdev.org – LSD – Laboratory for Simulation Development>

Although the model used as a basis has already been validated, it is necessary to validate the specific behavior of the ROA-enhanced model. In this respect, no historical records can be used to compare its accuracy, at least not in the energy sector, as proposed in this work, because the options real values are deciding, in general, on contract (one-to-one). However, the macroeconomics and sectorial behavior was validated on in previously published works (Dosi *et al.*, 2013, 2015a; Dosi, Fagiolo e Roventini, 2010; Lamperti, F. *et al.*, 2018).

3.2. The Energy Competitive Sector Dynamics

The firms in the competitive energy sector present similar, but not equal, behaviors to the consumption-good ones. The energy firms are conditioned to entry and exit rules and search for technological improvements. Aside from more than one energy firm in the sector, a competitive sector means that energy firms compete for energy supply.

Competition for energy supply is regulated and occurs on energy. The auctions are modeled in this version to consider the energy price and generation capacity as the criteria for allocating the demand. Implicitly, this defines the features of economic system dynamics regarding energy sources. In other words, heterogeneous energy supply firms compete in a centralized energy market.

The energy firm's success in auctions requires a better performance than other energy firms on the market on two main criteria: the energy generation capacity and the price signaled. That is, the firms are ranked on a priority list of supplying according to the energy price, and the supply capacity of each one of them determines how many of these firms will be needed to fulfill the effective energy demand in the economic system. A lower energy price depends on each firm's R&D and capacity planning improvements. The life flow of the energy firm is shown in Figure 17, and the equations mentioned there will be presented in this chapter.

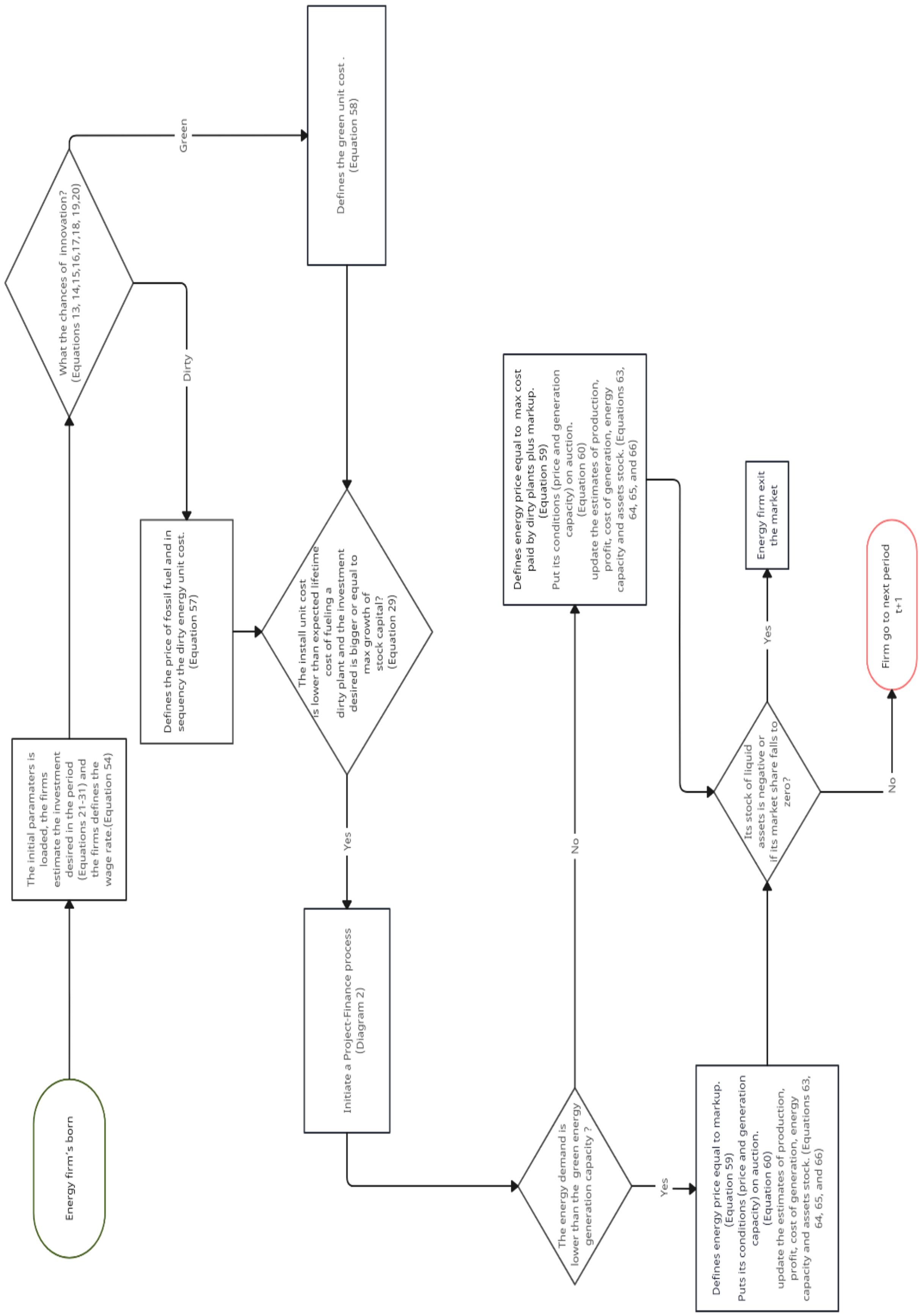


Figure 17 Life energy firm flow
Source: Own Elaboration

3.2.1. The Energy Generation Project Planning

The energy generation capacity planning can be separated into steps, each requiring a different decision. Initially, based on investment in R&D, energy firms search for more efficient, less pollutant, and cheaper technologies to improve green and dirty energy sources. This search can result in a successful technological innovation or imitation of other firms' technologies. From that, energy firms must decide to invest in new green or dirty power plants, depending on the expected lifetime cost of fueling a dirty plant.

The investment in green power plants, differently from dirty ones, is costly; in this model, it requires a capital expenditure (CAPEX) investment and, according to the configuration, requires bank financing. If the energy firm needs financial support, it may request project finance support from the commercial bank.

On a second recur timing step, the firm also must decide how much to increase its capacity to generate energy, and for this, it must first know its actual capacity. The energy generation capacity is defined by the sum of the existing energy generation and new green or dirty power plants created in the period minus the (deprecated) capacity decommissioned because of technical end-of-life. Defining how much capacity is needed beyond the existing stock is based on the expected demand from the other sectors. Not all requests are met whenever the firms opt for green plants and request project finance support. If its request is accepted, if the requests are not accepted, the firm will preserve the green choice only if the available funds are sufficient for the investment. Otherwise, it opts to meet the demand expectation by investing in dirty plants.

Investing in green energy requires machinery; the machinery must be ordered by firms in the capital goods sector and paid for beforehand. Both plants require workers to be operated, and they must be disputed in the labor market with capital and consumption-good firms. The number of machines required depends on the desired capacity and technology.

The number of workers depends on more than one factor. Naturally, the energy firm must estimate its workforce needs before disputing workers in the labor market. A firm's labor demand depends on the total energy demand (the sum of the demand for energy from the capital- and consumption-good sectors) and its work productivity. In the capital goods sector, the machinery demand can be calculated at each period precisely because all machinery needs to be ordered in advance. However, the consumption-goods demand is different; the demand is unknown ex-ante, as total demand depends on the total wages and prices. Besides, the work productivity level expresses the relation between the total output and the number of workers employed.

Figure 18 presents the energy firms' project financing process, and the equations mentioned there will be presented in this chapter. The rectangles indicate processes and the rhombus's decisions to be made.

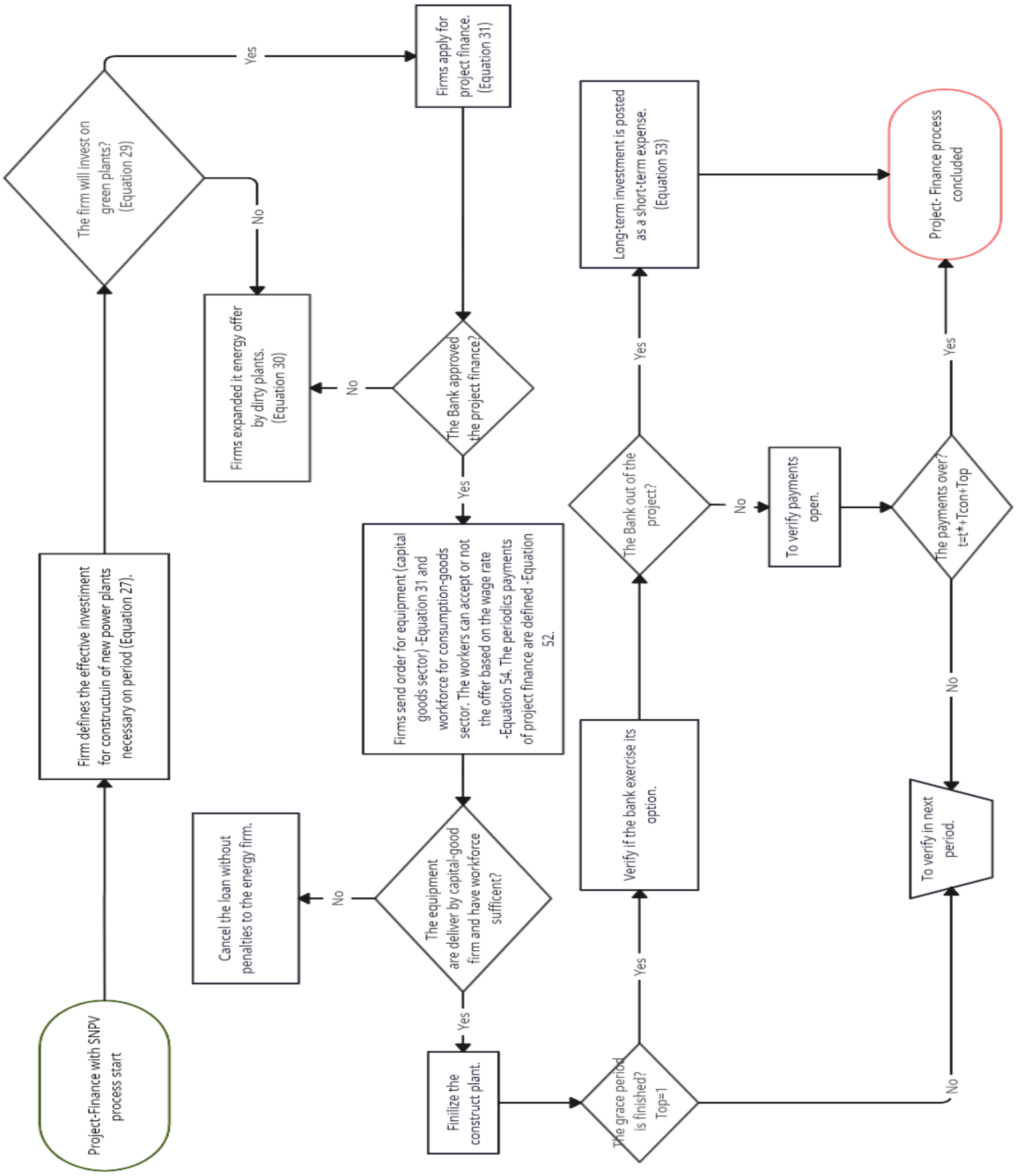


Figure 18 Energy firms project finance process
Source: Own Elaboration

3.2.2. The Bank' attributions: Project Finance Evaluation and Support

The banks may receive project finance requests from multiple firms each time step. In this perspective, the bank has a special reserve with funds dedicated to project finance (long-term loans), separated from the one for short-term credit. The amount dedicated to this reserve may be constrained according to a maximum leverage level allowed by prudential regulation – a model parameter.

All project finance requests are exclusively related to new green plant projects; for each, the bank will compute the investment's strategic net present value (SNPV) according to the principles set in Chapter 1. The SNPV is used as a feasibility parameter. When requests are over the available reserve, the bank uses the client's creditworthiness pecking order (see Dosi et al., (2015)) to define the priority of requests.

The amount requested in each project finance submission depends on the project and differs between energy firms. The loan should be repaid in equal installments, and the amortization period is the same for all cases. The bank uses the specific interest rate associated with each client, considering its creditworthiness (see [REF to JEDC2015] for details). Given the current applicable interest rate, it is then "frozen" concerning each project. Amortization payments are applied to the outstanding project loan balance, which is also used to define the interest to be paid.

There is a grace period for project finance amortization. This way, energy firms initiate the project finance amortization only after the green plant construction ends. The first amortization period also marks the option of exercise time. Currently, the bank is re-evaluating the project NPV using its most up-to-date expectations on the risk variables. If the NPV now shows negative, the bank exercises the loan-term anticipation option, and the firm projects outstanding debt is turned into a regular short-term loan. In some cases, firms becoming insolvent will lead to market exits. Figure 19 presents the bank's evaluation of process flow.

