INCORPORATING THE CLIMATE-WATER-ENERGY NEXUS IN THE BRAZILIAN POWER GENERATION EXPANSION PLANNING MODEL THROUGH MULTI-OBJECTIVE OPTIMIZATION

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Dissertação de Mestrado apresentada ao Programa de Pós-graduação em Engenharia de Sistemas e Computação, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Mestre em Engenharia de Sistemas e Computação.

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"If you want to find the secrets of
the universe, think in terms of
energy, frequency and vibration."
— Nikola Tesla

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you are now, but I am sure the
place is better and happier.

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INCORPORANDO O NEXO CLIMA-ÁGUA-ENERGIA NO MODELO BRASILEIRO DE PLANEJAMENTO DA EXPANSÃO DA GERAÇÃO DE ENERGIA ELÉTRICA APLICANDO OTIMIZAÇÃO MULTI-OBJETIVO

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Junho/2021

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Este trabalho aborda o problema da inserção do nexo Clima-água-energia na tomada de decisão do modelo de otimização oficialmente adotado para o planejamento da expansão da geração de energia elétrica no Brasil no longo prazo. O modelo, denominado Modelo de Decisão de Investimento, possui originalmente uma formulação que minimiza o custo total de expansão do setor com base em parâmetros técnicos e financeiros, necessitando inclusão do aspecto ambiental. Nesse sentido, a formulação foi modificada de forma a realizar uma otimização multiobjetivo que também busca minimizar as emissões totais de carbono e o consumo de água no ciclo de vida de diversas fontes de geração de eletricidade. A partir das duas abordagens de otimização multiobjetivo adotadas, foi possível verificar como todos os objetivos definidos estão conectados. Os resultados mostram que, em geral, há um aumento na expansão das energias renováveis, principalmente das fontes eólica, solar e de térmicas a biomassa, dependendo das premissas adotadas para as instâncias criadas. Ao mesmo tempo, observa-se um aumento do custo total da expansão aliado a uma diminuição das emissões de gases de efeito estufa e dos volumes de água consumidos, decorrente do fato das fontes com melhor desempenho ambiental serem mais caras. Por fim, conclui-se que é possível gerar um cronograma de investimentos que analise ambos os aspectos e, dessa forma, equilibre o aumento das despesas financeiras com a redução dos impactos ambientais analisados.

Abstract of Dissertation presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Master of Science (M.Sc.)

INCORPORATING THE CLIMATE-WATER-ENERGY NEXUS IN THE BRAZILIAN POWER GENERATION EXPANSION PLANNING MODEL THROUGH MULTI-OBJECTIVE OPTIMIZATION

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Department: Systems Engineering and Computer Science

This work tackles the problem of inserting the Climate-water-energy nexus in the decision making of the optimization model officially adopted for planning long term electricity generation expansion in Brazil. The model, which is called the Investment Decision Model, originally has a formulation that minimizes the total cost of expanding the sector based on technical and financial parameters, requiring the inclusion of the environmental aspect. In this sense, the formulation was modified in order to carry out a multi-objective optimization that also seeks to minimize total carbon emissions and water consumption in the life cycle of several electricity generation sources. From the two multi-objective optimization approaches adopted, it was possible to verify how all defined objectives are connected. The results show that, in general, there is an increase in the expansion of renewable sources, mainly wind, solar and thermal biomass, depending on the adopted premises for the created instances. They also demonstrate an elevation in the total expansion cost as well as a reduction in greenhouse gases emissions and in the volumes of consumed water due to the fact that the sources with better environmental performance are more expensive. Finally, it is concluded that it is possible to generate an investment schedule that analyzes both aspects and, hence, balances the rise in financial expenses with the decrease in the analyzed environmental impacts.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Power generation allowed hydraulic and steam mechanisms to migrate to a new era of a larger range of processes, executed more effectively and efficiently. In a short period of time, humanity started depending on such input for most of the activities and nowadays it became impossible to imagine a life without electrical energy. That being said, it is reasonable to affirm that ensuring electricity supply is crucial for maintaining a population's well-being, as well as the other economic activities. Interruptions may lead to physical, environmental, social and economic damages. In order to prevent them from happening, measures are necessary in various sectors of a society so that the appropriate generation, transmission, distribution and commercialization of such input is assured.

Concomitantly, humanity has been facing new challenges regarding power generation. As global population arises along with environmental concerns due to problems directly related to the whole energy sector, new technology and planning frameworks are being developed in order to attend electricity demand with less negative social and environmental impacts. Renewables, energy storage, industry 4.0 ([65]), energy transition and energy efficiency are all concepts being discussed throughout the nations as key factors towards sustainable development.

According to the paper "Our Common Future" ([12]), sustainable development is development that meets the present needs, without compromising the ability of future generations to meet their own needs. Irresponsible use of natural resources may lead to environmental degradation, which is the opposite of what sustainability seeks. Since electricity is an input resulting from the transformation of other forms of energy present in natural resources, its generation is often related to social and environmental impacts, depending on each nation's energy matrix.

Therefore, agencies responsible for planning the power generation expansion inside their nations must also be concerned on how to sustainably attend future's electricity demand. Fossil fuels are the main source of power for most countries in the planet ([56]), implying that electricity generation is one of the most greenhouse gases (GHG) emitting activities. According to [56], fossil hydrocarbons accounted for 64% of the global electricity generation, in which coal-fired power generation is responsible for 38%, representing 10,123 TWh of generated electrical energy. Figure 1.1 shows the share of each source for the year of 2018 around the globe.

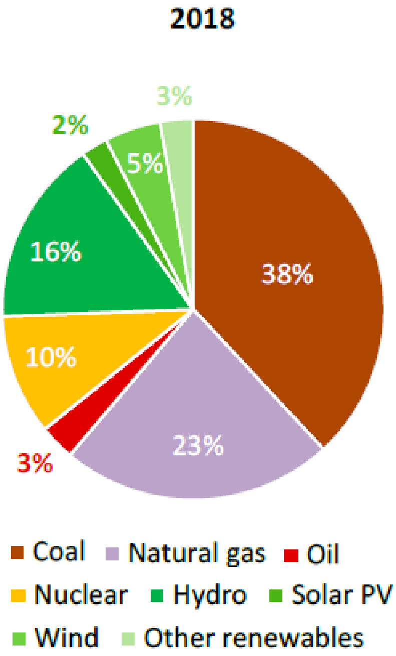

Figure 1.1: Global Electricity Generation Mix. Source: adapted from [56].

1.1 Brazilian Power System

Regarding Brazil, in 2018, the Internal Electricity Supply (*Oferta Interna de Energia Elétrica* - OIEE) was 636.4 TWh ([78]) distributed in several sources as shown in Figure 1.2. Renewables accounted for 83.3% of all generation due to hydropower, representing approximately 66.6% of all produced electricity ([78]). However, although fossil fuels were responsible for only 14.3% of all generated electrical energy, EPE (Energy Research Company), the public company linked to the Ministry of Mines and Energy (MME) in charge of Brazilian energy expansion planning, indicates an expansion of 27.8 GW of thermalpower from different fossil fuels until 2029, according to the 10-year Energy Expansion Plan (*Plano Decenal de Expansão de Energia* - PDE [91]).

In terms of existing power capacity, Brazil had in May 2019 approximately 164 GW ([91]) installed in the national interconnected system, which is the grid that connects the entire national territory in order to exchange power between the states. This grid, hereafter referred as SIN, offers security by ensuring electricity supply across the country when major problems prevent local generation within each federation unit.

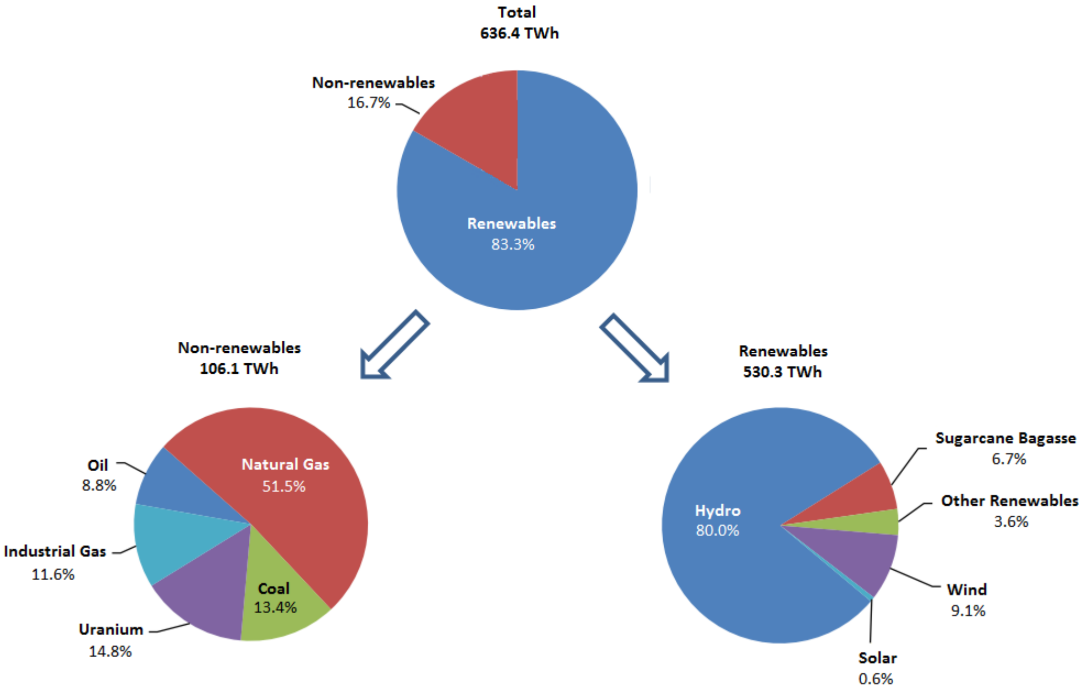

Figure 1.2: Brazilian Electricity Supply in 2018. Source: adapted from [78].

The existence of an interconnected transmission system allows the country to make the most out of each power generation source as it permits them to be installed where they best fit, using possible location and seasonality advantages. This is one of the reasons why [111] states that the Brazilian power system has singular and important characteristics which guide the decision making process for its operation and planning. According to him, other reasons are:

- Continental dimensions, considering Brazilian territorial proportions;
- Hydropower predominance with intensive participation of hydroelectric plants with regularization capacity;
- Hydrological diversity of hydrographic basins which allow complementarity among regions; and

- Participation of several agents with power plants on the same river, as well as transmission lines operated by different agents.

All these distinguishing characteristics conducted the country into developing itself based on hydropower, which explains the source's relevant participation in total supply as stated previously. In fact, hydroelectric power stands for 60% of all installed capacity while thermal power stands for 14% (natural gas 8%, coal 2% , oil 2% , diesel 1% and nuclear 1%). Imported power stands for 4% and the remaining share of the power generation matrix is composed by other renewables, in which wind represents 9% , biomass 8% , small hydro power plants 4% and solar 1% ([91]). Therefore, as electrical energy supply data from figure 1.2 corroborates with each source of power's total installed capacity, it is possible to affirm that all sources contribute effectively for attending demand, but it is also important to clarify that this data refers to centralized power generation for the SIN and it does not consider distributed generation.

Since Brazilian power system comprises mainly hydroelectric power plants aligned with thermal power plants, it is referred as a hydrothermal system. Most of electricity generation comes from hydropower because water is less costly than fossil fuels, but thermoelectric generation is also necessary to attend total demand, since the uncertainty in reservoirs' inflows and periods of drought may compromise hydroelectricity generation ([44]). In addition, thermal power plants also perform electrical functions in the system and are used to balance wind power intermittency. In fact, due to the increasing importance of wind farms in the energy matrix, some authors such as [31, 79] already consider the Brazilian power system as hydrothermal-wind, in which hydropower and wind generation are responsible for attending average demand while thermal power is used mostly for peak demands and possible operation constraints related to water management.

Operating a predominantly hydroelectric system requires an integrated framework that links the information of all hydropower plants and reservoirs existing in the same hydrographic basin, thus seeking an optimal operation for all of them. In this sense, it is necessary to efficiently control the volumes of water stored in the reservoirs for the purpose of guaranteeing electrical energy generation in the upcoming months because such characteristic makes the Brazilian electricity sector (SEB) heavily dependent on hydrological and rainfall regimes. Besides, volume management is also important for water uses other than power generation such as flood and drought control, maintenance of ecological flow in water bodies, navigation and irrigation. In fact, irrigation represents the most water-intensive activity in Brazil ([1]).

This relevant aspect of Brazilian power system must be considered when planning the amplification of electricity generation. The power generation expansion problem seeks to develop an optimal schedule of investments in order to continue attending electrical energy demand over the next years. Then, forecasting hydrological and rainfall regimes as well as reservoirs' operation are crucial activities for the expansion optimization. As they are strongly related to climate and environmental conditions, negative impacts on nature directly affects energy supply and investment possibilities.

Not only in this direction, but also in the other way around. Environmental conditions may affect electricity generation and electricity generation may affect environmental conditions. Disturbing natural characteristics alters resources such as water availability, wind regimes and biomass production, impacting in many different economic sectors other than electrical energy generation. Therefore, it is reasonable to affirm that promoting sustainability in power sector operation and expansion is important in order to preserve resources' conditions, ensuring the system's capability of generating electrical energy in the future and maintaining other economic activities.

As environmental aspects are not often accounted in energy planning frameworks, this dissertation will be tackling this specific problem of incorporating sustainability aspects into the official power expansion optimization model applied in Brazilian electricity sector.

1.2 The Problem

In terms of environmental problems related to power generation, emission of GHG due to the burning of fossil hydrocarbons is the most discussed as they contribute for climate change. Although deforestation and land use change are the most relevant emission sources in Brazil ([103]), the energy sector's contribution for the problem is significant mostly due to the transportation sector.

Brazilian GHG total direct emissions related to the energy sector were 410.6 MtCO_{2eq} in 2018, as cited in [78]. Electricity generation accounted for 11.5% of this amount, which represents approximately 47.2 MtCO_2 ([78]). PDE 2029 indicates that direct emissions in the energy sector will be 514 MtCO_{2eq} ([91]) in 2029, of which 51 MtCO_{2eq} refers to the power sector ([91]) considering centralized production, transmission and distribution related to SIN only for 2029.

Nonetheless, it is important to note that power sector GHG emissions in Brazil may vary substantially depending on hydrological conditions, creating different possible scenarios. Unfavorable hydrology situations lead to higher activation of fossil fuel thermal power plants and, thus, larger quantities of GHG emissions, as happened in the years 2014 and 2015 when emissions exceeded 65 MtCO_{2eq} ([91]).

As for the reduction of GHG emissions, nations pledged to adopt active measures under the Paris Agreement. Every year the Conference of the Parties (COP), the supreme organ of the UNFCCC (United Nations Framework Convention on Climate Change), holds the United Nations Conference on Climate Change at which members of different nations meet to discuss the goals for combating climate change. In its 21st edition, held in the city of Paris in 2015, an agreement was approved by the 195 member countries ([39]). It establishes a commitment of participating nations to promote actions to reduce GHG emissions in order to maintain the global average temperature increase below 2°C above pre-industrial levels and continue the efforts to limit the rise in temperature to 1.5°C above pre-industrial levels. At the end of 2016, all the 55 signatures needed for the agreement to come into force were reached ([48]).

PDE 2029 estimates that the country will have 224.3 million inhabitants at the end of the period under study (2019-2029), with an average increase of 3.8% per annum in the consumption of electricity per capita ([91]). In other words, Brazil will require large investments in power generation expansion from different sources throughout this period in order to attend future's demand.

However, Brazil has pledged to reduce 37% of its GHG emissions by 2025 (for the entire economy) under the Paris Agreement and, as a subsequent indicative contribution, to reduce its emissions by 43% by 2030, both based on 2005 emissions ([77]). Power generation participation in Brazilian GHG emissions is not the most significant when considering other sectors and the total volume, but its participation range increases in deeper analysis which accounts not only for generation itself, but also the whole chain of inputs and services comprised in electricity generation using Life Cycle Assessment - LCA - ([5, 96]). In this sense, measures become necessary in order to attend future's demand without breaking the official commitment.

Besides direct emissions from burning fossil fuels, there are emissions from the production and transportation of necessary material for power plants construction, from the production and transportation of fuels, other emissions related to the operation of plants, from the actual construction process and from decommissioning. In Brazil, all of them are excluded from expansion models, which means that provided results do not reflect the whole investment. Not considering emissions in planning frameworks might lead to biased decisions that become not only environmental unsustainable, but also inefficient through an economic perspective.

Furthermore, the emission of GHG is not the only environmental issue related to power generation expansion. In fact, each source of power has intrinsic characteristics that affect ecosystems and natural resources' availability differently. Increasing the share of renewable sources in the electrical matrix and investing in efficiency gains are measures commonly adopted in order to work towards achieving the goals established in the Paris agreement for most nations, but their specific impacts must also be considered for reaching optimal solutions through the sustainability perspective. For instance, hydropower plants flood extensive areas in order to create reservoirs and wind farms increase significantly noise levels which may disturb local fauna.

In fact, hydropower generation in Brazil has been fostering discussions in the sector due to the conflicting water uses in a scarce hydrological scenario that is becoming more common and intensive since the past few years, affecting food production, urban water supply and other uses.

In this sense, internalizing environmental impacts of electricity generation is imperative for proper planning. Optimization models that account for criteria other than technical and financial concerns may have fewer distortions from reality and are able to guide decision makers towards more sustainable decisions. In this context, it is important to assess how to efficiently and economically satisfy general environmental aspects relevant to power generation expansion over the planning horizon.

This dissertation aims to address the aforementioned problem by including environmental impact indicators into MDI (Investment Decision Model – MDI, originally), power expansion optimization model used in EPE's planning process. The original model formulation was developed under a Doctorate Thesis ([44]) and includes all existing power sources in Brazil as well as Brazilian's power system specifications, but it lacks an environmental approach.

Addressing sustainability in MDI will change the model's structure, as it will consider new objectives and new constraints. Besides that, as the official model adopted for expansion planning, it requires reliable good solutions that demonstrate the existing trade-off between economic expenses and better environmental outcomes through a multi-objective perspective. The model needs to be capable of providing different alternatives depending on defined priorities.

1.3 Our Contributions

The main objective is therefore to update MDI original's formulation in order to incorporate climate and water aspects and analyze the results upon the applied changes. In other words, to include an environmental perspective to MDI in terms of the Climate-Water-Energy nexus. The methodology is based on using mixed integer linear programming within a multi-objective optimization approach.

As well as minimizing total expansion cost, the formulation will also consist in minimizing total GHG emissions and water consumption originated from the power system's operation and expansion in order to develop a qualified model able to guide electricity generation expansion planning by a sustainable perspective. The optimization results will then be used to understand trade-offs among the objectives and construct the pareto-optimal curve, which reveals distinct feasible solutions important for the decision-making process by balancing the applied objectives.

Also, this dissertation aims to compare the executed instances' results with the official expansion schedule indicated by EPE according to the defined planning horizon, providing evidence on how optimal solutions vary when considering other aspects than technical and economic and how environmental concerns should affect planning decisions related to power generation.

In addition, this dissertation seeks to gather, treat and provide environmental data concerning the defined objectives for all the existing generation sources available for expansion according to EPE. In order to understand comprehensively the effects of all generation options in terms of sustainability, the impacts need to be addressed considering their whole life-cycle and currently there is not much collected and processed data specifically for the Brazilian system with its singularities.

1.4 Text Organization

The structure of this dissertation is organized as follows. Chapter 2 reviews fundamental concepts for the proposed work, exploring the existing literature over the Brazilian power system operation problem and expansion problem, the current computational frameworks, the consideration of environmental aspects in power generation models and multi-objective optimization, which is the core of the adopted approaches.

Chapter 3 introduces the defined environmental objectives as well as the implementation of the applied optimization methods, presenting and detailing all mathematical formulations. Chapter 4 describes the whole executed process of collecting and processing the required environmental information, presents the created model instances and discusses all the obtained results. Finally, Chapter 5 presents the final conclusions and future work recommendations based on this dissertation achievements.

Chapter 2

Literature Review

This section introduces the theoretical context that gives foundation for the problem being solved in this dissertation. The discussion on how to properly consider environmental aspects in a power generation expansion model for the process of energy planning requires an overview through different approaches related to the reported issue.

First the main characteristics and specifications of the optimization models currently applied for planning the operation of the Brazilian power system are discussed. Next, the Brazilian Power Generation Expansion Problem and its official model, MDI ([106]) based on Gandelman ([44]), are explored. Then, the process of considering environmental impacts into computational frameworks for the energy sector is analyzed, listing existing works and developed power expansion models that incorporated environmental considerations and how they were considered. Finally, the fundamental concepts and classic methods of multi-objective optimization are briefly summarized as they are necessary for the adopted methodology.

2.1 Brazilian System Operation Planning Models

ONS (*Operador Nacional do Sistema*) is the independent company responsible for coordinating the national system's operation, i.e. power plants generation and electricity transmission system. It develops a series of studies and actions in order to secure continuous supply across the Brazilian territory. Therefore, ONS' activities seek to meet two objectives simultaneously: electrical optimization and electrical safety ([111]). Electrical optimization is achieved by determining the optimal power generation of hydro and thermal power plants whilst electrical safety is achieved by managing the national transmission grid and associated equipment.

The hydrothermal system operation problem exemplifies one of the core issues of ONS, in which the operator must attend a certain power demand and then has to decide whether to prioritize electricity generation with a higher proportion of hydroelectric energy at relatively low operation costs, but preventing the future use of that volume of water, or to generate through thermoelectric power plants with a higher operating cost. As mentioned previously, this decision depends on current and future weather conditions, reservoir levels, historical data and possible hydrological scenarios, directly reflecting in the final cost of the supplied electricity to the population.

The hydrothermal system operation dilemma, hereafter referred as the operation problem, is then a mathematical problem solved using optimization techniques such as Stochastic Dual Dynamic Programming ([87, 89, 105]). In order to provide a feasible operation scheme, ONS uses a set of interconnected optimization models designed specifically for planning the operation of Brazilian power sector in terms of energy.

The purpose of optimization in the operation problem is to value the water in the reservoirs. It consists in efficiently controlling the volumes of stored water, i.e. defining the amount used for power generation and the amount kept in the reservoir ([44]). Therefore, the cost of operating the system depends on the water inflows in each reservoir, since less water leads to less hydropower generation and the increase in the need for activating thermalpower plants.