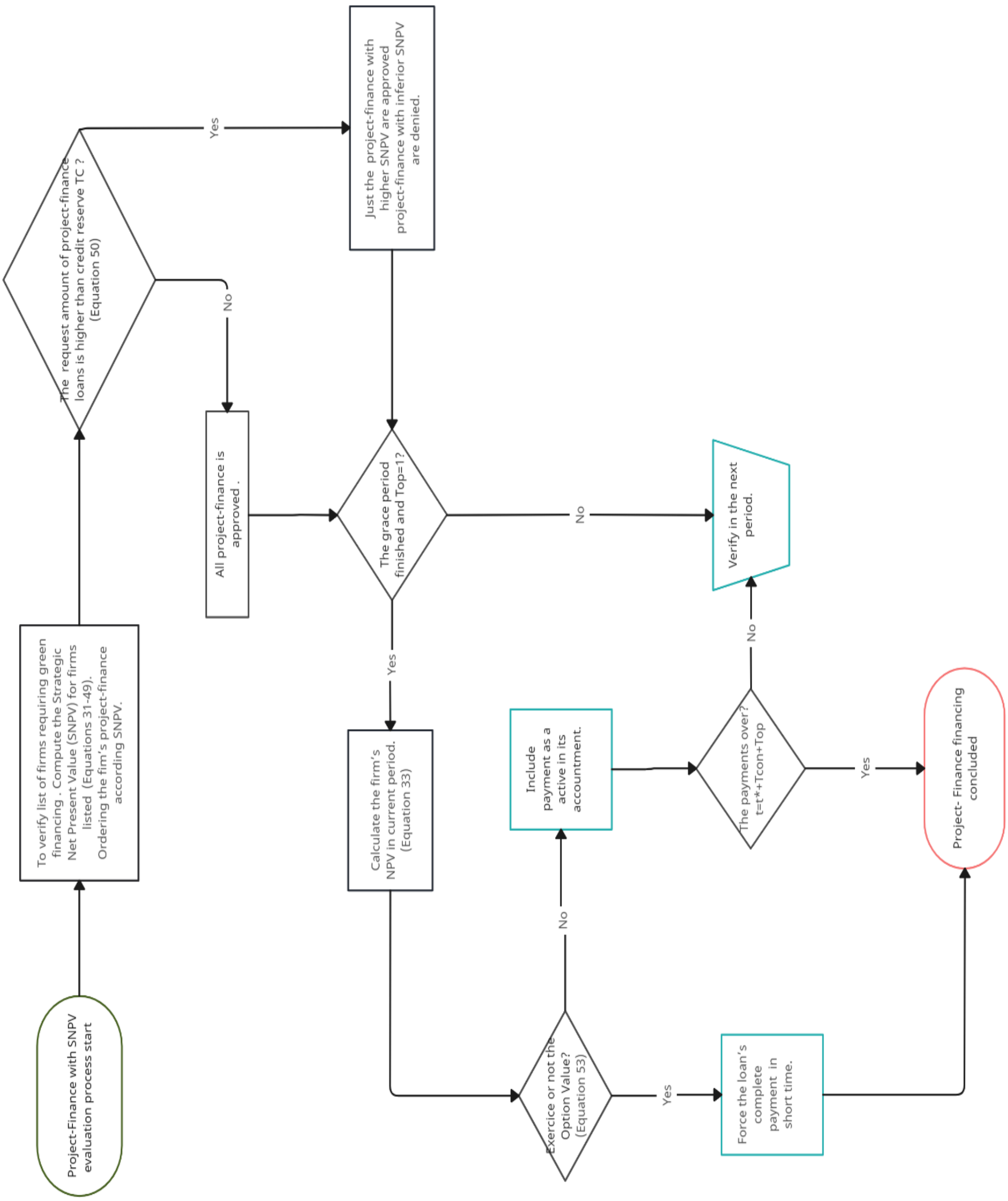


Figure 19 Bank evaluates process flow.
Source: Own Elaboration

3.3. Energy Firm and Bank Behavioral Rules

This section presents all the behavioral rules introduced or modified by this upgraded version of the K+S model. Appendix D introduces the most important components of the CO2-cycle model (climate box), based on Sterman et al. (2013)

applied similarly to the economic-climate dynamic by Lamperti et al. (2018), Appendix C.

3.3.1. R&D process at the energy producers

The energy producers, as well as the capital-good firms in the model, has k dimensions of the technologies obtained by the innovation process available in the company, $(A_{i\tau}^{k}, B_{i\tau}^{k})$. With $k \in \{LP, EE, EF\}$ the model explains LP: $A_{i,\tau}^{LP}$ as equivalent to the productivity of the capital good in the consumer goods industry and $B_{i,\tau}^{LP}$ the productivity of the production technique used to produce the machine. EE: $A_{i,\tau}^{EE}$, represents the productivity per unit of energy used by a consumer goods company using the technology developed and $B_{i,\tau}^{EE}$ characterizes the production of the capital goods manufacturing technique. There is yet another dimension to technology, the degree of respect for the environment, expressed by the EF dimension. Thus, $A_{i\tau}^{EF}$ refers to the environmental compatibility of the technology developed, while $B_{i\tau}^{EF}$ refers to the technical production efficiency of the capital goods company.

The technological change/advance is associated with a specific probability in Equations 13 and 14. The occurrence of innovation, just as in the real world, is not deterministic and is determined by the random drawing of a Bernoulli distribution, whose parameter $\theta_i^{in}(t)$, Equation 13, given that $0 < \zeta 1 \leq 1$. As is to be expected, the greater the resources allocated to the innovative discovery process, the greater the chances of success in innovating. The imitation like innovation process do not have a deterministic result (success or failure) and the possibilities them are related to a Bernoulli distribution ($Bernoulli\ (\theta_i^{im}(t)$) with $(0 < \zeta_2 \leq 1)$, Equation 14.

$$\theta_i^{in}(t) = 1 - \ e^{-\zeta_1 IN_i(t)} \tag{13}$$

$$\theta_i^{im}(t) = 1 - e^{-\zeta_2 IM_i(t)} \tag{14}$$

The proportion of technological advances to existing technology is defined as before, based on its particularities and the result of random draws as presented in Equations 15, 16, 17, and 18.

$$A^{k}_{i,\tau+1} = A^{k}_{i,\tau}\left(1 + x^{k}_{A,i}\right),\ k = \{LP, EE\}$$

15

$$B^{k}_{i,\tau+1} = B^{k}_{i,\tau}\left(1 + x^{k}_{B,i}\right),\ k = \{LP, EE\}$$

16

$$A^{EF}_{i,\tau+1} = A^{EF}_{i,\tau}\left(1 - x^{EF}_{A,i}\right)$$

17

$$B^{EF}_{i,\tau+1} = B^{EF}_{i,\tau}\left(1 - x^{EF}_{B,i}\right)$$

18

In the equations above $\left(x^{k}_{A,i},\ x^{k}_{B,i}\right)$ are independent random numbers whose distribution $Beta\left(a^{k}, \beta^{k}\right)$ has support in $\left[\underline{x}^{k},\ \overline{x}^{k}\right]$, respectively for $k \in \{LP,\ EE,\ EF\}$. In the case of successful innovation, the new technology will be characterized by a combination of labour productivity, energy efficiency and respect for the environment. Success in imitating, on the other hand, gives imitating companies access to the closest technology.

The technological search and innovation for energy firms are like the capital-good's firm search for innovation or technological advance. In dirty plants the innovation success implies on reduction of GHG emissions (em^{τ}_{de}) and by more thermal efficiency (A^{τ}_{de}), Equation 19 and Equation 20. In these equations $\left(x^{A}_{de}\right)$, (x^{em}_{de}) are random variables that follow a Beta distribution.

$$A^{\tau}_{de} = A^{\tau-1}_{de}\left(1 + x^{A}_{de}\right)$$

19

$$em^{\tau}_{de} = em^{\tau-1}_{de}(1 - x^{em}_{de})$$

20

These equations will be important to define the desired investment in green energy. Equations 29 and 31 are in the next subsection.

3.3.2. Demand expectation and investment decisions of energy producer

The desired new generation capacity of energy producers l in time t is:

$$I^{d}_{l,t} = \max\left(EI^{d}_{l,t} + SI^{d}_{l,t}, 0\right),$$

21

where $EI^{d}_{l,t}$ is the desired expansion capacity in new power plants, and $SI^{d}_{l,t}$ is the substitution capacity required to replace deprecated power plants in $t + T_{con}$, considering the time T_{con} required to build a new power plant, $T_{con} \in \mathbb{N}_{+}$ is a parameter. There is no accelerated disinvestment $I^{d}_{l,t} < 0$, that is, firms cannot reduce capital faster than the depreciation rate $1/\eta_e$, being $\eta_e \in \mathbb{N}_+$ a parameter defining the technical lifetime of power plants.

Desired substitution capacity is computed based on the planned scrapping of plants reaching the end of technical life:

$$SI_{l,t}^d = \sum_{p \in \Xi_{l,t}} K_{l,p}^e \,, \tag{22}$$

being $K_{l,p}^e$ the capacity of existing plant p, and $\Xi_{l,t}$, the set of plants of firm l in time t which have lifetime ending at $t + T_{con}$. Power plants have a fixed (technical) lifetime equal to $\eta_e \in \mathbb{N}_+$, a parameter.

Therefore, effective substitution investment is bounded between zero and $SI_{l,t}^d$:

$$SI_{l,t} = \begin{cases} SI_{l,t}^d \,, & \text{if } EI_{l,t}^d \geq 0 \\ \max\left(SI_{l,t}^d + EI_{l,t}^d, 0\right), & \text{otherwise} \end{cases}, \tag{23}$$

and, consequently, effective expansion investment is also bounded:

$$EI_{l,t} = \max\left(EI_{l,t}^d, 0\right). \tag{24}$$

Expansion investment can be calculated as:

$$EI_{l,t}^d = [1 + \iota_e]\, D_{l,t}^e - K_{l,t-1}^e - I_{l,t-1}^{con} \,, \tag{25}$$

$\iota_e \in \mathbb{R}_+$ is a desired-excess-supply parameter, $D_{l,t}^e$ is the expected future demand of firm l at time t for $t + T_{con}$, and $K_{l,t-1}^e$ is the total existing capacity. The capital investment already committed but still under construction is also considered and is defined by:

$$I_{l,t}^{con} = \sum_{h=0}^{T_{con}-1} I_{l,t-h} \,, \tag{26}$$

$I_{l,t}$ is the total effective investment, in capacity terms, of firm l in time t for the construction of new power plants, green or dirty, defined as:

$$I_{l,t} = EI_{l,t} + SI_{l,t} \,. \tag{27}$$

Expected future demand is defined as:

$$D_{l,t}^e = \widetilde{D}_{l,t-1}(1 + \tilde{g}_{t-1}^e)^{T_{plan}} \,, \tag{28}$$

where $\tilde{g}^e_{l,t}$ is the expected growth rate demand, calculated as the average of the previous firm demand $\widetilde{D}_{l,t}$ adjusted by total energy consumption mean growth, both computed as moving averages over the last $T_{plan} \in \mathbb{N}_+$periods, a planning-horizon parameter.

New generation capacity is built as green or dirty power plants. Green power plants are preferred if the green power install unit cost $IC^{ge}_{l,\tau}$ is lower than the expected lifetime cost of fueling a dirty plant, so the desired investment in green plants is:

$$I^{d,ge}_{l,t} = \begin{cases} \min\left(I^d_{l,t}, [1+\kappa^e_{max}]\, K^e_{l,t-1}\right), & \text{if } I^d_{l,t} \geq \kappa^e_{min} K^e_{l,t-1} \text{ and } IC^{ge}_{l,\tau} \leq b_e \dfrac{p^f_t}{A^{de}_{l,\tau}} \\ 0, & \text{otherwise} \end{cases},$$

29

being $\kappa^e_{max} \in \mathbb{R}_+$ the parameter governing maximum growth rate of the stock of capital. The qualifying conditions represent a required modularity efficiency $\kappa^e_{min} \in \mathbb{R}_+$, a parameter. Also, green plant is selected only if the initial investment $I^d_{l,t}$ is lower than the expected fuel cost of operating a dirty plant, where $b_e \in \mathbb{R}_+$ is the investment time horizon (payback period) parameter, p^f_t, the current price of fuel, and $A^{de}_{l,\tau}$, the energetic efficiency of the dirty power plants. The investment in dirty plants is then defined as:

$$I^{d,de}_{l,t} = \begin{cases} \min\left(I^d_{l,t}, [1+\kappa^e_{max}]\, K^e_{l,t-1}\right), & \text{if } I^d_{l,t} \geq \kappa^e_{min} K^e_{l,t-1} \text{ and } I^{d,ge}_{l,t} = 0 \\ 0, & \text{otherwise} \end{cases}.$$

30

Energy producers must buy machines from the capital-goods sector to build green power plants. The desired investment, in nominal terms, required to deploy green generation capacity is:

$$I^{d,ge,\$}_{l,t} = \frac{I^{d,ge}_{l,t}\, IC^{ge}_{l,\tau}}{p_{i,t}},$$

31

$p_{i,t}$ is the price of machine supplied by capital-good firm i chosen by energy firm l in time t.