Originally, only demanded electricity not produced by the set of hydropower plants and other renewable sources requires thermal power plants generation because generating electrical energy with renewables is cost-free. Due to this fact and the nature of the used resource, hydropower generation is also considered a renewable source and it is, hence, contemplated when the term renewables is used. In spite of that, since hydroelectric power plants in Brazil have elevated impact and significance with the regularization reservoirs being used for multiple uses, the term renewable sources in this dissertation will only refer to the other included options, standing for the intermittent sources as well as small hydro plants and small thermoelectric plants running on biomass fuels.

Considering that thermal generation and the calculated water value incur in operation costs, it is necessary to forecast the future thermal and hydrological dispatch expectation in order to estimate the future cost of operation. As it is a highly complex task given the Brazilian system, the use of computational models is essential to calculate the dispatch volumes and their costs.

The NEWAVE model ([19, 72]) seeks to minimize the future cost of operation considering various hydrological scenarios obtained from synthetic inflow series. Its objective is to reach an optimized water storage policy ([44]). This model has a medium-long term planning application with monthly discretization and representation of hydroelectric plants by sets called equivalent energy reservoirs (REE – *Reservatório de Energia Equivalente*) for computational effort reduction.

In fact, NEWAVE has two objectives. The first is to estimate the Future Cost Function (FCF) used to compose the operating policy, which discretizes the state space in a set of values. The second one is to evaluate the operating policy provided by the set of estimated values obtained through the FCF for each stage of the planning period.

In the case of the hydrothermal dispatch problem (SIN's operation), the objective function minimizes the total expected cost of operation, which is formed by the immediate cost plus the future cost. The immediate cost comprises operating the thermal units, which depend on the used fuel. The future cost related to water availability depends on the stored energy at the end of the time horizon. In other words, the objective function seeks to mitigate the impact of a decision made in the present in relation to the cost of operating the reservoirs in the future ([52]).

This is the core of Stochastic Dual Dynamic Programming. In order to have an operational strategy for each state of storage and future inflows in the system, it is necessary to have a function capable of valuing the water stored in the reservoirs in future periods and bringing this cost to the present ([7]).

As a mater of fact, the water value actually comes from the future cost curve in relation to the stored volume. This means that the closer the volume is to zero, the higher the value. Likewise, the closer you are to the maximum storage level, the more that cost will tend to zero. In contrast, the derivative of the immediate cost in relation to storage represents the cost of thermal generation or the deficit, if thermal generation is no longer possible. The optimum is located at the point where the sum of these two slopes is canceled, representing the lowest operating cost ([36]).

Summarily, NEWAVE's procedure is based on making decisions at present so that the reservoir reaches, at the end of the planning period, the volume that guarantees the lowest total cost without exhausting the possibility of using the resource. However, as mentioned previously, the model is only for medium-long term planning application.

For short-term planning, another model also developed by CEPEL is used: DECOMP ([17, 71]). In the short term, with a horizon of up to 12 months discretized in weekly and monthly stages, the individual generation goals of the system's hydraulic and thermal plants are determined. It considers the operation expected cost until the end of the horizon and the goals obtained in the medium term by NEWAVE. DECOMP presents an individual representation of the hydropower plants that were grouped in equivalent energy systems previously, as well as the inclusion of each one's operational restrictions.

In relation to NEWAVE, DECOMP incorporated some distinguishing characteristics in order to provide flexibility and proximity to the system's reality ([17]):

- Weekly stages, with the representation of the load curve in levels;
- Water balance in the reservoirs considering the travel time between the existing cascaded hydropower plants and evaporation in the reservoirs;
- Representation of the scheduled maintenance regimes related to the generator turbine groups through unavailability rates;
- Variable productivity of hydroelectric plants according to the height of fall, represented by the energy production functions pre-established for each plant; and
- Transmission constraints that translate generation limitations in sets of power plants in order to consider spots in the electrical system that deserve special attention.

Despite these features, DECOMP is not sufficient for hourly variations and constraints on smaller scales, requiring another model to conduct the operation's daily schedule. A new optimization model was developed to overcome these limitations: DESSEM ([18]). It implements techniques and tools that solve the problem of optimizing the hourly operation of hydrothermal systems, considering, in the most accurate possible way, aspects that are not considered or not effectively represented in the models with a longer planning horizon, such as those related to the electric grid.

DESSEM includes functionalities such as DC (direct current) modeling of the electrical grid with losses and flow limit constraints in the circuits, individualized representation of the reservoirs with water travel time between consecutive cascading plants, unit commitment ([83]) with minimum times and maximum ramps for taking or relieving load. The entire set of functionalities allows the model to integrate electricity generation and transmission with the physical and electrical limits that exist in reality.

These models are applied to define the power system's operation scheme and their results guide the energy prices in the energy market. Although they might be used for investment purposes, they are not, due to the distinctive nature between the operation and investment problems. Anyhow, the generated operation schemes are important inputs for expansion models since feasible investments may only occur when considering future power plants' operation.

In fact, both problems are deeply intertwined and might be integrated in a single framework. Solving the expansion problem traditionally involves dividing it into two subproblems, one of operation and another of expansion, which can also be called investment subproblem referring to the construction of new plants ([42, 50, 92]). When the investment subproblem reaches an optimal solution, an investment schedule is obtained and its information is passed on to the operation problem, so the operation planning incorporates the power plants invested in the previous step. This interaction among both problems is performed a number of times until the lowest cost of operation and expansion is found simultaneously ([80]).

2.2 Brazilian Power Generation Expansion Problem

Contrary to the operation problem, the power generation expansion dilemma, hereafter referred as GEP - the Generation Expansion Planning - problem, refers to determining the least costly expansion schedule possible to ensure continuity of an operation at minimal cost ([80]).

Due to the inherent uncertainties of planning, it is not possible to guarantee the full attendance of demand, but a level of reliability ([68]) can be assured, hence there will be no problems in the supply of energy for most of the analyzed scenarios. However, ensuring power supply is not enough. It is essential to provide a robust and inexpensive power system that will also attend the increase in electricity demand in the short term.

Therefore, power expansion planning is finding suitable options between conflicting objectives. Obtaining a low cost of electricity for the final consumer is one of the main targets in planning, but it conflicts, for example, with the objective of attending power demand with quality and safety ([44]), as these attributes require greater investments in order to prevent variations or cuts which may harm the infrastructure.

In addition, there are conflicts associated with each generation technology, which, as the operation problem, implies in a decision-making process under uncertainty. Dimensioning the electricity generation is to analyze the benefits of each source and compare them with their corresponding costs. In this sense, planning is a key element for the resolution of these conflicts and it is imperative to make decisions concerning the allocation of investments and the percentage of each source's power generation in order to maximize the benefits.

In this context, EPE defines an indicative expansion presented in the PDE to attend the needs of consumer agents in the medium and long term according to the different demand scenarios. The developed studies generate necessary information for new investment decisions, which depend on the expected evolution of the generation costs

([112]). The plan guides actions and decisions aimed at balancing economic growth and the necessary expansion of the power supply with adequate technical costs. Figure 2.1 represents the referential indicative power expansion according to PDE 2029.

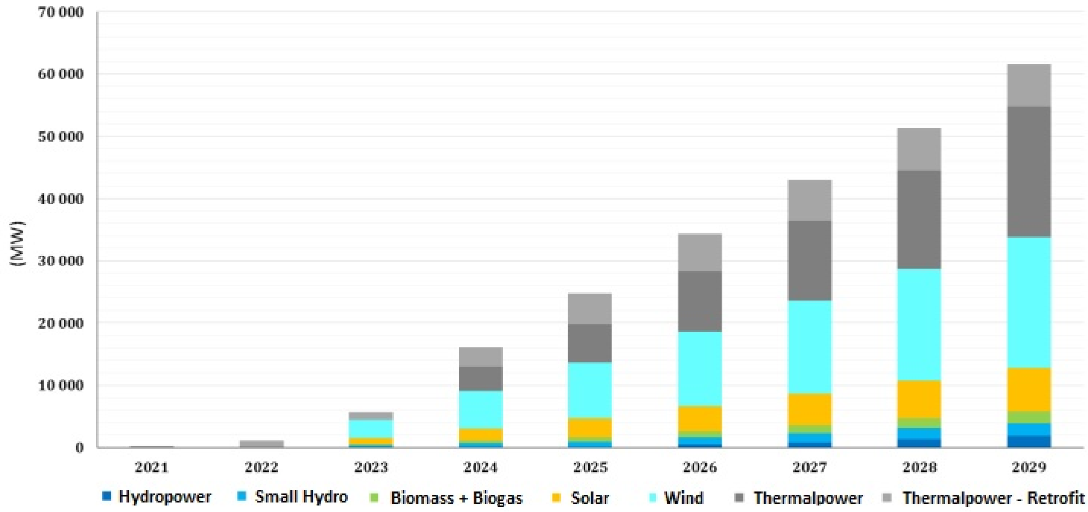

Figure 2.1: Referential Indicative Power Expansion. Source: adapted from [91].

Planning the system's expansion implies indicating that new units should be incorporated in order to sustain future's supply. Such units relate to generation power plants or transmission infrastructure. The selection of new units is directly associated to the cost and the benefit they present for the system and, from an economic perspective, plants that have the lowest total cost value between the energy production cost summed to the cost of constructing a new unit should be invested. However, there are constraints other than economic that must be considered, which are often related to a technical perspective concerning the equipments.

Thus, power expansion planning encompasses two activities: investing in increasing the generation park and investing in increasing the transmission grid, besides operating the existing and new investments. Investing in new generation units from different sources depend on fuel availability, location and construction and operation costs. They also depend on source dispatchability because some are able to provide easily dispatchable energy, e.g. thermal power plants, while others relate to seasonality, storage, climate conditions and intermittence, e.g. solar and wind sources.

In terms of transmission expansion, planning seeks to ensure that electricity reach the consumption location, respecting the quality and safety requirements of the system and at the same time minimizing the cost of installing new units and reinforcing existing ones. In a scenario with increase in intermittent generation with renewables, transmission plays a relevant role and require robust planning, as discussed in [76].

Transmission planning may require special attention due to project scale. While power plants usually have local and regional impacts, transmission lines often cross extensive territories and might affect environmental protection zones as well as other protected areas if production and consumption locations are distant.

Then, due to the problem's complexity, optimisation models are usually applied. In order to obtain the indicative power generation expansion, EPE uses an optimization model called MDI - *Modelo de Decisão de Investimento* ([44]). The expansion problem is usually addressed as a mixed integer programming problem with integer variables (relative to investment in specific power plant projects) and continuous variables (relative to investment in electricity generation sources with no project specification and also to operation variables) ([67]).

Besides this usual deterministic approach, some papers attempted to develop other formulations for the same problem using, among other possibilities, metaheuristics. For instance, [84] formulates the GEP problem with a nonlinear approach and proposes an improved genetic algorithm to solve it. Similarly, [42, 86, 117] also apply the genetic algorithms technique, [42] in a interactive version, [117] mixing it with adaptative simulated annealing and [86] incorporating a long-term dynamic simulation to estimate the electricity demand and price evolution.

Oh the other hand, [59] proposes a stochastic process model also to describe the evolution of the uncertainty about future electricity demand and fuel prices, which are addressed in the formulation, whilst [40] presents a new scenario reduction algorithm considering the uncertainty in future fuel prices and power demand through long-term historical trends' statistical extrapolation.

Regarding existing power expansion models in Brazil, it is possible to cite: DESELP - *Determinação da Expansão do Sistema Elétrico no Longo Prazo* ([113]) - the first developed expansion model for the Brazilian power system. Then, there is MODPIN - *Modelo de Expansão sob Incerteza* ([50]) - developed by CEPEL. OptGen is the model developed by PSR consultancy for the expansion problem and is being applied to a diverse range of countries ([14]). In addition, there is a methodology ([73]) which guided the development of MELP - *Modelo de Expansão de Longo Prazo* ([67]) - also from CEPEL. More recent works include [21, 28, 88, 100]. Many of the techniques and assumptions reported in these previous papers inspired MDI.

All these different methodologies are based on the same core formulation for the expansion problem, which, adapted from [99], is:

$$\text{Minimize } z = \sum_{t \in T} \beta_t \left(C_t\, x_t + D_t\, y_t \right) \tag{2.1}$$

Subject to:

$$A_t\, x_t \geq b_t\,, \qquad t \in T \tag{2.2}$$

$$\sum_{t \in T} E_t\, x_t + F_t\, y_t, \geq d_t\,, \qquad t \in T \tag{2.3}$$

$$x_t \in \{0, 1\}\,, \qquad t \in T \tag{2.4}$$

$$y_t \geq 0\,, \qquad t \in T \tag{2.5}$$

in which x_t is the binary investment decision variable in period t; C_t is the investment cost in period t; y_t is the continuous operation decision variable in period t; D_t is the operation cost in period t; β_t is the discount factor in period t; b_t is the minimum investment in period t; d_t is the demand to be met in period t; A_t, E_t, F_t are transformation matrices; and T is the set of time periods.

The Objective Function (2.1) aims to minimize the total expansion cost composed by the sum of the total investment cost with the total operation cost. Constraints (2.2) guarantee minimum investment conditions, such as minimum dates for an investment to occur. Constraints (2.3) ensure minimum operation conditions, for instance, that electricity generation will meet the power demand. Lastly constraints (2.4)-(2.5) define the variables' domains.

Starting from the premise that future is predictable, these models plan the investments based on the most probable scenario, since parameters such as demand increase, fuel availability and price, construction time, economic growth and others are uncertain, indicating distinct action plans depending on their values. Determining the mean value for those uncertain factors, based on probabilistic analysis, is the simplest way to solve the problem ([14, 73]). Nonetheless, uncertainties might also be considered through scenarios tree analysis and stochastic optimization ([50]).

As an example, OptGen ([14]) is a model that estimates the operation cost using Stochastic Dual Dynamic Programming (SDDP model). OptGen determines and sends an expansion plan to SDDP model and it estimates the cost of operation. If the optimal condition is not reached, a Bender's cut - Bender's decomposition ([45]) - is generated for the expansion problem. The process occurs recursively until the stop criterion is reached. The same approach is observed in ([80]).

MDI, as it is currently used by EPE studies, addresses uncertainties using a scenario tree solved by a deterministic equivalent approach, not using any decomposition method. This approach limits the number of branches on the scenario tree because the time to solve the problem is exponential with the number of branches within the tree. As this work will be using a reformulation of MDI, the next section is dedicated to a description of the model, including characteristics and parameters.

2.3 MDI – Investment Decision Model

As mentioned previously, the Investment Decision Model (MDI) is an optimization model developed under the doctoral thesis of Dan Gandelman for solving the GEP problem ([44]). EPE first applied MDI for the Brazilian expansion planning in 2017, when it published PDE 2026 in relation to the period from 2016 to 2026. In 2018, EPE published PDE 2027 (2017 - 2027) in which the expansion plan used a reformulation of MDI named MDI-Patamares, still currently used in recent versions of PDE.

This dissertation will then utilize a reformulation of MDI-Patamares by adding modifications concerning an environmental perspective. The specifications of each version of MDI is described below.

2.3.1 Original MDI

The original MDI ([44]) was written using OPL (Optimization Programming Language), which is part of the CPLEX software package, being a language created by IBM itself. It aims to simplify the description of decision-making problems through syntax and structures aimed precisely at the rapid implementation of optimization models, allowing easier communication with the solver.

As referred in the previous section, the mathematical formulation uses mixed integer programming techniques. Integer programming is necessary to model discrete decisions such investing or not in power plants using binary variables. For the investment decision, time discretization occurs in months, so that when a project is invested, it enters completely in the system, providing all its power capacity from that moment until the end of the planning horizon. This is how hydroelectric projects as well as biomass, small hydro and nuclear projects are represented. It is understood that there is no point in building half a hydroelectric plant in a location that supports a larger one. There would be no correct capture of scale gains and the project would not be economically viable.

However, if this approach were proposed for renewable projects, a problem would arise. For instance, thousands of binary variables would be needed just for the representation of wind farms because their installed power capacity is low, making it arduous to solve the optimization problem in a reasonable time. The same happens to other renewable sources such as solar photovoltaics. Therefore, an an option, MDI indicates for both wind and solar the amount of power expansion throughout the planning period considering a continuous growth (continuous variables). Projects might be contracted using the model's decisions as a reference, indicating a possible increase of installed capacity in the power system.

Since the objective function seeks the least expensive expansion schedule, the preferable option would be not to operate the system and not to expand it, if there were no constraints. Yet, the first constraint is that the sum of electrical energy production of all sources must be greater or equal than demand at all times, which is called the demand meeting constraint. When supply and demand are discretized on a monthly basis, averages should be used. This average, considering a time interval, has an energy unit, but it does not comprise smaller time scale demand variations. In other words, this constraint guarantees that the month average demand will be met, but hour peak variations might not, causing the system to have an energy deficit. Then, another constraint is needed regarding the instantaneous maximum demand.

This one aims to promote peak balancing, which exists because only electricity demand constraint does not guarantee supply during peak consumption times. In addition to monthly attending the demand for power, it is necessary to ensure that this energy need will be met at the exact moment it occurs, considering daily variations in consumption or variations resulting from possible events. In this context, there is a necessity for dispatchable sources that are capable of generating when it is required, which usually does not occur in the case of renewable sources due to their intermittency and dependence on external factors. For example, wind and solar sources depend on weather conditions and, therefore, undergo seasonal variations. Thus, in order to invest in renewables, there must also be investments in sources able to guarantee this peak demand service, such as thermal power plants, even if they are only activated in case of need.

In addition to the demand related constraints, there are other concerning the energetic attendance set: generation capacity limit and generation minimum for each source, electricity transmission limit between regions, projects availability and others. In this conxtext, MDI's is composed of existing plants, already contracted, and candidate projects for expansion and the demand increase forecast is calculated by EPE itself, in line with the economic outlook, as stated in ([91]).

As previously mentioned, Brazilian power system is interconnected through a grid, SIN, and the hydroelectric plants are represented in aggregating groups called equivalent energy reservoirs (REE's). These sets of REE's divide the SIN into different regions called subsystems. In other words, the Brazilian power system is divided into different groups formed by hydropower plants that belong to the referred REE and power plants of other sources that are usually located in the same geographic region, sharing similar characteristics. These subsystems are the ones connected by an extensive grid of transmission lines, forming the SIN.

In MDI, the subsystems are represented as vertices of a graph with their connections as edges. Each one of the vertices has electricity and instantaneous maximum power demand forecasts and each link has a maximum exchange capacity (one for each direction) and a related expansion cost (expressed in R$/kW).

In order to estimate the future operation cost, it is necessary to predict the future thermal dispatch, which depends on the wind, solar and hydrological specific energy series for each subsystem. While wind and solar energy series are calculated by an internal EPE methodology, hydrological scenarios tree are obtained from synthetic flow series. The water inflow history represents an insufficient sample to estimate risk indices with acceptable uncertainties. However, the basic characteristics of the historical series can be captured by stochastic models capable of producing synthetic series of inflows that differ from the historical ones but are equally probable ([70]), hence being included in MDI for future dispatch considerations.

The Variable Unit Cost (CVU) is the variable cost related to the fuel consumed by each thermoelectric power plant and it determines the thermal power plant's dispatch, thus being the parameter that directly affect the system's total operating cost ([44]). For instance, fuel price projections from the Annual Energy Outlook ([56]) published by EIA (Energy Information Administration) guided CVU calculations in PDE 2029.

In terms of investment costs, MDI incorporates the Brazilian energy long-term contracts. In this, electrical energy supply is contracted between 20 and 30 years: hydroelectric plants 30 years, other sources 20 years. The supplier receives according to its production through a monthly payment. The amount already includes maintenance, investment and capital costs, hence the total investment is diluted during the contract term. In other words, a project is remunerated in each period for its cost from the start of operation until the end of the planning horizon.

Without this approach, there would be a problem on considering the investment cost of a project that will be amortized over 20 or 30 years during a planning period of 10 or 15 years. When calculating this monthly cost, even if the payment for the project exceeds the planning horizon, there will be the correct cost allocation for the energy supplied within the considered horizon. If the total payment for a plant was considered in the period in which it was built and its energy was needed only in the last year of planning, the entire cost would be disbursed for the plant to operate only a few months. Explicitly, the plant would continue to operate beyond the planning horizon, but the mathematical model would not consider this since it is out of the model's perception.

These are the main features concerning the original formulation of MDI. Other details are described in [44]. After its application in PDE 2026, EPE received feedback regarding the computational model from the power sector agents with insights on its implementation. Then, some new additions as well as modifications were made leading to the model recently applied in PDE 2027 and PDE 2029. The new framework, MDI-Patamares, is explored in the next section, which is dedicated to its differences from the original formulation.

2.3.2 MDI-Patamares

The idea of MDI-Patamares was, in fact, to reformulate original MDI in order to be accessible for market agents that were interested in conducting their own analysis. Therefore, MDI-Patamares was created in Python language and the code was released publicly ([38]). The author of this dissertation participated of this reformulation as one of the main model developers, coding all the existing structure.

As the original formulation, MDI-Patamares seeks to minimize the total cost of expansion, composed of the sum of the investment cost and the operating cost over the planning time period. Besides that, it also portrays the Brazilian power system with three major different types of units: existing power plants, contracted power plants that have not started to operate and candidate projects for expansion. Subsystems continued to be represented as a graph.

However, MDI-Patamares differs from the original version developed by Gandelman due to the inclusion of demand representation by load levels. Four load levels have been introduced, but the model accepts representation in any number if the necessary data are provided. Yet, the higher the number of levels, the greater the computational effort required. This modification implies in having a demand constraint for each level. All load levels have an associated value of duration and weight in relation to the average load.

MDI benefits from this modification due to a more coherent assessment of adequacy of generation sources with load behavior. However, for non-dispatchable sources, it is necessary to estimate their average contribution for each different load level. Usually, energy sources with a generation profile similar to the load profile tend to be more competitive compared to others.

Inflow randomness for the representation of hydroelectric plants is still represented through the construction of energy scenarios produced by each power plant associated with a certain occurrence probability. Then, operating costs obtained by dispatches of thermal power plants by load level are computed by the expected value of dispatches of each scenario weighted by the respective probability.