3.3.3. Long-term financing decisions of the bank

Once the desired investment in a new green power plant is made, firms apply for project finance at the current bank. If the bank approves the project finance, the plant construction starts. If application is unsuccessful but existing liquid funds (NW) are sufficient ($NW_{l,t-1} \geq I^{d,ge,\$}_{l,t}$), the new green plant is still built. Otherwise, a dirty energy one is constructed. Suppose project finance is approved, but the machine supplier does not deliver the equipment (capital goods) ordered for plant construction. In that case, the loan is canceled without penalties to the power firm (other than the missing capacity).

Banks compute the strategic net present value of project finance requests from electrical energy production firms:

$$SNPV_{l,t} = NPV_{l,t}^{ge} + OV_{l,t}^{ge} \,, \tag{32}$$

where $NPV_{l,t}^{ge}$ is the usual expected net present value (discounted cashflow) of the project, and $OV_{l,t}$ is the (real) option value of the bank acquiring the right to leave the project at a certain time in the future. The expected net present value of a project finance request from producer l is calculated as:

$$NPV_{l,t}^{ge} = I_{l,t}^{d,ge} \sum_{i=1}^{\eta_e} \frac{\tilde{p}_{t-1}^{e}\, \tilde{u}_{t-1}^{e} - \dfrac{\widetilde{w}_{t-1}}{\tilde{A}_{t-1}^{e}}}{\left(1 + r_{l,t}^{deb}\right)^{T_{con}+i}} - I_{l,t}^{d,ge,\$} \,, \tag{33}$$

where $r_{l,t}^{deb}$ is the applicable interest rate to firm l at time t, $(T_{con}, \eta_e) \in \mathbb{N}_+^2$ are parameters defining the construction and operation (technical life) times of power plants, $\tilde{p}_t^e$ is the expected electric energy tariff, $\tilde{u}_t^e$ is the expected power plant utilization, w_t is the wage, and $\tilde{A}_t^e$ is the labor productivity. Expected values are defined as T_{plan}-period moving averages of the respective sectoral weighted means. The term $\tilde{p}_t^e\, \tilde{u}_t^e$ represents the expected revenue per unit of generation capacity, while $\widetilde{w}_t / \tilde{A}_{l,t}$ is the expected unit cost of production. So, the first term represents the expected operational cash flow for the lifetime of the green power plant with capacity $I_{l,t}^{d,ge}$. The investment $I_{l,t}^{d,ge,\$}$ required for the construction is paid upfront. Notice that at time t, only $t-1$ values for the expectational elements are available for this decision.

The risk-adjustment project value assumes that the expectational error on the four modeled uncertainty dimensions ($\tilde{p}_t^e$, $\tilde{u}_t^e$, $\widetilde{w}_t$, $\tilde{A}_{l,t}$) has lognormal distribution with standard deviation:

$$\sigma = \frac{\log(\Pi_{best} - \Pi_{worst})}{\sqrt[4]{\eta_e}} \,, \tag{34}$$

$$\Pi_{worst} = I_{l,t}^{d,ge} \sum_{i=1}^{\eta_e} \frac{\left(1 - \delta_p\right)\tilde{p}_{t-1}^{e}\, (1 - \delta_u)\tilde{u}_{t-1}^{e} - \dfrac{(1 + \delta_w)\widetilde{w}_{t-1}}{(1 - \delta_A)\tilde{A}_{l,t-1}}}{\left(1 + r_{l,t}^{deb}\right)^{i}} \,, \tag{35}$$

$$\Pi_{best} = I_{l,t}^{d,ge} \sum_{i=1}^{\eta_e} \frac{\left(1+\delta_p\right)\tilde{p}_{t-1}^{e}\,(1+\delta_u)\tilde{u}_{t-1}^{e} - \dfrac{(1-\delta_w)\widetilde{w}_{t-1}}{(1+\delta_A)\tilde{A}_{l,t-1}}}{\left(1+r_{l,t}^{deb}\right)^{i}},$$

36

being $\left(\delta_p, \delta_u, \delta_w, \delta_A\right) \in \mathbb{R}_+^4$ the project-risk parameters. Given σ, the best- and worst-case scenario risk factors for a period Δt can be then computed, respectively, as:

$$\phi^u = e^{\sigma\sqrt{\Delta t}}, \qquad \phi^d = \frac{1}{\phi_u}.$$

37

To compute the option value, we need first to build the project- and option-valuation trees for the involved decision moments $m = 0, 1, 2$. m represents the three project decision moments: (0) project conception/valuation, (1) construction start, and (2) operation beginning. m is not directly tied to the simulation periods t. The time lapse between $m = 0$ (when the project valuation data is collected) and $m = 1$ (when the construction starts) is $\Delta t = T_{plan}/2$, and between $m = 1$ and $m = 2$ (when the construction is over) is $\Delta t = T_{con}$.

The initial node of the project-valuation binomial tree ($m = 0$) is the expected discounted cashflow at time $t - 1$, that is, $NPV_0 = NPV_{l,t}^{ge}$. So, the risk-adjusted expected valuations for first two branches ($m = 1$) are computed as ($\Delta t = 1$):

$$NPV_1^u = NPV_0\,\phi_1^u = NPV_{l,t}^{ge}\,e^{\sigma\sqrt{\frac{T_{plan}}{2}}},$$

38

$$NPV_1^d = NPV_0\,\phi_1^d = NPV_{l,t}^{ge}\,e^{-\sigma\sqrt{\frac{T_{plan}}{2}}},$$

39

Finally, the final four branches ($m = 2$) can by calculated as ($\Delta t = T_{con}$):

$$NPV_2^{uu} = NPV_1^u\,\phi_2^u = NPV_1^u\,e^{\sigma\sqrt{T_{con}}},$$

40

$$NPV_2^{ud} = NPV_2^{du} = NPV_1^d\,\phi_2^u = NPV_1^d\,e^{\sigma\sqrt{T_{con}}},$$

41

$$NPV_2^{dd} = NPV_1^d\,\phi_2^d = NPV_1^d\,e^{-\sigma\sqrt{T_{con}}}.$$

42

After the risk-adjusted project-valuation tree is computed, the corresponding (real) option-valuation tree can be derived by back induction. The value of any end node can be calculated as:

$$OV_{m-1} = e^{-r_{l,t}^{deb}\Delta t}[q_m \, NPV_m^u + (1-q_m) \, NPV_m^d] \, , \tag{43}$$

$$q_m = \frac{e^{-r_{l,t}^{deb}\Delta t} - \phi_m^d}{\phi_m^u - \phi_m^d} \, . \tag{44}$$

Therefore, in our case, the intermediate ($m = 1$) option values ($\Delta t = T_{con}$) are:

$$OV_1^u = e^{-r_{l,t}^{deb}T_{con}}\left[q_2 \, NPV_2^{uu} + (1-q_2) \, NPV_2^{du}\right] \, , \tag{45}$$

$$OV_1^d = e^{-r_{l,t}^{deb}T_{con}}\left[q_2 \, NPV_2^{ud} + (1-q_2) \, NPV_2^{dd}\right] \, , \tag{46}$$

$$q_2 = \frac{e^{-r_{l,t}^{deb}T_{con}} - e^{-\sigma\sqrt{T_{con}}}}{e^{\sigma\sqrt{T_{con}}} - e^{-\sigma\sqrt{T_{con}}}} \, . \tag{47}$$

And the initial ($m = 0$) option value ($\Delta t = 1$) is:

$$OV_0 = e^{-r_{l,t}^{deb}\frac{T_{plan}}{2}}\left[q_1 \, NPV_1^u + (1-q_1) \, NPV_1^d\right] \, , \tag{48}$$

$$q_1 = \frac{e^{-r_{l,t}^{deb}\frac{T_{plan}}{2}} - e^{-\sigma\sqrt{\frac{T_{plan}}{2}}}}{e^{\sigma\sqrt{\frac{T_{plan}}{2}}} - e^{-\sigma\sqrt{\frac{T_{plan}}{2}}}} \, . \tag{49}$$

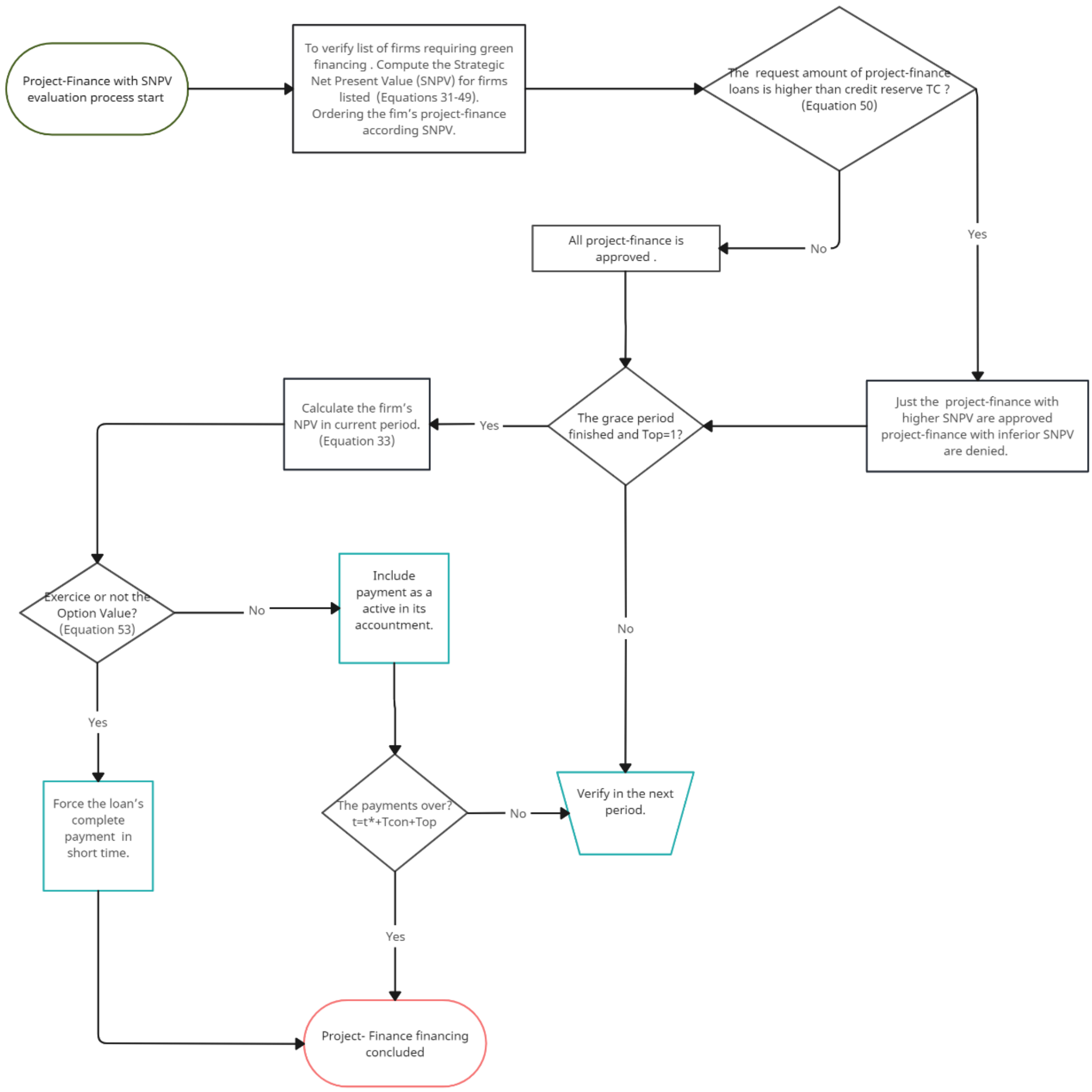
So, the total real option value of the green energy plant construction can be derived by:

$$OV_{l,t}^{ge} = OV_0 + \max\left(OV_1^u, OV_1^d, 0\right) . \tag{50}$$

Banks rank firm's project-finance requests according to the $SNPV_{l,t}$, and grant loans according to a dynamically allocated credit pool for this kind of loan:

$$TC_{k,t}^{ge} = \frac{NW_{k,t-1}^b}{\tau_{ge}\left(1 + \beta_b \, Bda_{k,t-1}\right)} \, . \tag{51}$$

$\tau_{ge} \in \mathbb{R}_+$ is a parameter defining the leverage allowed to bank k to invest in project finance, and $\beta_b \in \mathbb{R}_+$ is the bank sensitivity to its financial fragility $Bda_{k,t}$. If the total requested amount of project-finance loans is higher than $TC_{k,t}^{ge}$, projects with inferior $SNPV_{l,t}$ are denied, so $\sum_{p\in\Upsilon} I_{p,t}^{d,ge,\$} \leq TC_{k,t}^{ge}$, where Υ is the set of approved loans. Unused funds allocated to project finance $TC_{k,t}^{ge}$ cannot be reallocated to the pool $TC_{k,t}$ reserved for regular finance, and conversely.