The cost of operation in the problem is given by the sum of the cost of thermal generation and the penalty for energy deficit. Other sources do not have costs related to operation because their power plants are considered to generate electricity with a zero-cost fuel, e.g water, sun and wind ([80]). Consequently, renewable source generation is not accounted in operation costs. This premise does not actually reflect the reality since there are costs referring to financial compensation of projects and costs related to the charge for the use of Brazilian water resources, as one of the management instruments of the National Water Resources Policy ([27]) to prevent scarcity. Still, this simplification is commonly adopted.

Due to the consideration of load levels, the model also differs from [44] in the aspect of the capacity constraint (instantaneous maximum demand). In the new formulation, there is one load level specific for the representation of peak demands and, therefore, this constraint seeks to attend the require installed capacity in the peak load level. Regarding this constraint, each source's contribution to the overall necessary capacity varies according to its energy production during the peak load level.

In terms of representing sources of power generation, hydroelectric plants have a simplified representation through the electricity generation and power supply scenarios available for each month of the planning period. Hydrothermal simulations calculate these scenarios with mechanisms and parameters such as risk aversion using the CVaR measure and deficit cost function ([38]). SUISHI, a model developed by CEPEL that is responsible for individual units simulation in interconnected hydrothermal systems, provides this information following two different steps: hydrothermal balance optimization among equivalent subsystems and simulation of individual power plants. While the first one defines targets for hydraulic generation of each equivalent reservoir (REE), based on the operating policy defined by NEWAVE, the other verifies the feasibility of these targets ([20]). These two operations are automatically executed iteratively using heuristic optimization rules that provide results for individual plants, considering the general aspects of the Brazilian power system.

Regarding the representation of thermoelectric power plants, MDI-Patamares decides electrical energy dispatch for each plant at each load level for each period, respecting minimum dispatch constraints. Input data includes all existing and contracted plants with their operation start date and decommissioning already defined. Candidate projects for expansion in MDI-Patamares are implemented as continuous variables in case of generic source expansion (natural gas, coal or oil) or binary integer variables for specific projects in which the decision of investment is conditioned to the construction of the project in its total installed capacity, as the investment in hydropower plants.

Renewable projects expansion also occur by their source (wind, solar, biomass, small hydro), hence being included in the model as continuous variables due to representation problems. Although original MDI formulation presented some renewable projects as binary variables, in MDI-Patamares all renewable sources are invested in terms of continuous increasing capacity. Moreover, new options were included. Besides the original renewable options, MDI-Patamares also enables storage expansion through two different possibilities: batteries and pumped hydropower reservoirs. In addition, in terms of hydropower, the model also considers the possibility of remotorization of existing plants as well as retrofit in existing thermal units ([38, 106]).

Regarding computational characteristics, MDI-Patamares was developed in Python 3 language using object-oriented programming and functional programming as paradigms. Each source is represented in a distinct class with its own attributes and methods concerning the source's specifications and needs. In order to facilitate the communication with the optimization solver, usually CPLEX, the model uses a Python library called Pyomo (Python Optimization Modeling Objects), a package that supports a set of optimization capabilities. Data input is provided by an Excel spreadsheet containing all required information.

MDI-Patamares was the core power generation expansion computational model used for the implementations and analyses conducted under this dissertation.

2.4 Environmental Externalities in the Power Sector

The widespread effect of the energy sector on global greenhouse gas emissions is well known. According to the International Energy Agency - IEA, global energy-related CO_2 emissions rose to a historic high in 2018, driven by higher energy demand. The rise was around 1.7%, reaching 33.1 $GtCO_2$ with the power generation sector accounting for nearly two-thirds of this direct emissions growth ([55]).

Global electricity demand in 2018 increased by 4% to more than 23,000 TWh ([55]). Generation from coal- and gas-fired power plants also rose considerably to meet this demand, driving up CO_2 emissions from the sector by 2.5%. Emissions from power generation reached about 13 $GtCO_2$, or 38% of total energy-related CO_2 emissions ([55]). IPCC's Fifth Assessment Report revealed that, in 2010, 60% of total GHG emissions can be counted only for the combustion of fossil fuels ([57]). Therefore, finding ways to reduce the dominant GHG contributions from the energy sector is clearly a very relevant discussion to reach the 2 °C limit of increase in the planet's temperature established in the Paris Agreement proposed at COP21 ([39]).

However, as previously mentioned, the emission of greenhouse gases is not the only environmental impact related to power generation. Section 1.2 cites as examples hydropower plants requiring flooded areas and wind turbines being responsible for an increase in local noise pollution. In terms of other sources, biomass for energy use may conflict with food production while solar panels include hazardous materials in the manufacturing process and also present impacts related to land use change.

Then, this work not only assess the effects of considering GHG emissions, but also the consumption of water. Environmental analyses concerning emissions and water stress in relation to energy aspects configure the Climate-water-energy nexus ([22, 24, 60]). The nexus consists of the intrinsic link between them, indicating that the processes and stages regarding power generation are highly dependent on water availability and have emissions attached when considering the plants' whole life cycle - LCA.

This connection is essential in the case of Brazil due to the share of hydropower generation in the power matrix. Climate change is capable of altering rainfall regimes and hydrological cycles, directly affecting power generation. Then, Brazilian power system is potentially vulnerable to the increase in the planet's temperature, as discussed by [69], who proposes a methodology to assess the climate change vulnerability of the Brazilian hydropower sector. This problem needs to be addressed when planning the system's expansion, being the reason why the Climate-water-energy nexus is the focus of this dissertation, as it is explained in Section 2.4.2.

Therefore, analyzing possible trajectories of power generation expansion constitutes essentially an multicriteria problem. Ideally, several aspects must be assessed from an integrated perspective, which reduces the risk of biased analysis ([25]). The usual procedure of prioritizing economic variables in these evaluations are due to the vast and historical availability of techniques to monitor them, but they have been demonstrated insufficient to tackle the problem ([16]). Thus, it is necessary to understand how to feasibly incorporate other variables into the process, including environmental-related ones.

2.4.1 Concept of Externalities and the ExternE Study

One of the most widely accepted approaches to compare and include environmental impacts in production and consumption processes is the internalization of external environmental costs, also called externalities. Although they contain important information about the production and distribution of electricity, externalities are usually not accounted in the process of planning a power system's expansion. That represents loss of information for modeling frameworks since deciding on a specific electricity generation technology may vary depending on the consideration of these externalities, as they can alter the technology's viability.

Externalities are defined as an effect of one economic agent's action on another, which occurs outside the market. In other words, externalities are not subject to market forces. Economic theory deals more often with negative externalities, which constitute the theoretical basis for the study of environmental problems ([30]). A classic example in the literature is the effect of one company's pollution on resources such as water, which are used by another company. If the pollution resulting from the production of company A results in higher production costs for company B, located downstream of A (therefore B captures water contaminated with A's effluent), the production of company A produces a negative externality for company B. If there is no control over the pollution of company A, there will be an inefficient allocation of resources, as company A will produce in excess (due to the non-internalization of these costs), with costs for company B ([30]).

The internalization of external environmental costs in the power sector has been studied in several countries, mainly in relation to GHG emissions due to their influence on Climate Change. Given the fact that most nations still have fossil fuel-based energy matrices, understanding how thermoelectric plants and, thus, the entire electricity generation sector will be directly affected by emission restrictions or penalties is extremely valuable for planning and operation purposes. As an example, [46] wrote an article in which the quantification of external GHG costs is presented in order to allow producers to internalize the impacts in the cost and prices of electricity production. Other works concerning different environmental externalities rather than GHG emissions include [8, 26, 82], all related to power generation applications.

The ExternE Project was the first comprehensive attempt to employ a consistent methodology with the objective of assessing the external costs associated specifically with the production of electricity ([108]). The methodology provides a useful framework for converting impacts that are expressed in different units into a common expressive unit: monetary values. Using the approach called “Impact Pathway” (IPA), which is the methodology used for the quantification of environmental impacts, the ExternE Project aimed to provide a reliable tool for the incorporation of environmental costs related to the electricity sector in projects during its planning phases and development of environmental policies ([9]).

ExternE Project results have been applied in a wide range of publications worldwide. In Europe, in addition to Greece, other nations like France, Belgium, Germany and Switzerland also carried out analyses and projections for their energy sectors using the results of ExternE through what was called "ExternE National Implementation". That was a continuation of the project in which the main objective was to establish a broad, useful and comparable set of data on electricity production externalities for all members of the European Union ([108]).

Among Brazilian publications, ExternE results were used in [32] and [2]. For the necessary calculations, [32] followed the ExternE methodology in the case of externality costs for GHG emissions related to the generation of energy by fossil fuel plants. In [32], it was also considered the established value of US\$ $25/tCO_{2eq}$ as a monetary conversion of the original amount in Euros, which is presented in the update of the ExternE methodology. In the same way, [2] also adopted the associated costs for the reduction of emissions based on updating the ExternE methodology for the fulfillment of targets established in the Kyoto Protocol, recently replaced by the Paris Agreement.

However, as already stated, there are other environmental and social impacts related to power generation which generate different costs that must be addressed in order to actually evaluate sustainability. The next section presents which and how environmental externalities have been already considered for the Brazilian power sector in the literature.

2.4.2 Environmental Externalities in the Brazilian Power Sector

In order to internalize environmental costs - externalities - into the power generation planning process, it is necessary to correlate these costs with environmental aspects that somehow well represent issues originated due to the impacts of electricity generation in the referred power system. In this sense, selecting the represented environmental impacts is an important part of the problem as they need to be relevant to the decision-making process and able to be quantified.

For instance, [25] aimed to discuss the possibilities of incorporating environmental criteria in the decision-making process for the power generation expansion in the long run. He opted to analyze three different aspects: i) greenhouse gas emissions; ii) transformed area; and iii) water consumption. These impacts were selected in order to contemplate different environmental compartments: soil, hydrosphere and atmosphere.

The GHG emission factors were defined based on an IPCC's study about emissions in the life cycle of different power generation sources. This study presents a mean value of GHG emissions for each source and, in terms of renewables that do not consume hydrocarbons and do not produce any direct emissions, the values correspond to stages prior electricity generation: equipment production, transportation and installation.

Transformed area refers to ecosystem modification in relation to the construction of new projects - land use change. Although measuring this impact is not something trivial, available locations for the installation of power plants might be designated for other uses: agriculture, cattle raising, preservation and others. Then, it is reasonable to minimize area transformation, which is different depending on each electrical energy source. For hydropower, [25] used flooded area in km^2, while for the others he adopted mean values found in the literature multiplied by their unit's electricity generation estimation.

Water use is particularly relevant for the Brazilian power system because electricity generation competes with other usages such as urban water supply, animal watering and irrigation. Moreover, renewable sources, usually considered better options than thermal power plants for not emitting GHG, may present different water uses during their lifespan depending on the source. In this sense, [25] considered water consumption as an aspect of water usage through values also found in the literature for each source.

However, Water consumption is not fully representative as a related environmental impact indicator. It actually depends on the multiple uses assigned to each catchment basin and even water body. Brazil faces different hydrological scenarios across the territory and the relation between water demand and supply varies significantly. In this case, it is preferable to address water stress, indicating the eventual scarcity resulting from ineffective and inefficient water resources management and existing conflicting uses.