3.3.4. Long-term debt repayments

The energy producers try to repay the project-finance principal according to the contracted terms, along a period $T_{op} \in \mathbb{N}_+$, a parameter, of each bank-financed green power plant. Project-finance loans have deferred initial principal payment equivalent to the plant construction time T_{con}, and fixed interest rate equal to the one applicable to the firm r_{l,t^*}^{deb} when the loan was approved $(t = t^*)$. For simplicity, the model adopts an even principal payment schedule, so the periodic due payments of loan p from firm l are:

$$PMT_{l,p} = \begin{cases} I_{l,t^*}^{d,ge,\$}\ r_{l,t^*}^{deb}\ , & \text{if } t^* < t < t^* + T_{con} \\ I_{l,t^*}^{d,ge,\$}\left(\frac{1}{T_{op}} + \frac{t^* + T_{con} + T_{op} - t}{T_{op}} r_{l,t^*}^{deb}\right), & \text{if } t^* + T_{con} \le t < t^* + T_{con} + T_{op} \\ 0\ , & \text{otherwise.} \end{cases} \quad (52)$$

Banks recompute the discounted cashflow of each project-finance loan when power-plant construction is finished ($t^{\#} = t^* + T_{con}$), using the then current expectations for the tariff $\tilde{p}^e_{t^{\#}-1}$, utilization $\tilde{u}^e_{t^{\#}-1}$, wage $\widetilde{w}_{t^{\#}-1}$, and productivity $\tilde{A}_{l,t^{\#}-1}$.

3.3.5. Real-Option Exercise

There is a grace period, so the debt repayment will be initiated only after the green energy plant has started operating. This way, after the construction, the bank must evaluate if it will exercise its option of exiting the finance project.

If the net present value $NPV^{ge}_{p,t^{\#}}$ of any project p becomes negative, the bank exercises the real option and demands the early maturity of the loan, Equation *53*. In this case, all the scheduled long-term payments $PMT_{l,p}$ are anticipated and added to the short-term due debt of the energy producer l.

$$RO = \begin{cases} Deb^{ge}_{p,l,t} = PMT_{l,p}, & if\ \ NPV^{ge}_{p,t^{\#}} \ge 0 \\ Deb^{ge}_{p,l,t} = I^{d,ge,\$}_{l,t^*}\left(1 + r^{deb}_{l,t^*}\right), & if\ \ otherwise \end{cases} \quad (53)$$

3.3.6. Labor demand by energy producers

The model also generically proposes the interactions between the supply and demand of the workforce in the energy sector. The labor demand is the sum of all labor demand in the economy, that is, the sum of the consumption-goods, capital goods, and energy market workforce demand, and the supply workforce is exogenous and not elastic.

The labor market is centralized, workers are homogeneous, and all companies pay the same wage. Companies, based on energy demand (energy sector), orders received (capital goods sector), expected demand (consumer goods sector), and current levels of labor productivity, decide whether to (i) hire new workers, (ii) lay off part of the existing workers or (iii) keep the workers. If the total supply of (unemployed) labor is less than the companies' demand for new workers, the resulting labor shortage is shared among industrial companies in proportion to individual demand. The aggregate labor supply is normally fixed, and all unemployed workers can be hired anytime. Banks and the government do not employ any workers. Unemployed workers receive unemployment benefits from the government.

The wage rate definition is not trivial, in Equation 54 the institutional factors are represented by the parameters (ψ_{123}). The variable $(\overline{AB})$ is the average work productivity, (cpi) the prices consumer index and (U) the unemployment rate.

$$w(t) = w(t-1) + \left(1 + \psi_1 \frac{\Delta\overline{AB}(t)}{\overline{AB}(t-1)} + \psi_2 \frac{\Delta cpi(t)}{cpi(t-1)} + \psi_3 \frac{\Delta U(t)}{U(t-1)}\right)$$

54

3.3.7. Energy producer unit cost

Adding new technological dimensions to the innovation process of capital goods companies imposes the determination of new unit costs. In this sense, all industries must now consider the cost and use of energy. Equation 55 shows the unit cost of production for consumption-good firms, while Equation 56 shows the unit cost for capital-good firms. In both equations $c^{en}(t) \subset \{c_{de}, c_{ge}\}$ represents the cost of energy.

$$c_i(t) = \frac{w(t)}{B_{i\tau}^{LP}} + \frac{c^{en}(t)}{B_i^{EE}}$$

55

$$c_j(t) = \frac{w(t)}{A_{i\tau}^{LP}} + \frac{c^{en}(t)}{A_i^{EE}}$$

56

In energy market the planned operational unit cost of dirty energy for each firm is determined by Equation 57 and for the green energy Equation 58 where m_{ge}, m_{de} is the workers units required by machines.

$$c_{de} = \frac{p_f}{A_{de}^{\tau}} + m_{de} \cdot w_t$$

57

$$c_{ge} = m_{ge} \cdot w_t$$

58

3.3.8. Pricing behavior of energy producer and the energy auction

The energy price is defined based on a fixed mark-up and the average cost of the power plant, Equation 59. The variable $\overline{c}_{de}(\tau,t)$ represents the maximum unit cost paid by dirty plants or $\overline{c}_{de}(\tau,t) = \max_{\tau \in IM} c_{de}(\tau,t)$.

$$p_e(t) = \begin{cases} \mu_e & if\ D_e\ (t) \leq K_{ge}(t) \\ \overline{c_{de}}(\tau,t) + \mu_e & if\ D_e(t) > K_{ge}(t) \end{cases}$$

59

The energy demand is allocated by a short-term first price sealed-bid auction, based on prices offered by producers and the supply energy generation, Equation 60 present the order' firms by increasing energy prices.

$$O\big(l(i)\big) = p_{e,l}$$

60

The relative capacity of each firm to supply the total energy demand for the period, on the other side, is expressed in Equation 61.

$$k_l^e(t) = \frac{K_l^e(t)}{\sum_{l=1} K_l^e(t)}$$

61

The auctions will distribute the total energy demand of the period by the energy suppliers in order to Equation 60, proportionally to Equation 61 until all energy demand to be supplied (Equation 62).

$$D_e(t) = \sum (\,O\big(l(i)\big) \cdot k_l^e(t))$$

62

If demand exceeds the total offered generation, excess demand is allocated proportionally to offered capacity among suppliers in the same way but with dirty energy.

3.3.9. Profit, Cost and Net Worth

The competitive energy production is determined by the energy demand $D_e(t)$ and its profits are determined in Equation 63.

$$\Pi_e(t) = p_e(t)\, D_e(t)\ - PC_e(t) - \ IC_e(t) - RD_e(t)$$

63

In Equation 63 $PC_e(t)$ the total cost of generating, $IC_e(t)$ the expansion and replacement investment and $RD_e(t)$ represents R&D expenditure. As you can see, each variable is specific to the sector, i.e. all the variables are specific to energy production, whether green or dirty. Plants whose production is geared towards green energy, because they have freely available inputs, have zero-unit production costs $\left(c_{ge}(t) = 0\right)$ and produce exactly as much as they can $\left(Q_{ge}(t) = K_{ge}(t)\right)$.

It is an intuitive notion that if the energy firm can choose which power plant to use, it will choose to use green power plants first, because their unit cost of production is zero. However, as the model explains, if the energy produced is not enough to supply the market, the energy firm will use the dirty energy plants, choosing to activate those with the lowest production cost first. In the model, this behavior is modeled as follows: (1) the company evaluates whether $D_e(t) \leq K_{ge}(t)$, in which case all the activated plants (IM) are green; (2) if $D_e(t) > K_{ge}(t)$ the production cost $PC_e(t)$ will be positive and determined according to Equation 64.

$$PC_e(t) = \sum (g_{de}(\tau, t)\, c_{de}(\tau, t) A_{de}^{\tau})$$

64

The energy producer will eventually need to update or replace the technology it uses, and similarly, as society evolves, it will also need to expand its production. In this sense, resources must be earmarked for replacing and expanding its energy generation capacity. Upgrading or replacing technology requires fewer resources than building new plants.

They assume it is in the energy producer's interest to expand its production capacity to sources whose unit production cost is zero, i.e., green energy generation. Lamperti et al., (2018) normalizes the cost of building new dirty plants to zero and highlight regard need for green plants $IC_{ge}^{\tau}$to be sustained. About the capital stock $K_e(t)$, the model proposes that it be obtained by adding up the energy capacities of the plants (green or dirty), including the inactive ones, as shown in Equation 65.

$$K_e(t) = \sum_{\tau} g_{de}(\tau, t) \ + \sum_{\tau} g_{ge}(\tau, t)$$

65

Completing the investment cycle, production, and results, the monetary resources, or the liquid assets stock Equation 66 is updated after profit estimation and is based on the difference between the profit and the finance resources used internally plus the not used liquid assets stock.

$$NW_j(t) = NW_j(t-1) + \Pi_j(t) - cI_j(t)$$

66

3.4. Experiments, Results and Discussions

The experiments presented in this section consider three stylized scenarios. The first is the Only regular credit scenario, where the economic system does not have project finance credit, and the loans should be paid in the short term. The second is the Long-term green credit lines scenario, which has project finance credits, but a real option possibility does not exist. The SNPV/RO project finance scenario comprises project finance credit and option real exercise.

Table 9 resumes the scenarios' fundamental features and the result experiments represent four hundred (400) simulations of each scenario. Furthermore, this model shares a modular structure[3], and because of this, the dynamic core of the economic system still presents stylized facts.

Table 9 Scenarios' fundamental features

Scenario	Project finance credit	Option real exercise	Grace period
Only regular credit	No	No	No
NPV project finance	Yes	No	Four periods
SNPV/RO project finance	Yes	Yes	Four periods

Source: Own Elaboration

The innovation process is the initial point of all dynamics in this model, and in this sense, it is important to qualify the innovation process on scenarios analyzed. Figure 20 compares the share of dirty firms' energy innovation by the scenarios in Table 9.

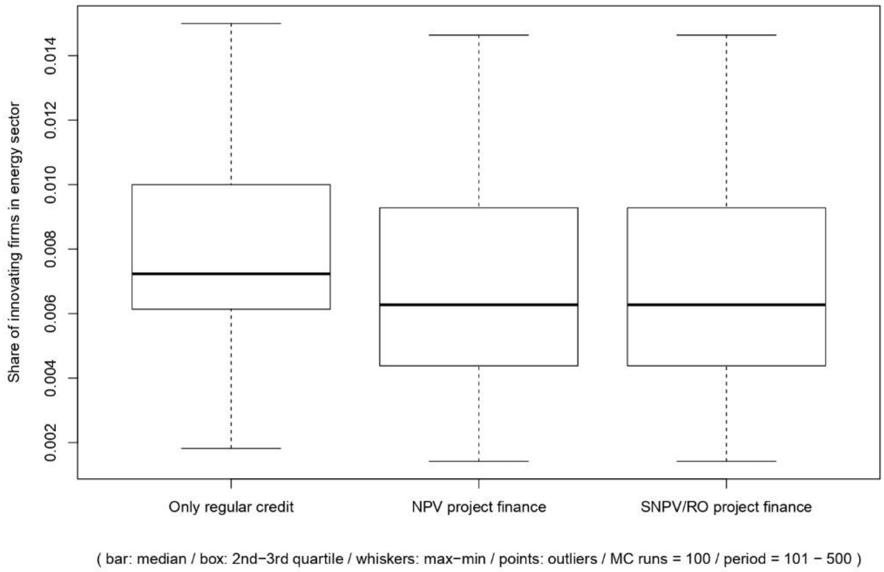


Figure 20 Dirty-energy firms' innovation in three scenarios (100 times, 400 periods, 1 period= 1 quarter)
Source: Original results

[3] See more on (Dosi *et al.*, 2013, 2015b, 2022; Dosi, Fagiolo e Roventini, 2010; Lamperti, F *et al.*, 2018)

In both scenarios, the NPV project finance and SNPV/RO project finance, the share of dirty energy innovation is lower than in the regular credit scenario. The opposite is seen in Figure 21, where the green firm's energy innovation is lower in a regular credit scenario.

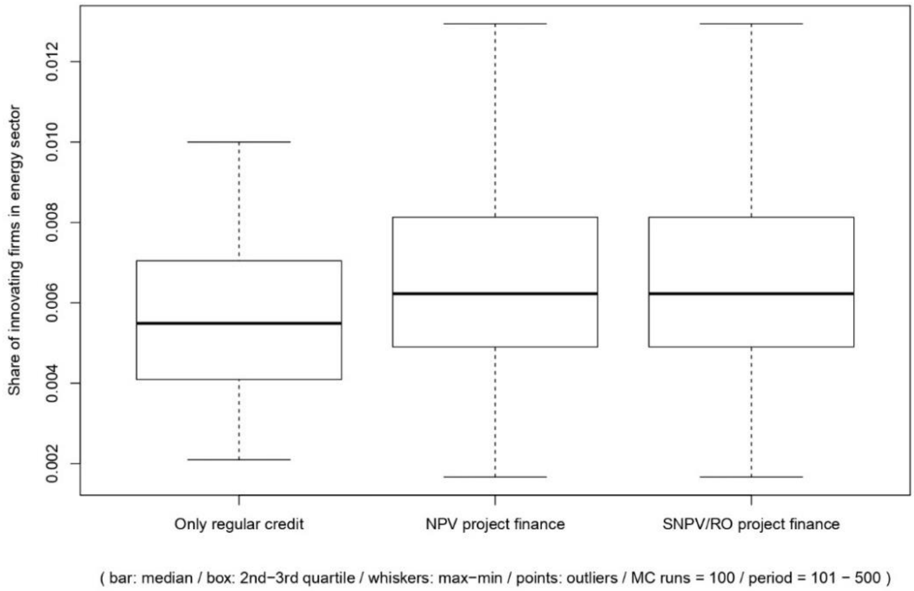


Figure 21 Green-energy firm's innovation in three scenarios (100 times, 400 periods, 1 period= 1 quarter)
Source: Original results

Comparing the innovation process in the energy sector with the capital-goods sector, the green-energy innovation, despite better NPV and SNPV/RO project finance scenarios, is less strong than the capital-goods firms' innovation, Figure 22.

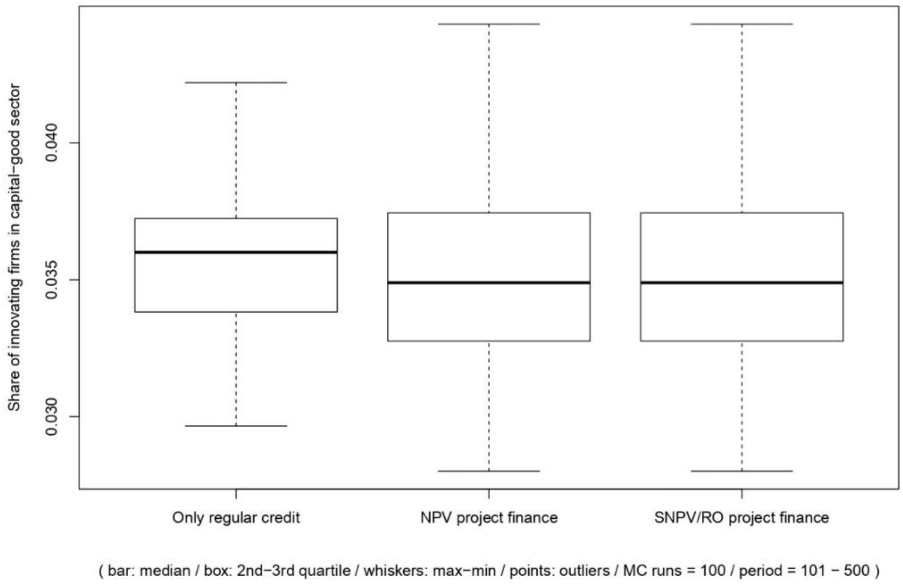


Figure 22 Share of innovating firms in the Capital-goods sector (100 times, 400 periods, 1 period= 1 quarter)
Source: Original results

The bank credit supply and firm loan behavior were similar in all scenarios. However, the thermal efficiency of energy generation was much better in the SNPV/RO and NPV project finance scenarios, Figure 23. This can be noted in both situations short and long term, but more strongly in the long term.

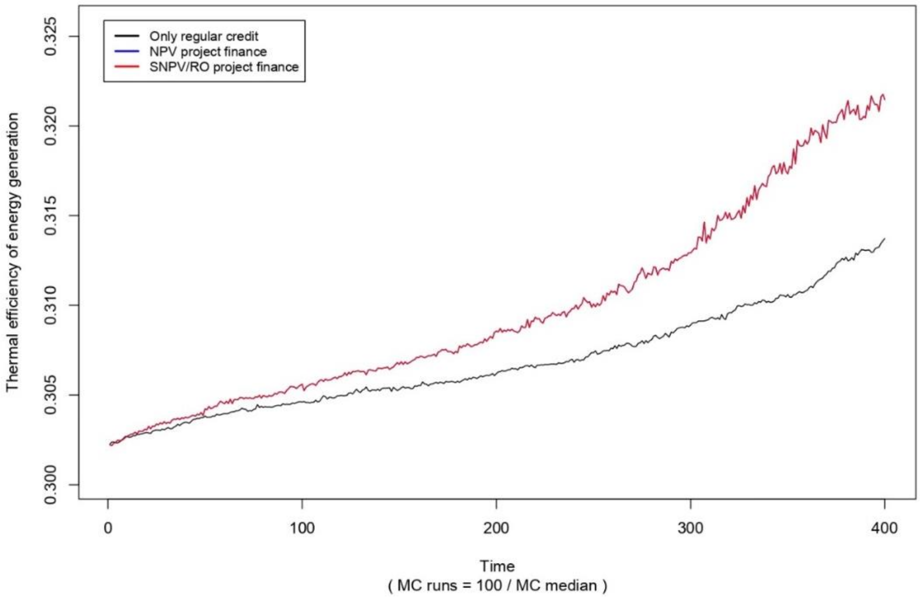


Figure 23 Thermal efficiency (all experiments), 400 periods.
Source: Original results

The efficiency shown in Figure 23 is supported by results obtained about CO2 emissions in Figure 24. As it is possible to note, the level of CO2 emissions is lower in SNPV/RO and NPV scenarios than in the regular in the long term.

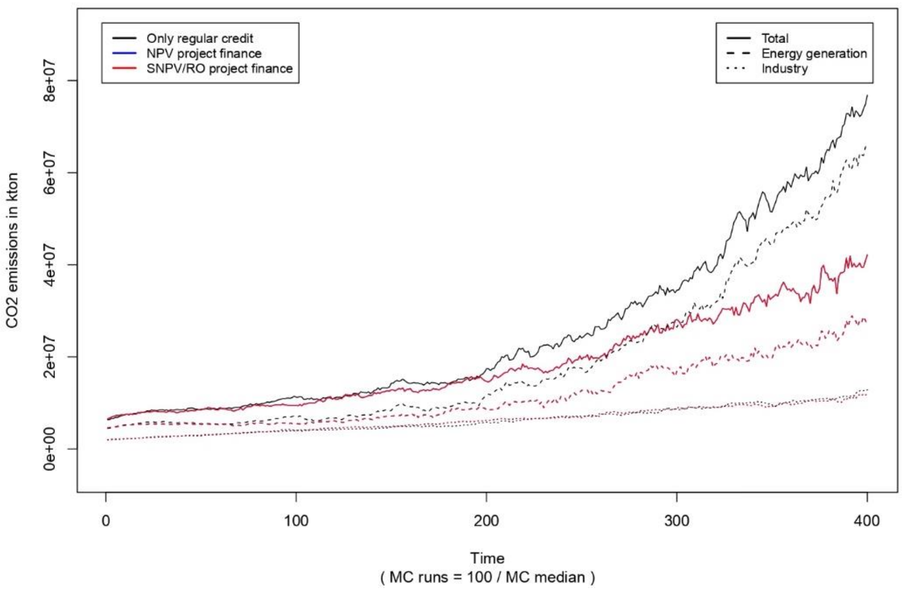


Figure 24 CO2 emissions (all experiments) 400 periods.

Source: Original results.

Consequently, the level of CO2 In the atmosphere was lower in SNPV and NPV project finance scenarios. But this difference, as Figure 25 shows, is a consequence seen just in the long term.

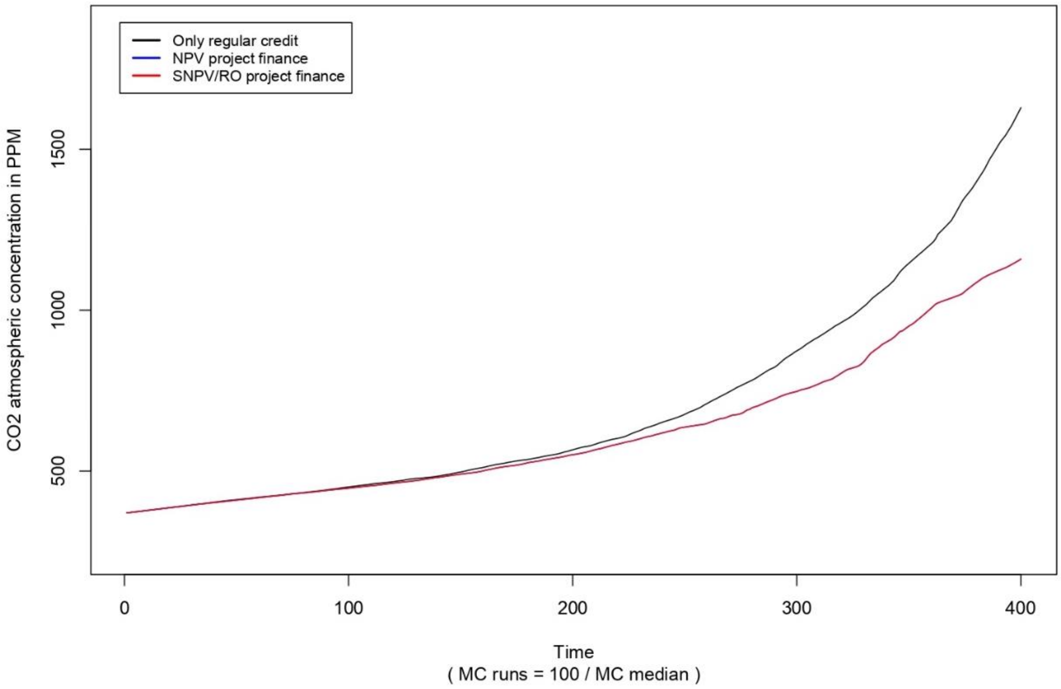


Figure 25 CO2 in the atmosphere concentration in the time (400 periods)
Source: Original results

Analyzing the green energy share and installed capacity share the different perspectives (Figure 26), it is possible to see that in the beginning, the number of green energy plants was lower than others, conforming the time they adopt an increasing trajectory that stabilizes after some time. The same does not occur with the dirty plants, which had an increasing trend initially but decreased after 200, 50 years later.

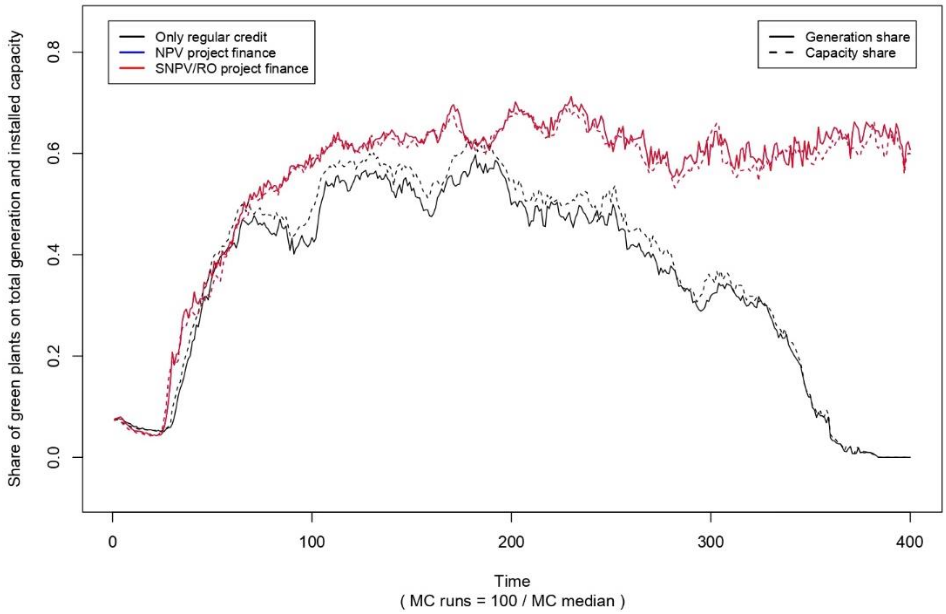


Figure 26 Share of green plants on total generation and installed capacity in the time (400 periods)
Source: Original results

Regarding macroeconomics features, it is important to highlight that the GDP, inflation, government income, government expenditure, deficit and debt, real wage, and unemployment do not have substantial discrepancies between scenarios. Regarding the energy market, all scenarios present low concentration indices Herfindahl-Hirschman, but in the regular scenarios, the competitiveness was stronger, Figure 27.