As measuring water stress or incorporating all aspects of water use is complex and distinct for each specific region, water consumption is adopted as an impact because it is a simpler strategy to express the importance of representing possible changes in water availability in the context of Climate-water-energy nexus.

Another approach is proposed in [99], which incorporates environmental aspects by including them as external costs, that is, by assigning an economic value to them. The internalization of environmental externalities consists of converting decision variables of the objective function to the same measuring unit. In order to be comparable, i.e. in the same unit, different impacts are assessed and assigned costs through a process called environmental valuation.

According to [100], environmental valuation seeks to represent on a monetary scale the values associated with environmental goods and services that do not have a market price. The methodologies used for this valuation set the premise of maximizing the utility of economic agents, making possible to infer values to those goods and services from observing the agents' behaviour, whether they are producers or consumers ([100]). Yet, the process is directly attached to human preferences, which may arise questions over the results' ethics. In order to exemplify, [99] compares the extinction of species, people's lives and the price of some products, which are not in the same scale.

For the above reason, cost values assigned to environmental goods or services might be underestimated or overestimated, casting doubts on this method effectiveness to incorporate environmental issues as determinants of a decision-making process ([62, 109]). Still, when the power sector planning is based on using economic cost minimization models, not including the environmental costs generated by the impacts of the power plants, whether on the objective function or as constraints, is the same as considering them non-existent, which is not true in any case, as stated by [99].

Therefore, [100] opted to investigate an electricity generation expansion planning methodology which internalizes specific environmental costs that he considers to be representative of the Brazilian power sector. Among all the existing environmental services mentioned in the thesis, the ones that he actually defines as relevant for being affected during the construction and operation of power plant units are: provision services, regulation services and cultural services.

In [100], provision services included food and fibers as well as genetic resources and biochemicals, in which food as an environmental service is related to the ecological process of converting solar energy into eatable plants and animals and fibers are related to the conversion of solar energy into biomass. In the same way, genetic resources and biochemicals are normally used to produce cosmetics, medications or even assist in the food production ([100]). Both require space and resources, but, specifically for genetic resources, the decrease in natural areas affects biodiversity, disrupting their availability and discovery of new genes or compounds.

Regulation services concern climate and air quality regulation in [100]. The balance between all emitted and captured GHG by the ecosystems globally influences the amount of retained heat in the Earth's atmosphere, hence magnifying several climate manifestations as well as worsening human health due to the concentration of air pollutants ([100]).

In terms of cultural services, the idea of increasing the population's well-being as a direct effect over the appreciation or simple existence of an ecosystem is incorporated. According to [100], the beauty and uniqueness of each biotic and abiotic element implies a service of contemplation, associated with cultural aspects of a certain population.

These aspects were incorporated in a power expansion planning methodology through specific monetary values defined in the literature. For each power generation source, the aforementioned environmental services were analyzed and a price of externality was assigned to each one of them in order to internalize the influences of that source in the service's provision.

Hydropower generation relates to almost all the mentioned environmental services due to the necessity of flooding large land extensions. In [100], only air quality regulation is not addressed, which means that all the others were valuated. In order to calculate these values, each project's total flooded area was determined, which allowed him to quantify mean flooded area and mean total externality factors per unit of power for each Brazilian subsystem in the case of hydropower capacity expansion. These factors are stated in Table 2.1. Although these values present significant standard deviation for Brazil due to the large diversity of power plants, they are still valid for the purposes of this dissertation.

Table 2.1: Mean Total Flooded Area and Externality for Hydropower Expansion. Source: the author, adapted from [100].

Subsystem	**Mean Flooded Area (m^2/W)**	**Mean total externality (US$/$kW$)**
Southeast	0.79	53.41
South	0.82	63.83
Northeast	0.31	21.79
North	0.97	112.04
Isolated	1.58	259.39
Total	0.70	62.78

In terms of thermal power generation, maintaining the air quality is one of the main challenges, being the most affected service. The emission factors were estimated according to the type of fuel and the technology used, based on previously published data ([100]). Differently from hydropower, thermal power generation external costs are in US dollars per unit of produced electrical energy while hydropower's are in US dollars per unit of installed power capacity. That means that for hydropower generation, environmental costs are internalized in terms of the investment decision since these costs are related to the project's construction. However, for thermal power generation, environmental costs are mostly related to direct emissions from the unit's operation. Table 2.2 refers to thermal power generation external costs.

The presented table shows average emission factors for different pollutants depending on the plants' fossil fuels and on their location in terms of Brazilian subsystems. Although all these pollutants are related to thermal power generation, nowadays there are feasible technological options that allow the reduction of almost all emitted PM (particulate matter), SO_x and NO_x.

For electricity transmission and investment in new lines, [100] considered a percentage of the total investment cost as environmental externality. However, no external costs were included for renewable sources of power because, although they exist, they represent only a small fraction of the conventional sources' environmental and social costs, as affirmed in [100] based on studies of [94, 97].

In this dissertation, the data presented in [100] is transformed and used jointly with the official data provided by EPE ([91]) and other sources in order to be implemented in the Brazilian official power expansion optimization model, MDI-Patamares. By incorporating environmental information the model is expected to present different expansion scenarios, thus proving how considering environmental impacts in energy planning alters the optimal electricity generation expansion and their avoidance gives incomplete economic signals.

Nevertheless, external costs for renewable sources were also applied in this work because, although they are usually discarded, this dissertation seeks to incorporate all possible information in order to assess and validate the obtained solutions.

Table 2.2: External Costs for Thermal Power Expansion. Source: the author, adapted from [100].

			Emission Factors					Externality Cost					
Subsystem	**Source**	**Unit Type**	**PM10 kg/MWh**	**CO2 kg/MWh**	**CH4 kg/MWh**	**NOx kg/MWh**	**SOx kg/MWh**	**PM10 (Urb) $/MWh**	**PM10 (Ru) $/MWh**	**CO2 $/MWh**	**CH4 $/MWh**	**NOx $/MWh**	**SOX $/MWh**
Southeast	Natural Gas	Open Cycle	-	408.96	0.01	0.53	0.15	-	-	6.13	0.00	0.67	0.20
		Combined Cycle	-	681.60	0.01	0.89	0.25	-	-	10.22	0.00	1.12	0.33
	Imported Coal	-	1.53	1,276.80	0.01	3.57	1.81	8.26	2.39	19.15	0.00	4.51	2.44
	Diesel	-	0.09	667.8	0.03	1.57	0.84	0.49	0.14	10.02	0.01	1.98	1.12
	Fuel Oil	-	0.09	936.00	0.03	2.09	1.11	0.49	0.14	14.04	0.01	2.64	1.50
	Sugarcane Bagasse	Condensed	0.49	-	0.03	0.34	0.04	2.65	0.77	-	0.01	0.43	0.05
		Gasified	0.19	-	0.03	0.34	0.04	1.03	0.30	-	0.01	0.43	0.05
South	Natural Gas	Open Cycle	-	408.96	0.01	0.53	0.15	-	-	6.13	0.00	0.67	0.20
		Combined Cycle	-	681.60	0.01	0.89	0.25	-	-	10.22	0.00	1.12	0.33
	National Coal	Pulverized	1.53	1,135.20	0.01	3.57	1.81	12.48	0.24	17.03	0.00	4.51	2.44
		Fluidized	1.15	851.40	0.01	2.68	1.36	9.36	0.18	12.77	0.00	4.51	2.44
		Gasified	1.02	756.80	0.01	2.38	1.21	8.32	0.16	11.35	0.00	3.01	1.62
	Fuel Oil	-	0.09	936.00	0.03	2.09	1.11	0.73	0.01	14.04	0.01	2.64	1.50
Northeast	Natural Gas	Open Cycle	-	408.96	0.01	0.53	0.15	-	-	6.13	0.00	0.67	0.20
		Combined Cycle	-	681.60	0.01	0.89	0.25	-	-	10.22	0.00	1.12	0.33
	Imported Coal	-	1.53	1,276.80	0.01	3.57	1.81	3.82	0.13	19.15	0.00	4.51	2.44
	Sugarcane Bagasse	Condensed	0.49	-	0.03	0.34	0.04	1.22	0.04	-	0.01	0.43	0.05
		Gasified	0.19	-	0.03	0.34	0.04	0.47	0.02	-	0.01	0.43	0.05
	Fuel Oil	-	0.09	936.00	0.03	2.09	1.11	0.22	0.01	14.04	0.01	2.64	1.50
	Diesel	-	0.09	667.8	0.03	1.57	0.84	0.22	0.01	10.02	0.01	1.98	1.12
North	Imported Coal	-	1.53	1,276.80	0.01	3.57	1.81	1.64	0.01	19.15	0.00	4.51	2.44
	Diesel	-	0.09	667.8	0.03	1.57	0.84	0.10	0.00	10.02	0.01	1.98	1.12
	Fuel Oil	-	0.09	936.00	0.03	2.09	1.11	0.10	0.00	14.04	0.01	2.64	1.50
	Sugarcane Bagasse	Condensed	0.49	-	0.03	0.34	0.04	0.53	0.00	-	0.01	0.43	0.05
Isolated	Diesel	-	0.09	667.8	0.03	1.57	0.84	0.00	0.00	10.02	0.01	1.98	1.12
	Fuel Oil	-	0.09	936.00	0.03	2.09	1.11	0.00	0.00	14.04	0.01	2.64	1.50
	Natural Gas	Open Cycle	-	408.96	0.01	0.53	0.15	-	-	6.13	0.00	0.67	0.20
		Combined Cycle	-	681.60	0.01	0.89	0.25	-	-	10.22	0.00	1.12	0.33

2.5 Addressing Sustainability in Power Generation Optimization Models

Recently, as the environmental concerns started to increase and their relation with the power sector became relevant and disseminated in energy discussions, the generation planning process began to incorporate environmental sustainability concepts worldwide. In terms of expansion or operation optimization models, analyses comprehending environmental aspects have been introduced in the literature through different methods. One of them is the multi-objective optimization.

As an example, [95] develops a multi-objective optimization model which combines the minimization of energy cost with the minimization of environmental impacts in order to obtain the optimal operating strategy of a distributed energy system. Environmental impacts are assessed in terms of CO_2 emissions through externalities and there are two objective functions. By keeping the objectives separate, the paper expected to illustrate the trade-offs among them. Results demonstrated that the operation of a distributed energy system is more sensitive when there is also an environmental objective.

A similar approach is presented in [61], which proposes a method for the design of trigeneration plants by also using economic, energetic and environmental performance indicators. The used framework is based on a multi-objective evolutionary algorithm. According to the paper, the use of a single-objective function does not properly indicate a solution that facilitates the judgement of the decision maker because it is usually a weighted combination of several objectives and it is difficult to interrelate them.

The work states that the multi-objective approach is interesting because there are important trade-offs between those conflicting objectives and, thus, claiming that there is only one optimal solution for the problem would be wrong ([61]). Therefore, multi-objective optimization techniques allow the decision-maker to have a broader perspective of the possibilities since they provide a set of non-dominated optimal solutions, known as Pareto optimal set, which eases a judgment examination.

In [95] the solution vector is also not determined by a unique combination but by a set of optimal arrays. That is to say that the paper applies as well the Pareto optimal set, whose graphics are trade-off curves when two objectives are involved. Then, the two objectives defined in the model imply in the trade-off curve which constitutes the optimal choices' range usable by decision-makers. Basically, for each one of the Pareto arrangements, it is not possible to improve one objective value without deteriorating the other and thus the decision becomes related to the planner major intentions.