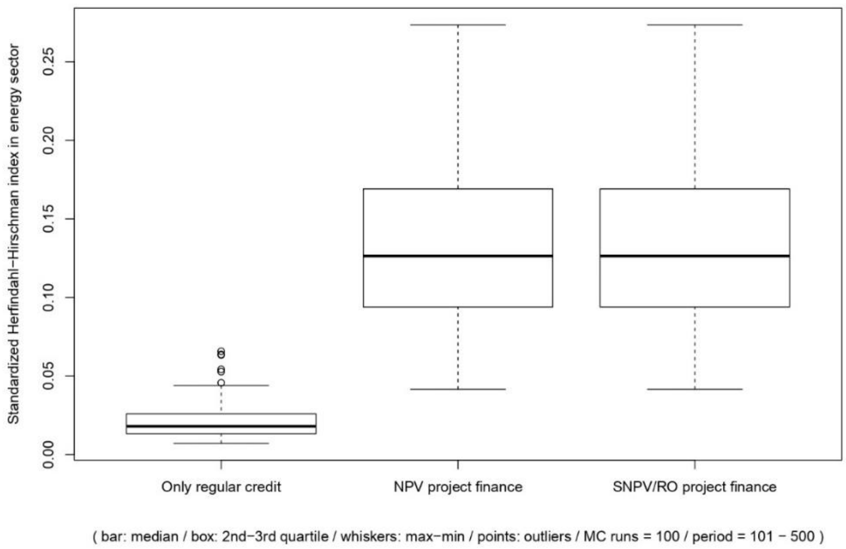


Figure 27 HH index in energy sector for all experiments.
Source: Originals results

In terms of electrical energy price, in the short term the difference between the scenarios it is almost impossible to note. Just about the 290 period the differences are noted, and the price of electrical energy turn more expensive in SNPV/RO and NPV project finance scenarios, Figure 28.

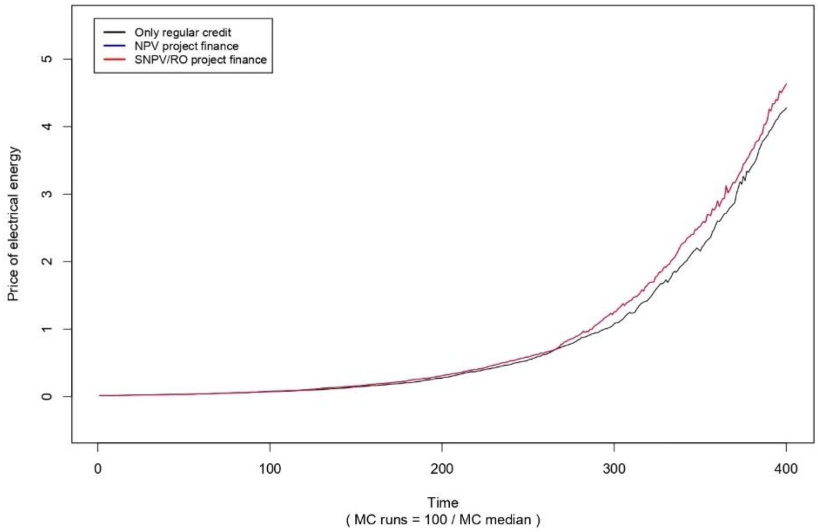


Figure 28 Electrical energy price of energy (all experiments) In the time - 400 periods
Source: Original results

The behavior of prices in Figure 28, can explain in the long term the biggest concentration observed in Figure 27 in the scenarios SNPV/RO and NPV project finance, but can't explain the short-term.

3.4.1. Monte Carlo Validation

The ADF test first tested the presence of unit roots to evaluate whether the series obtained is stationary, whether the results and analysis can be generalized and used for predictions, or whether point changes and standards are significant. The test was applied in all series of all scenarios.

Also, the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test evaluates if the time series has a stationary trend. The KPSS test helps to distinguish the series that seems stationary from the series that seems to have a unit root or the series that does not have sufficient data to confirm the stationary.

In the same way, it was tested if the series is independent and identically distributed (i.i.d) by the test Brok, Dechert, Scheinkman (BDS). When the series is i.i.d, all observations have the same distribution and are independent of one of the others.

To analyze if the series has a linear behavior or normal distribution, the Kolmogorov-Smirnov (KS), Anderson-Darling (AD), and Shapiro-Wilk (SW) tests were also applied. Furthermore, these tests evaluate ad-hoc if the series is ergodicity or not. The series presented problems like non-stationarity, not distribution, i.i.d, and not ergodicity.

We also did the correlation between the variables in all scenarios. Figure 29 shows the correlation between the variables in the regular scenario. It is easy to see that unemployment is strongly negatively related to GDP, Consumption, and investment. The energy demand is also strongly related positively to GDP and Consumption and negatively to unemployment. The energy demand and the emissions are related negatively but also strongly with unemployment. This seems to be a reasonable appointment.

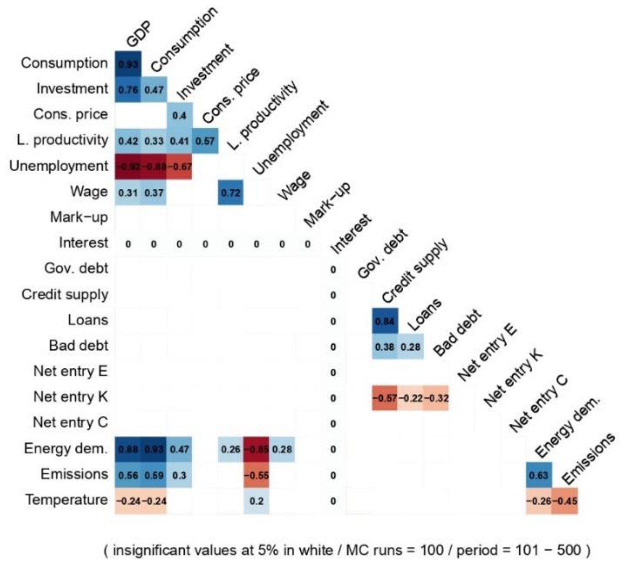


Figure 29 Correlations of Pearson between variables in the models (all experiments)
Source: Original Results

The situation about correlation is that these variables in the NPV or SNPV/RO scenarios do not change. Still, the correlation between unemployment and energy demand is bigger in these scenarios than in others.

3.5. Conclusion

This chapter provide a deep understanding of the incorporation of real option analysis in a dynamic economic model with a competitive energy sector. In the model proposed here was considered a competition between different private's energy producers in a partial regulated market, with energy auctions and the option of long-term financing energy projects, by real option propose.

The experiments from three scenarios highlights purpose to gain a better understanding about the conditions under which the real options analysis can make SNPV/RO project finance more attractive for a greater number of economics agents. The macroeconomics analysis shows that in terms innovation, CO_2 emissions, thermal efficiency, and energy transition (with more green energy plant than dirty in the end) the SNPV/RO and NPV project finance scenarios has positive impacts compared to the regular credit scenario.

The argument K+S model offers a more extensive structure for analyzing the interaction between the finance sector, the energy sector, workers, the biome, and the consumption-good and capital-good sectors. The realistic elements added to the energy sector enrich the comprehension of green energy investment in an economic system.

However, as the series showed characteristics of instability, it is still necessary to further calibrate the model to find a scenario that favors the energy transition and, at the same time, can be used as a reference in the decisions of public policymakers.

General Conclusions

The main purpose of the thesis was to develop an Agent-Based Model of green energy transition with a new financing criterion that considers the main features of economic dynamics and the possibility of new green energy finance criteria. Notwithstanding, its central objective is to investigate the adoption of real options analysis (ROA) and its effects on green energy financing in a complex economic system. For this, first, we show the applicability of this methodology in a real economic situation and use a Brazilian case study. In sequence, we selected the best economic model for applying the ROA methodology and analyzed its implementation for financing green projects.

From Chapter 1, we extensively explored the existing ROA literature. We explored the uncertainty associated with cost-side variables such as wages and labor productivity in energy production, an ROA-augmented methodology to analyze the impacts of its adoption as a criterion for the financial evaluation of green energy projects from the Brazilian perspective. The ROA-augmented methodology proved efficient in making energy projects like the one analyzed in Chapter 1, section 1.4, more financially attractive.

However, despite contributing to the project appraisal process, presented in Chapter 1, the ROA-augmented methodology requires more statistical analysis to address volatility and uncertainty levels, particularly in developing countries. This is because the ROA-augmented approach presented in Chapter 1 is limited to static scenario. From the point of view of public policymakers aimed at mitigating the impacts of climate change, it was necessary to incorporate them into a complex environment that considers both the economic and climate dynamics.

Agent-based models can incorporate the complex interactions between firms (capital goods, consumer goods, and energy providers), banks, households, and the natural environment. In this sense, chapter 2 summarizes an important search process using the best existing economic model compatible with the ROA-augmented methodology application. This chapter demanded an extensive mapping to general equilibrium, network or complex system, and agent-based economic models. Besides this, chapter 2 provides a general view of the most relevant economic growth models, according to Scopus web science, that incorporate environmental elements. No one had ever condensed this theory this way before.

As well as micro-founded macroeconomic models focusing on economic growth, policies, and distributional conflicts based on equilibrium general theory, the application of Agent-Based Models (ABM) to analyze the energy transition and the impacts of climate change, from complexity theory, on the economic system has advanced over the last twenty years. Recent studies aim to understand the economic impacts of mitigation policies, comparing technological incentives and carbon taxes.

The model by Dosi, Fagiolo, and Roventini (2010) is the basis of the model presented in chapter 3 of the thesis, where the authors combine post-Keynesian (PK) theory and neo-Schumpeterian evolutionary theory. As a complex model, Dosi, Fagiolo, and Roventini (2010) use the ABM methodology to incorporate some of the realistic assumptions adopted by PK theory, introducing different behaviors and characteristics of economic agents and converting the idea of path dependence as an institutional structure.

However, Chapter 2 showcases the ongoing development of numerous studies through several models. These models demonstrate the progress and underline the importance of continuing research efforts in this field. Table 8 shows various studies related to climate change and the application of ABM, each with a different approach and focus. Some research has focused on analyzing more significant climate change events and their economic consequences. Others focus on a regional level or from the perspective of the entrepreneur. These differences imply different criteria for analysis and how they deal with uncertainty. Some of this research explores the tension and heterogeneity of the system from different scenarios and mitigation strategies.

The theoretical mapping or condensation provided in Chapter 2 opens new possibilities for discussion: How has the theory on agent-based models progressed, especially those that include climate elements? What are the discrepancies or deficiencies in the theoretical representation?

Chapter 3 contributes to expanding the legacy "Schumpeter Meeting Keynes" model (K+S) (Dosi et al., 2015; Dosi, Fagiolo e Roventini, 2010), including the "Dystopian" extension (DSK) (Lamperti et al., 2018), to offer a proper set-up to evaluate the effects of the adoption of real options analysis (ROA) when evaluating green energy investment projects. When compared to the existing K+S versions, we add: (i) a fully competitive energy sector, with multiple private energy-producing firms competing in a partially regulated market, including energy auctions; (ii) a long-term project finance alternative provided by banks for the investment of energy producers in new green energy power plants; and (iii) an enhanced climate subsystem ("climate box"), considering the full CO2 cycle as prescribed by the reference C-ROADS model (Sterman et al., 2012).

The K+S model and its counterparts provide a complex system of interactions between different types of firms, consumers, banks and the natural environment, which allows it to be adapted with a fully competitive energy sector, unlike Lamperti et al. (2018) which has a non-competitive energy sector, a long-term project financing with ROA analysis, unlike Dosi et al. (2013, 2015) which has a quantitative financing constraint based only on the banking network, and a complete climate box based on Sterman et al. (2012).

In this final chapter, we implement the ROA-augmented methodology into a dynamic economic and environmental system incorporating a more realistic representation of the energy sector, thus filling the gap identified in Chapter 1. The experiments from three scenarios underscore the aim to enhance our comprehension of the conditions under which real options analysis can render SNPV/RO project financing more appealing to a larger pool of economic agents. The macroeconomic analysis indicates that in terms of innovation, CO2 emissions, thermal efficiency, and energy transition (with a higher proportion of green energy plants than polluting ones in the end), the SNPV/RO and NPV project finance scenarios have positive impacts compared to the regular credit scenario. However, given the instability characteristics exhibited by the series, it remains necessary to further calibrate the model to identify a scenario that promotes energy transition and can concurrently serve as a reference for public policymakers' decisions.

Therefore, this thesis has shown that the adoption of the ROA-augmented methodology has the potential to expand banking finance with significant microeconomics and environmental impacts as well on innovation performance generation, and in the green energy transition, making it possible to reduce greenhouse gas emissions in the long run.