In terms of solution methods, [95] opted for using compromise programming, in which the decision model is modified in order to consider only one objective that minimizes the distance between the criterion values and their optimum values. However, there are other possibilities for solving multi-objective optimization problems, such as global criterion method and goal programming ([95]). For instance, [61] opted for using an evolutionary technique: genetic algorithms. The paper states that since the objective functions contain discrete variables as well as continuous decision variables and the nature of the applied tariffs in the problem results in discontinuous derivative functions, conventional gradient-based optimization methods would be inappropriate ([61]).

Following the same path of evolutionary techniques, [13, 115] apply the particle swarm optimization method to solve the referred problem of power dispatch with environmental and economic perspectives by the multi-objective approach. In this sense, [115] implements a fuzzified multi-objective particle swarm optimization (FMOPSO) algorithm in order to handle the complexity and nonlinearity of the problem, discussing advantages and disadvantages of the technique.

The standard PSO algorithm is not suited for solving multi-objective optimization problems that present no absolute global optimum, thus [115] makes some modifications and the most challenging one was figuring out a scheme for choosing both and local guides for each particle in the swarm. For that, a fuzzification mechanism is introduced for the selection of global best position because, in multi-objective optimization problems, particles should select the best one based on the Pareto optimal concepts. This approach allows to consider the best global position as an area instead of a single point, i.e. each point within the area has different possibilities of being chosen as the best.

On the other hand, [13] decided to address the problem through the chaotic particle swarm optimization (CPSO) method. In this case, the proposed approach aimed to minimize two objective functions simultaneously, fuel cost rate and pollutants emission, based on a two-phased iterative strategy which includes an adaptive inertia weight factor in the PSO technique and a chaotic local search. While PSO with the factor performs global exploitation, chaotic local search performs locally oriented exploitation ([13]).

Nevertheless, despite all the literature examples provided above, none of them refer to the exact problem tackled in this dissertation: GEP - Generation Expansion Planning. Next session will specifically address GEP optimization models developed and implemented under a sustainability perspective.

2.5.1 GEP Optimization Models with Sustainability Aspects

As previously stated, GEP problem's typical formulation uses mixed-integer programming models that aim to increase power generation capacity by investing in different generating units or projects over a long-term planning horizon while minimizes the total cost, comprised by the investment cost with the system's operation cost. This original formulation is focused on obtaining the maximum economic benefit, but some existing papers in the literature proposed new approaches in order to address GEP through a sustainability perspective with different environmental considerations.

For instance, [101] establishes a framework including sustainability regulations and policies for integrated multiperiod power generation and transmission expansion using multistage stochastic programming. Also, [15] solves the GEP problem using the generalized Bender's decomposition method while considering quota obligations, carbon tax, emission trading and the impacts of feed-in tariffs, while [107] develops a GEP model incorporating limiting constraints for the emission of SO_2 and PM_{10} as well as environmental costs. Finally, [102] applies sustainability aspects in the development of a risk-averse single-stage model for the GEP problem.

In terms of the multi-objective approach, [110] proposes an optimization model that considers CO_2 and NO_x emissions while also captures demand uncertainty and units' availability through Monte Carlo simulation and [49] introduces a multi-objective mixed-integer linear model in which CO_2 emissions and energy price risk are addressed for the GEP problem. On the other hand, [75] applies nonlinear programming to formulate the problem as a single-period multi-objective mixed-integer model considering fuel price risks and CO_2 emissions.

Therefore, several methods have already been proposed in order to solve the problem. Regarding the Brazilian power system, some previous works have been made in order to adapt existing power expansion optimization models to include environmental considerations. Among them, it is possible to cite Santos in his master's dissertation ([99]) and Santos in his doctoral thesis ([100]) as well as Conde, also in his master's dissertation ([25]).

For instance, [99] opted for reformulating a GEP optimization model mentioned previously, MELP ([73]), which was developed by Machado Junior and modified in [67]. The new formulation was called "MELP Ambiental" - Environmental MELP - and included external costs from the impacts of power generation activities.

The major difference between MELP Ambiental and the original model relies on the objective function. In the original model, the objective was to minimize the sum of investment and operating costs discounted over time, as a typical formulation for a GEP problem. The formulation can be represented as follows ([99]):

$$\text{Minimize} \sum_{k=1}^{K} \frac{1}{(1+\tau)^k} \left\{ [\textit{investment cost}] + [\textit{operation cost}] \right\}, \tag{2.6}$$

in which k is time period, K is the set of time periods and τ is the discount rate.

Total investment cost is the sum of each investment cost of chosen hydropower units and thermal power units, chosen additional motorization in existing hydropower units and chosen new transmission lines. Total operation cost is the sum of operating thermal plants at that specific time period with the electricity deficit at that period.

MELP Ambiental adds to the original objective function environmental costs associated with hydropower plants, transmission lines and thermal power generation. In this sense, the new objective function becomes ([99]):

$$\begin{aligned} \text{Minimize} \sum_{k=1}^{K} \frac{1}{(1+\tau)^k} \Bigg\{ \Bigg[& \sum_{j\in J^{HP}} \left(\phi P_j^k + \phi E_j^k\right) \cdot xh_j^k \; + \sum_{j\in J^{GP}} \phi g P_j^k \cdot xg_j^k \; + \\ & \sum_{j\in J^{TP}} \phi P_j^k \cdot xt_j^k \; + \sum_{j\in J^{ZP}} \left(\phi P_j^k + \phi E_j^k\right) \cdot xz_j^k \Bigg] + \\ & \Bigg[\sum_{l=1, j\in J^t}^{L} \left(\gamma_j^k + E\gamma_j^k\right) \cdot \widehat{t}_{j,l}^k; + \sum_{l=1, j\in J^W}^{L} \delta_{j,l}^k \cdot \widehat{w}_{j,l}^k \Bigg] \Bigg\}, \end{aligned} \tag{2.7}$$

in which τ is the discount rate, ϕP_j^k is the investment cost of project j in stage k, including expenses operation and maintenance of the enterprise, ϕE_j^k is the externality cost caused by the construction of the project j in the k stage, xh_j^k is the construction of hydropower plant j in stage k, $\phi g P_j^k$ is the investment cost of the additional motorization project j in stage k, xg_j^k is the construction of the additional motorization j in stage k, xt_j^k is the construction of the thermal power plant j in stage k, xz_j^k is the construction of the transmission line j in stage k, γ_j^k is the cost of thermal production of plant j during stage k, $E\gamma_j^k$ is the externality cost caused by the power generation of the plant j during the k stage, $\widehat{t}_{j,l}^k$ is the energy production by thermal power plant j at load level l during stage k in average conditions, $\delta_{j,l}^k$ is the deficit cost j at load level l during stage k and $\widehat{w}_{j,l}^k$ is the amount of electricity demand not attended generated by deficit j at load level

l during stage k under average conditions.

However, regarding thermal power plants, this formulation only considers externalities for their operation, adopting the premise that the simple existence of these plants do not create environmental costs ([99]). This is the exact opposite of hydropower plants, which generate externalities without even being activated due to the reservoirs.

In terms of constraints, MELP Ambiental maintains the same set which are commonly seen in a mixed-integer formulation of the GEP problem. There are the investment constraints, the constraints responsible for ensuring that the demand will be met and operation constraints. There are also constraints related to critical conditions, once even during critical periods the firm energy available from all sources in period k in each region i, taking into account electricity exchanges between regions, must be sufficient to meet the total energy demand in all load levels.

On the other hand, [25] opted for changing the formulation of another GEP optimization model called PLANEL. PLANEL was developed by EPE and it is based on MELP's original formulation, but it presents adaptations regarding its computational and operational aspects. It is also a mixed-integer optimization model whose objective function is to minimize the present value of the total cost.

PLANEL presents a similar set of constraints as MELP, including the ones relate to expansion, operation and fuel consumption. However, in its original formulation PLANEL already presents an environmental constraint which establishes an annual emission limit of CO_2. Then, in order to improve the environmental dimension of the formulation, Conde decided to turn the model into a multi-objective model despite the original mono-objective approach. Among all the possible techniques to construct a multi-objective model, he adopted the weighted-sum method.

In this method, multi-objective programming problems are transformed into mono-objective problems by defining a set of weights for each objective of the problem and summing them together in a weighted average. With the transformed objective function, it is possible to use traditional linear programming to find the optimal solution to the problem. Therefore, defining the weights is an important part of the methodology, as it represents each impact's relevance in the decision-making process.

For building the environmental objective function, [25] selected three aspects as previously stated in section 2.4.2. This function is then composed by three distinct functions, one for each environmental impact. They were formulated using the existing decision variables from PLANEL, which are binary variables for the investment decision on projects and continuous variables to indicate power dispatch. Then, maximum and minimum value limits were defined for these functions and min-max normalization was applied in order to standardize the functions units, hence allowing the weighted-sum method. The multi-objective function with the modifications is presented as follows ([25]):

$$\text{Minimize}\, U = (1-\alpha)\cdot \bar{Z} \;+\; \alpha \cdot (\rho_s \cdot \bar{f}_s + \rho_a \cdot \bar{f}_a + \rho_e \cdot \bar{f}_e), \tag{2.8}$$

in which U is function which aggregates both economic and environmental dimensions, $\bar{Z}$ is the normalized economic function, α is the environmental dimension weight, ρ_s is the transformed area related weight, ρ_a is the water consumption's weight, ρ_s is the GHG emissions objective's weight, $\bar{f}_s$ is the normalized transformed area function, $\bar{f}_a$ is the normalized water consumption function and $\bar{f}_e$ is the normalized GHG emissions function.

The mathematical formulation proposed by ([25]) required the determination of two sets of weights. One representing the relative importance between the impacts concerning the environmental dimension and the other representing the relative importance of the economic and environmental dimensions. The environmental aspects' weights were defined based on a form completed by experts. The form information was compiled and then a software was used to calculate and provide the weight values.

A more recent work regarding the GEP problem with environmental aspects was also presented in [100]. In his doctoral thesis, Santos introduced a new formulation for the original Machado Junior optimization model, MELP ([73]). This new methodology was called MAPE - Environmental Model for Electricity Expansion Planning - and incorporates more environmental costs associated to the construction and operation of power plants in regard of the Brazilian long-term expansion planning process.

The major difference between his doctoral thesis and master's dissertation relies in a deeper study and consideration of externalities. While MELP Ambiental is a GEP optimization model which includes environmental costs for hydropower plants and thermal power generation, MAPE is an environmental model for determining the electricity generation expansion schedule, i.e, it is focused in the environmental dimension of the problem. This new methodology covers an extensive set of environmental services, split into three categories: provision services, regulation services and cultural services, as it has been previously stated in section 2.4.2.

The methodology consists of a two-step optimization process. According to [100], in the first stage the deterministic optimization problem seeks an individual solution to each considered scenario. For each scenario, all uncertain parameter values are known for the entire planning horizon, making it possible to find an optimal investment plan for all of them. Then, in the second stage, a minimax optimization problem finds an investment strategy which minimizes the maximum regret, defined as the differences between the optimal solution for each scenario and the selected strategy's cost ([100]).