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Appendix A

A.1. Resume: Schumpeter meeting Keynes (K+S) (Dosi et al. 2010)

The model proposed by Dosi, Fagiolo e Roventini, (2010), the basis for the DSK model, comprises three different types of agents. The first represents companies, the second consumers, who also offer their labor force, and the third agent represents the public sector.

There are two different types of firms in the model. In one of the industries, the participating companies carry out research and development (R&D) and produce tools and machines that are different from each other. In the other industry, the component companies produce a homogeneous consumer good and invest in new machines and tools. As the agent representing the public sector, the government levies direct taxes (on wages and profits) and provides the unemployed with a fraction of the market wage (Nelson e Winter, 1982).

Innovations are the uncertain result of firms producing capital goods and affect the whole development of the economy as they can make the production process less costly. The diffusion of technology happens when new companies acquire new machines and tools.

In this sense, as proposed by Schumpeterian theory, the search for innovation is the basis for all interactions between agents in this model. Therefore, companies in the capital goods industry seek to improve their processes and products and, consequently, their market share and profits based on Equation *68*.

$$RD_i(t) = v\,S_i(t-1) \tag{67}$$

In Equation *68*, the subscript i differentiates the companies participating in the market, and the time (t) allows us to determine the order and sequence of the interactions. Furthermore, $v \in 0{,}1$ represents the fraction of sales S_i accumulated in the previous period $t-1$ invested by each company in R&D.

The innovation process was separated by Nelson e Winter (1982) and, also in this model, as the set of two possible actions: innovation IN and imitation IM. In this way, the entrepreneur will divide his resources in an attempt to succeed in either of the possibilities according to the parameter $\xi \in 0{,}1$ as shown in Equations *68* and *69* below.

$$IN_i = \xi\,RD_i(t) \tag{68}$$

$$IM_i = (1-\xi)\,RD_i(t) \tag{69}$$

The occurrence of innovation, just as in the real world, is not deterministic and is determined by the random drawing of a Bernoulli distribution, whose parameter $\theta_i^{in}(t)$, Equation 70, given that $0 < \zeta 1 \leq 1$. As is to be expected, the greater the resources allocated to the innovative discovery process, the greater the chances of success in innovating.

$$\theta_i^{in}(t) = 1 - e^{-\zeta_1 IN_i(t)}$$

70

It is important to note that the model establishes an indirect conversion of resources dedicated to R&D into the salaries w_t of researchers. In this way, the unit cost of producing capital goods is defined by Equation 71, where the superscript τ (always positive) refers to the current technology batch.

$$c_i(t) = \frac{w(t)}{B_i^{\tau}}$$

71

Wages through the unit cost shown in Equation 72 end up indirectly affecting the prices of the capital goods produced p_i. Equation 72 determines the prices, and, as you can see, pricing includes a fixed markup ($\mu_1 > 0$).

$$p_i(t) = (1 + \mu_1)c_i(t)$$

72

Successful innovation can result in different technologies. If the company has succeeded in innovating, it can, in this model, develop a new product/machine from two technological possibilities: A_i^{in}, B_i^{in}. Each technological possibility is associated with a specific probability, as shown in Equations 73 and 74.

$$A_i^{in} = A_i(t)\left(1 + x_i^A(t)\right)$$

73

$$B_i^{in} = B_i(t)\left(1 + x_i^B(t)\right)$$

74

In these equations (Equation 73 and 74), x_i^A and x_i^B are independent and part of the distribution $Beta\,(\alpha_i, \beta_i)$ while the set of values possible to be assumed is determined by $\left[\underline{x_1}, \overline{x_1}\right]$. The imitation like innovation process do not have a deterministic result (success or failure) and the possibilities them are related to a Bernoulli distribution ($Bernoulli\ (\theta_i^{im}(t))$ with ($0 < \zeta_2 \leq 1$), Equation 75.

$$\theta_i^{im}(t) = 1 - e^{-\zeta_2 IM_i(t)}$$

75

As closer be ζ_2 parameter to one biggest the chances of success on imitation process. The firms imitate the closer technology (A_i^{im}, B_i^{im}) or won't be possible the good reply. In terms of simulation, this indicates an Euclidean metric peer-to-peer application. The choice of current technology is evaluated by price and efficiency, as shown in Equation 76. Equation 76 defines three technological possibilities: the firms can choose still with the same technology, adopt a new one (innovation), or reply to someone else (imitation). Parameter b, on Equation 76 presents the period of economic positive return to the technology.

$$\min\left[p_i^h(t) + bc_i^h\left(A_i^h, t\right)\right],\ h = \tau, in, im$$

76

The available technologies are identified by the firms for their prices and productivity on a technological menu. Each firm send a technological menu for both: the firms that in sometime have bought some technology them (HC_i) and the firms that should be a client (NC_i). Both groups are proportional to each other, that is, $NC_i(t) = \gamma HC_i(t)$ were $\gamma \in (0,1)$.

The consumption-goods firms offer homogeneous goods and its production process exhibit constants scale' return (Nicholson, 2005). The consumption-good output (Q_j) it results that combination between capital and work' inputs and the adaptative demand expected (D_j^e), Equation 77. The expected demand is formed by the effective demand on times before like $D_j(t-1)$ and so forth.

$$D_j^e = f\left(D_j(t-1), D_j(t-2), \ldots, D_j(t-h)\right)$$

77

However, the consumption-good output desired (Q_j^d) depends not just the expected demand but also to the desired stock (N_j^d) and that real stock N_j, Equation 78. The desired stock is an arithmetic progression to D_j^e, that is, $N_j^d(t) = \iota D_j^e(t)$, $\iota \in [0,1]$.

$$Q_j^d = D_j^e(t) + N_j^d(t) - N_j(t-1)$$

78

As a real life the consumption-goods production depends on capital stock (K_j) which is expanded when the desired capital stock (K_j^d) is bigger than the actual capital stock level. In these cases, the firm should expand its capacity of production EI_j,. This way, the desired expansion of production capacity is the difference between the capital stock and the desired capital stock, Equation 79.

$$EI_j^d(t) = K_j^d(t) - K_j(t)$$

79

The firm's capital stock is composed by different technology levels organized in something like a variable file $\left(\Xi_j(t)\right)$. These technologies are listed by firm and is updated each time, replacing olds technologies by its prices $\left(A_i^\tau \in \Xi_j(t)\right)$. The investment required by technological replace $\left(RS_j(t)\right)$ is calculated from sum of all other technology on $\left(\Xi_j(t)\right)$, Equation 80.

$$RS_j(t) = \left\{ A_i^\tau \in \Xi_j(t) \colon \frac{p^*(t)}{c\left(A_{i,\tau,t}\right) - c^*(t)} \leq b \right\}$$

80

The right side of Equation 57 comprises the capital-good's price and the difference between the unitary work cost (Equation 81) and the technology unitary cost on file variable.

$$c\left(A_{i,}^\tau t\right) = \frac{w(t)}{A_i^\tau}$$

81

New technology access by consumption-good firms occurs by similar internals menu by the known information about the capital-good firms technology that they already had contact. From this internal menu the consumption-good firms choose the technology be acquired from price and unitary production cost $\left(p_i(t) + b\, c(A_i^\tau, t)\right)$. All technology request is received at end of each period.

The consumption-good firms' total investment $\left(I_j(t)\right)$, this way, is defined by expansion and replacement investment $\left(EI_j + RS_j\right)$. The sum of all consumption-good firms' investment defines the aggregate investment $\left(I(t)\right)$. It is worth noting that this is not the only way to represent the investment function with an increase in technology in macroeconomic models. Other macroeconomic models, such as the one presented in (Caiani, Godin e Lucarelli, 2014), present this function based on two capital stocks, one traditional and one innovative, both driven by demand variables.

Investments should be financed, as well as the worker's salary. In this sense, the model adheres to the theory of imperfect capital markets according to Greenwald e Stiglitz, (1993); Hubbard, (2001); Stiglitz e Weiss, (1992). Generally speaking, this means that the cost of obtaining external capital is higher than the use of internal capital and that the supply of credit is not unlimited. It is, therefore, more advantageous for consumer goods firms to first use their stock of liquid assets (NW_j) to finance their production. Suppose these stocks are insufficient to cover production costs fully. In that case, they must seek access to external capital subject to an interest rate r that does not exceed the maximum debt/sales ratio (Λ). The priority of resources in the model is for production, i.e., only those companies that can afford to finance their production will be able to carry out investment plans and, if necessary, use their residual debt capacity.

Knowing the capital stock, the consumption-goods define the capital average productivity and the marginal production cost. So, the firms can define the consumption-goods price and their markup Equation 82 and 83, respectively.

$$p_j(t) = \left(1 + \mu_j(t)\right) c_j(t)$$

82

The markup variable it is calculated and updated as relation between its markup in the period before and the evolution of firms' market share $\left(f_j\right)$, moreover, in Equation 83, $0 \leq v \leq 1$.

$$\mu_j(t) = \mu_j(t-1)\left(1 + \ v \ \frac{\left(f_j(t-1) - f_j(t-2)\right)}{f_j(t-2)}\right)$$

83

There is also imperfect information in the consumption-goods market. Consumers can not instantly choose more competitive consumption-goods because they need to learn about them. Therefore, the firms' competitiveness cannot be determined by their prices. Because of this, the firms' competitiveness is defined by price and the last period of unmet demand Equation 84.

$$E_j(t) = \ -w_1 p_j(t) - w_2 l_j(t)$$

84

The average sector competitiveness is obtained after each firm knows their competitiveness and is resulted by the sum of firms' competitiveness weighted by their market share Equation 85. This competitiveness it used as a selection criterion that, ceteris paribus, drives, expands, contracts, and extinguishes firms in the market, thus altering its structure.

$$\overline{E}(t) = \sum_{j=1}^{F_2} E_j(t) \ f_j(t-1)$$

85

There are a noticeable connection between the Equation 84, Equation 85, Equation 86, and the Equation 83, all them needs to market share variable $f_j(t)$. The market share is determined by Equation 86, were $\chi > 0$.

$$f_j(t) = f_j(t-1)\left(1 + \chi \frac{\left(E_j(t) - \overline{E}(t)\right)}{\overline{E}(t)}\right)$$

86

The consumption-good firm's profit (Π_j), is determined by the difference between the revenues, total cost, and the debts on the period (Equation 86). The profit can be positive or negative, implying market share gains or losses. Market share variation promotes adjustments in prices and, consequently, in sales. This guarantees a concentration of long-term market dynamics.

$$\Pi_j(t) = S_j(t) - c_j(t)\,Q_j(t) - r\,Deb_j(t)$$

87

Completing the investment cycle, production, and results, the monetary resources or the liquid assets stock Equation 88 is updated after profit estimation and is based on the difference between the profit and the finance resources used internally plus the not used liquid assets stock.

$$NW_j(t) = NW_j(t-1) + \Pi_j(t) - cI_j(t)$$

88

The model also analyzes, but more generic, the interactions between the supply and demand of the workforce. The workforce demand is the sum of all workforces' demand in the economy, that is, the sum of the consumption-goods market and capital-goods market workforce demand, and the supply workforce is exogenous and not elastic.

Nevertheless, the institutional factors are represented by the parameters (ψ_{123}). The variable $(\overline{AB})$ is the average work productivity, (cpi) the prices consumer index and (U) the unemployment rate.

$$w(t) = w(t-1) + \left(1 + \psi_1 \frac{\Delta\overline{AB}(t)}{\overline{AB}(t-1)} + \psi_2 \frac{\Delta cpi(t)}{cpi(t-1)} + \psi_3 \frac{\Delta U(t)}{U(t-1)}\right)$$

89

However, the total consumption or aggregate consumption by workers and unemployed workers considers the government benefits received by the unemployed workers, presented by a fraction of the actual wage of the market Equation 90. The total output of that economy is calculated from the aggregate consumption, the total investment, and the stock variation, Equation 91.

$$C(t) = w(t)L^D + w^u\left(L^S - L^D(t)\right)$$

90

$$Y = C(t) + I(t) + \Delta N$$

91

Thus, the dynamics of the model impose the following order: (1) first, the initial conditions are established; (2) the amount invested in R&D is determined; (3) considering the possibility of success in innovating or imitating and the technologies obtained as a result, the wage rate is determined, (4) then the unit cost and (5) the price. Once prices have been set, capital goods companies send their portfolios to consumer goods companies, which (6) determine their production based on the combination of capital and labor and expectations of demand, (7) then update their investment in expansion, and (8) replacement investments. Then (9) consumer goods companies determine total investment at time t, and (10) determine the price of their products based on their competitiveness and markup. After this, (11) companies in both sectors whose market share is close to or below zero are excluded from the market and replaced by new companies. Then, the consumer goods companies (12) update their profit estimates and inventories. Finally, (13) aggregate consumption is determined, and (14) market output can be calculated.

Appendix B

B.1. Resume: The growth of the credit system and the banking sector- (Dosi et al. 2013 and Dosi et al. 2015)

In addition to the structure presented in the previous section, the DSK model includes a credit system and the banking sector based on the model proposed by Dosi et al., (2013, 2015). In this model, the authors only considered commercial banks. These banks must determine the amount of credit to be allocated to each company based on the existing demand for credit.

In the model presented in the previous section, the resources earmarked to finance investments by consumer goods companies were obtained from the sum of replacement and expansion investments. Only those companies that could finance their production with their resources could access external capital, given a certain debt quota.

The model proposed by Dosi et al., (2013) provides consumer goods companies that cannot finance their production and investment using their stock of liquid assets with external funds from the bank. In this sense, Equation 92is the equality relation that satisfies the resource constraint.

$$c_j(t)Q_j(t) + EI_j^d(t) + RS_j^d(t) \leq NW_j(t-1) + CD_j(t)$$

92

In Equation 92, the term $c_j(t)Q_j(t)$ present the total production cost, $EI_j^d(t)$ the expansion investment, $RS_j^d(t)$ the replacement investment, $NW_j(t-1)$ the liquid stock in period before and the $CD_j(t)$ firms' credit demand. The maximum level of firms' demand debt is depending on it saved liquid resources, Equation 93.

$$CD_j(t) \leq \Lambda S_j(t-1)$$

93

The credit supply also has constraints and uses the multiplier rule for this. The maximum supply credit is defined in Equation 94, and the credit allocation is based on a hierarchical relation between the liquid assets and the sales of each firm. Then, the credit allocation must be lower or equal to the firms' credit demand.

$$MTC(t) = k\left(\sum_{i=1}^{F_1} NW_i(t-1) + \sum_{j=1}^{F_2} NW_j(t-1)\right),\ k > 0$$

94

When the credit demand is lower than the credit supply, all firms must receive from the bank, and on the opposite, the firm or firms will be forced to do rationing. This argument is at odds with what Keynesian models usually use as a criterion for determining credit, as Godley, (1999) shows.

On each period, the bank's stock of credit must satisfy the restriction presented in Equation 95. Its profit is calculated from loan's interest rate received, Central Bank interest rate paid by the reserves and by the interest rate paid by deposits.

$$\sum_{j=1}^{F_2} Deb_j(t) = Loan(t) \leq MTC(t)$$

95

The Central Bank interest rate paid by the reserves (r_L) and by the interest rate paid by deposits (r_D), are subject to credit (not related to loans prices) available, Equation 96 and 97.

$$r_D = (1-\psi_D)r,\ 0 \leq \psi_D \leq 1$$

96

$$r_L = (1+\psi_L)r,\ 0 \leq \psi_L \leq 1$$

97

The bank's profits make up the reserves kept at the Central Bank, and their excess is used against potential losses in unproductive businesses. The growth of the financial market and the banking sector in this model alters the levels of corporate indebtedness, highlighting the fragility of companies whose production costs induce constant financial indebtedness.

Appendix C

C.1. Climate box, carbon cycle and temperature: Dystopian Schumpeter Meeting Keynes (DSK) model – (Lamperti et al. 2018)

Considering that the production of capital goods and consumer goods imposes a certain amount of CO2 on the environment and that the concentration of this gas affects the evolution of the climate, the DSK model proposed by Lamperti et al., (2018) adds the perception and interaction of the environment in economic growth through the carbon cycle (represented by a climate box).

The climate box turns possible evaluate the GHG emissions and its effects on carbon cycle. (Lamperti, F *et al.*, 2018) propose a Biome that was named by net primary production (NPP) that increase logarithmically sequestering carbon $\left(C_a(t)\right)$, but the average increase of climate temperature by surface (T_m) has negative affect on Biome increase, Equation 98.

$$NPP(t) = NPP(0)\left(1 + \beta_c \log\frac{C_a(t)}{C_a(0)}\right)\left(1 - \beta_{T_1} T_m(t-1)\right)$$

98

At Equation 98, β_c represents the fertilization feedback intensity, that is, the increase of sequestering carbon in the atmosphere, while β_{T_1} compile the amplitude effect of average temperature on Biome. The sequestering carbon by oceans, or its endurance to them $\left(\Omega(t)\right)$, influences on total sequestering carbon' equilibrium $\left(C_m(t)\right)$, Equation 99.

$$C_m(t) = C_m^*(t)\left[\frac{C_a(t)}{C_{a(0)}}\right]^{1/\Omega(t)}$$

99

The resistance of oceans to sequester carbon increases with higher GHG emissions, according to Goudriaan e Ketner, (1984); Rotmans, Boois, De e Swart, (1990). This resistance is modeled by Equation 100, where $\delta > 0$ is the sensibility that sequesters carbon increase.

$$\Omega(t) = \Omega(0) + \delta \log\left[\frac{C_a(t-1)}{C_a(0)}\right]$$

100

At each period the carbon sequesters, that is sensible to changes on (β_{T_1}) and (T_m) is updated Equation 101. The net carbon flow sequestered by oceans on each period is defined by Equation 102and is inversely proportional to oceans deepness and measure to diffusion factor of compounds dispersed in the atmosphere $\left(k_{eddy}\right)$.

$$C_m^*(t) = C_m(0)\left[1 - \beta_{T_2} T_{m(t-1)}\right]$$

101

$$\Delta C_{md}(t) = k_{eddy} \frac{\left[\frac{C_m(t-1)}{d_m} - \frac{C_d(t-1)}{d_d}\right]}{\overline{d}_{md}}$$

102

In Equation 101, d_d, d_m , and $\overline{d}_{md}$ represent the thickness of the deep, mixed, and middle ocean layers, respectively. Common to Equations 93 and 96, the atmosphere's average temperature is determined by the sum of the heat from the surface and the oceans (in their different layers). This way, Lamperti et al., (2018) determines the temperature in the surface and mixed layers of the ocean by Equation 102 and the deep layer by Equation 103.

$$T_m(t) = T_m(t-1) + c_1\{F_{co_2}(t) - \lambda T_m(t-1) - c_3[T_m(t-1) - T_d(t-1)]\}$$

103

$$T_d(t) = T_d(t-1) + c_4\{\sigma_{md}[T_{ms}(t-1) - T_d(t-1)]\}$$

104

In Equation 104, λ represents the climate feedback and c_1 , c_3 the temperature diffusion factor on Biome and deep oceans temperature, respectively. In Equation 104, c_4 indicates the atmospheric sensibility to the deep ocean, and σ_{md} is a parameter that reflects the transfer water rate among deep oceans and not deep oceans, as well as the calorific capacity of water.

Biome and oceans that define the global oceans' conditions, F_{co_2}, that emulates the GHG influences on the atmospheric global. Global warming affects the Biome and oceans carbon sequester.

$$F_{co_2}(t) = \gamma \log\left(\frac{C_a(t)}{C_a(0)}\right)$$

105

The climate change impacts are absolved by the economic system by Equation 105. Equation 106 randomly incorporates each firm in the economic system by $a(t)$ and $b(t)$ (Equation 107 and 108), an economic loss proportional to climate change impacts.

$$f(s; a, b) = \frac{1}{B(a,b)} s^{a-1}(1-s)^{b-1}$$

106

$$a(t) = a_0[1 + \log T_m(t)]$$

107

$$b(t) = b_0 \left[\frac{\sigma_{10y}(0)}{\sigma 10y(t)}\right]$$

108

The carbon emission tracking is done from Equation 109. There, the total carbon emission $Em(t)$ is the sum of that total industry's carbon emissions, including the energy sector. The sector's carbon emissions are obtained period to period from the relation between the technology environmental compatibility coefficient $A_{i\tau}^{EF}$ and the total energy used in the same period.

$$Em(t) = \sum_{\tau}\left(\sum_{i} Em_{i,\tau}^{F_1}(t) + \sum_{j} Em_{j,\tau}^{F_2}(t) \ + Em_{\tau}^{en}(t)\right)$$

109

Appendix D

D.1. Climate Box Sterman

The C-ROADS model proposed by Sterman et al., (2013) is like a cyclical box that simulate the GHG effects on weather. The climate box it is composed by observations about radiative forcing, global mean surface temperatures, sea level rise and ocean surface ph. The model was validated with data about weather from 1850 and do previsions until 2100, for individuals' countries and regionals groups.

The CO^2 and others GHG emissions are used as input for determinate atmospherics' concentration and weather. The atmospherics' concentration and weather impacts are determined based on ocean level and surface ph. The model also considers the impact of variation atmospheric concentration and climate change on themselves. Equation 110, present the net primary production.

$$NPP_t = NPP_0(1 + \beta_C \ln\left(C_a/C_{a_0}\right))(1 - \beta_{T_L}\Delta T)$$

110

Being the current and initial primary production, which is the flow of carbon from the atmosphere to biomass that expands with atmospheric CO2 and reduces with temperature.NPP, NPP_0, C_a is the stock of atmospheric carbon, C_{a_0} is the initial stock of atmospheric carbon. In such a way that:

$\uparrow C_a \rightarrow \uparrow NPP$ $\uparrow \Delta T \rightarrow \downarrow NPP$

The concentration of carbon in the ocean is the reference concentration value and is the Revelle factor $C_m C_{m^*} \xi$, Equation 111.

$$C_m = C_{m^*}\left(\frac{C_a}{C_{a_0}}\right)^{\frac{1}{\xi}}$$

111

In such a way that:

$\uparrow C_a \rightarrow \uparrow C_m$

However, the Revelle factor also changes according to atmospheric carbon, such as Equation 112.

$$\xi = \xi_0 + \delta_b ln\left(\frac{C_a}{C_{a_0}}\right)$$

112

The reference concentration value of carbon in the ocean changes according to temperature, according to Equation 113.

$$C_{m^*} = C_{m_0}(1 - \beta_{T_o}\Delta T)$$

113

In such a way that:

$\uparrow \Delta T \rightarrow \downarrow C_{m^*} \rightarrow \downarrow C_m$

The composition of the ocean is layered deeply, affecting the concentration of carbon in each layer, according to Equation 114.

$$\frac{dC_{ij}}{dt} = e(C_i/d_i - C_j/d_j) \,/\, \langle d_{ij}\rangle$$

114

Being the thickness of layer i: is the average of the thicknesses of layers I and J: is the diffusion parameter $d_i \langle d_{ij} \rangle e$.

As mentioned Sterman et al., (2013) consider others GHG emissions besides CO^2, between them the methane, nitrous oxide, and other fluorinated gases. The cycle in methane in the atmosphere is represented by Equation 115.

$$E = E^A + E^N$$

115

The total methane emission is equivalent to the sum of atmospheric methane () and natural methane () $E^A E^N$. The cycle of natural methane is altered by temperature variations, according to Equation 116.

$$E^N = E_0^N(1 + \beta_M \Delta T) + \beta_p max(0, \Delta T - \Delta T^*)$$

116

In such a way that:

$\uparrow \Delta T \rightarrow \uparrow E^N$

The increase in greenhouse gases alters the temperature of the oceans at the rate given by Equation 117.

$$\frac{dH_m}{dt} = F_T - R - \frac{dH_{md1}}{dt}$$

117

Being the increase in temperature in the ocean in each layer of the ocean, the variation in temperature in the first layer of the deep ocean, is net radiative forcing of the total emissions of (CO2, methane and others), and is the long wave radiation to space. In such a way that Equation 118:

$$F_T = F_{CO_2} + F_{other}$$

118

The radiative forcing of CO2 increases with increasing concentrations of carbon in the atmosphere Equation 119:

$$F_{CO_2} = \gamma ln\left(\frac{C_a}{C_{a_0}}\right)$$

119

However, the value of the long wave radiation to space is altered by changes in temperature Equation 120:

$$R = \frac{\gamma \ln(2)\Delta T}{S}$$

120

Being the sensitivity of the weather S.

Finally, varying temperatures increase the chance of melting Arctic areas Equation 121:

$$\frac{dSLR}{dt} = (\alpha_0 + \beta_1)(\Delta T - \Delta T_0) + \alpha_1 \frac{d\Delta T}{dt}$$

121

D.1.1. The dynamics of the climate box:

First, the flux of carbon into the atmosphere is influenced positively by the concentration of carbon in the atmosphere () and negatively influenced by the rise in temperatures (), according to Eq. 110. Second, the concentration of carbon in the atmosphere affects the concentration of carbon in the ocean (), as Eq. *111* and *112*. As a feedback mechanism, the increase in temperature decreases the concentration of carbon in the ocean, according to Eq. *113*. On the other hand, the rise in temperatures activates another feedback mechanism, which is the increase in natural methane emissions, according to Eq. *115* and *116*. Third, the increase in the concentration of greenhouse gases alters the temperature of the oceans, according to Eq. *117* to *120*. Finally, the increase in temperatures increases the possibility of melting in Arctic and Antarctic areas, according to Eq. *121*, $C_a \Delta T C_m$.