As in MELP Ambiental, environmental variables representing external costs are introduced in MAPE's formulation by modifying the objective function. However, unlike most cost-minimizing multiperiod models, MAPE uses equivalent annual costs (EAC) in its objective function instead of net present values (NPVs) because the construction and operation costs of hydroelectric and thermoelectric plants are quite different ([98]). While hydropower plants have high construction costs and lower operation costs, thermal power plants have high operation costs and lower construction costs. Besides, their life expectancy also differ as hydroelectric plants have a much longer lifetime than thermal units. According to [98], the equivalent annual costs are used because they capture these different characteristics.

Therefore, the deterministic stage is formulated as follows ([100]):

$$\begin{aligned} \text{Minimize} \sum_{k=1}^{K} \frac{1}{(1+r)^k} \Bigg\{ \Bigg[& \sum_{j\in J^H} \left(FCC_j^k + ECC_j^k\right)\cdot \sigma h_j^k \; + \sum_{j\in J^T} FCC_j^k \cdot \sigma t_j^k \; + \\ & \sum_{j\in J^Z} \left(FCC_j^k + ECC_j^k\right)\cdot \sigma z_j^k \Bigg] + \Bigg[\sum_{j\in J^t} \sum_{l=1}^{L} \left(FOC_j^k + EOC_j^k\right)\cdot \widehat{t}_{j,l}^{k} \Bigg] \Bigg\}, \end{aligned} \tag{2.9}$$

in which K is the set of years, r is the discount rate, FCC_j^k is the equivalent annual cost of building the unit (or system component) j in year k, ECC_j^k is the equivalent annual environmental cost of building the unit (or system component) j in year k, σh_j^k is the binary variable which indicates whether hydropower plant j is available in year k, σt_j^k is the binary variable which indicates whether thermal power plant j is available in year k, σz_j^k is the binary variable which indicates whether transmission line j is available in year k, FOC_j^k is the equivalent annual cost of operating the unit (or system component) j in year k, EOC_j^k is the equivalent annual environmental cost of operating the unit (or system component) j in year k and $\widehat{t}_{j,l}^{k}$ is the energy production by thermal power plant j at load level l during stage k in average conditions.

Through these presented methodologies Santos and Conde brought to light the importance of considering environmental aspects into optimization models created to solve the GEP problem, focused in the Brazilian case. Their results indicated significant differences in the investment schedules provided by the models whenever sustainability aspects are incorporated. In this sense, their works influenced the production of this dissertation and their approaches will also figure in the process of inserting the environmental dimension into the MDI formulation.

2.6 Multi-objective Optimization

As previously stated, solving the GEP problem is finding suitable options between conflicting objectives and, therefore, implies in a multi-objective analysis. Formally, mono-objective optimization problems ([29]) can be generally represented by a single objective function $f(x) \rightarrow \mathbb{R}$ and a set of constraints, as follows:

$$\text{Minimize } z = f(x) = c^T x \tag{2.10}$$

Subject to:

$$A\,x \geq b, \tag{2.11}$$

$$x \geq 0, \tag{2.12}$$

where $x = (x_1, x_2, ..., x_n) \in \mathbb{R}^n$ represents the vector of decision variables, c^T is the transpose of the cost vector $c = (c_1, c_2, ..., c_n) \in \mathbb{R}^n$, $b = (b_1, b_2, ..., b_n) \in \mathbb{R}^n$ is the vector of independent terms, and $A = [a_{ij}]_{m \times n}$ is the coefficient matrix, containing m lines (constraints) and n columns (variables), where $a_{ij} \in \mathbb{R}^n$, $1 \leq i \leq m$, $1 \leq j \leq n$.

Conversely, a multi-objective analysis relates to problems involving different interests when possible solutions may not only be mutually exclusive, but also produce trade-offs. In other words, an effective and efficient solution for one specific objective might impact negatively another. Within a multiple criterion decision-making - MCDM ([58, 63]) - context, all the existing objectives must be properly addressed, respecting the established relations between them and the defined priorities, since a single solution will most likely not optimize all objectives simultaneously.

In fact, each objective function can be either maximized or minimized and there are no maximum number of objectives. Therefore, one of the differences between single-objective and multi-objective optimization is that the existence of more than one objective function constitutes a multi-dimensional space, in addition to the usual decision variable space ([33, 64, 81]). Mathematically, a general multi-objective problem can be described as:

$$\text{Minimize } z_1 = f_1(x) \tag{2.13}$$

$$\text{Minimize } z_2 = f_2(x) \tag{2.14}$$

$$\vdots$$

$$\text{Minimize } z_{|\Xi|} = f_{|\Xi|}(x) \tag{2.15}$$

Subject to:

$$A\,x \geq b \tag{2.16}$$

$$x \geq 0 \tag{2.17}$$

where $x = (x_1, x_2, ..., x_n) \in \mathbb{R}^n$ represents the vector of decision variables, $b = (b_1, b_2, ..., b_n) \in \mathbb{R}^n$ is the vector of independent terms, $A = [a_{ij}]_{m \times n}$ is the coefficient matrix, and its objective is composed of a set Ξ of distinct objective functions (2.13)-(2.15).

In general, there is one different optimal solution x_k^* associated to each f_k objective function, since the distinct objectives are often conflicting and the optimality of one objective implies in worse solutions to the other. This is the reason why a diverse range of optimal solutions exists, depending mainly on the defined priorities associated to the problem.

Therefore, the concept of optimality in multi-objective optimization ([34, 81]) is normally associated with the definition of a set of solutions that best suits all the objectives and the existing trade-offs between them. In order to reach that, Pareto Dominance ([35, 114]) is applied, since it guides the definition of the Pareto optimal set of solutions. As briefly introduced in Section 2.5, this Pareto optimal set refers and denominates the group of feasible solutions that most efficiently solve the problem considering all the defined objectives.

Given a set of feasible solutions $X \in \mathbb{R}^n$ for a multi-objective problem which seeks to minimize $f_\xi(x)$, $\xi \in \Xi$, and two solution vectors $x_1 \in X$ and $x_2 \in X$, a Pareto dominance relationship is established so that:

- If $f_\xi(x_1) \leq f_\xi(x_2)$, $\forall\ \xi \in \Xi$, then $f(x_1)$ dominates $f(x_2)$ and the solution vector x_1 dominates the solution vector x_2. Conversely, if $f_\xi(x_2) \leq f_\xi(x_1)\ \ \forall\ \xi \in \Xi$, then $f(x_2)$ dominates $f(x_1)$ and x_2 dominates x_1; and
- If $f_\xi(x_1) \nleq f_\xi(x_2)$ and $f_\xi(x_2) \nleq f_\xi(x_1)$, $\forall\ \xi \in \Xi$, then $f(x_1)$ is indifferent to $f(x_2)$

and vice versa, as well as the solution vector x_1 is indifferent to the solution vector x_2 and vice versa.

In this sense, a solution x^* is named Pareto optimal if there is no other solution x' within the problem's feasible solution space X that dominates x^*. Then, a Pareto optimal solution is also called a non-dominated solution. Consequently, a set of solutions P^* is named Pareto optimal if all the solution vectors $x \in P^*$ are non-dominated solutions. Finally, the Pareto Front represents the Pareto optimal set in the solution space of the objective functions, i.e. $PF = \{f(x) : x \in P^*\}$.

Therefore, as previously stated, it is necessary to have a decision-making agent to evaluate and choose the best one for the problem when applying multi-objective approaches ([6]). However, defining the best solution is a complex task because it may relate to biasing the analysis according to one objective's perspective. In order to manage this issue, different techniques are applied for multi-objective optimization problems.

In this work, two of the most used techniques are applied to solve the new formulated version of the Brazilian GEP problem with environmental criteria: the Weighted Sum Method and the $\boldsymbol{\epsilon}$-Constraint Method. Both are defined as classical methods ([33]) and are explained in the following subsections.

2.6.1 Weighted Sum Method

The weighted sum method involves the transformation of the multi-objective function (2.13)-(2.15) into the new mono-objective function (2.18) by applying a $\boldsymbol{w_\xi}$ multiplier to each original objective function $\boldsymbol{f_\xi, \xi} \in \Xi$, representing the weight (contribution) of each of these objectives in the new objective function. Thus, as the name suggests, the method solves a single objective problem that consists of the weighted sum of all objectives. This is often referred as the simplest approach and the most widely used ([33]). The weighted sum single objective function is defined as:

$$\textbf{Minimize } \boldsymbol{z} = \sum_{\boldsymbol{\xi} \in \Xi} \boldsymbol{w_\xi} \, \boldsymbol{f_\xi}(\boldsymbol{x}) \tag{2.18}$$

Weighting the objective function, however, might not be simple. The multiplying parameters $\boldsymbol{w_\xi}$ depend on each objective's importance in the context of the problem. Therefore, the results need to be analysed under the selected perspective. As a consequence, the scaling factor and objective priorities must be properly defined and agreed when solving problems with this method. When setting the objective functions' weights, it is also important to scale them appropriately so that each has approximately the same order of magnitude ([33]).

This method is often applied in problems whose feasible region of the objective functions is convex because it is possible to obtain the Pareto optimal solutions by altering the weights used in the objective. In fact, [33] indicates that a solution to a multi-objective problem is certain to be Pareto-optimal if the defined weights are positive for all the problem's objectives. Moreover, for convex multi-objective problems, there is at least one positive weight vector for each Pareto-optimal solution ([33]).

However, as an disadvantage, problems with both maximization and minimization type objectives need to have all the objectives converted into just one type. Besides this limitation, another disadvantage is that the method might not be suitable if the problem has a non-convex solution space because it cannot find certain Pareto-optimal solutions in this case ([33]). Still, Pareto optimal solutions are able to be found when the Pareto Front is convex despite a non-convex solution space.

2.6.2 $\boldsymbol{\epsilon}$-Constraint Method

Considering that the Weighted-sum Method is most suitable according to the solution space's convexity, other methods are necessary in order to ensure that all Pareto-optimal solutions of a non-convex problem are reachable. In regard to this, [51] introduced the $\boldsymbol{\epsilon}$-Constraint Method, which is fully applicable regardless of convexity.

As the Weighted-sum method, this one is also based on converting a problem with multiple objectives into a mono-objective problem. However, instead of creating a single objective function formed by the original objectives weighted by factors, one of them is set as the problem actual objective function while the others are included in the formulation as constraints.

In this sense, the objective function will comprise the objective considered the most relevant. All the following analyses are then conducted keeping this objective's perspective as the center. The other objectives defined as constraints will help shaping the solution space according to the their associated independent terms vectors.

In other words, given a multi-objective problem, in which Ξ represents the set of existing objectives and $\boldsymbol{\xi}^* \in \Xi$ is considered to be the most relevant one, the other objective functions $\boldsymbol{f_{\xi}(x)}, \boldsymbol{\xi} \in \Xi \setminus \{\boldsymbol{\xi}^*\}$ are included as constraints associated with the independent terms vectors $\boldsymbol{\epsilon_{\xi}(x)}, \boldsymbol{\xi} \in \Xi \setminus \{\boldsymbol{\xi}^*\}$ that define the maximum value that each objective can achieve ([33]). The corresponding mathematical formulation is as follows:

$$\textbf{Minimize } \boldsymbol{z} = \boldsymbol{f_{\xi^*}(x)} \tag{2.19}$$

Subject to:

$$\boldsymbol{f_\xi(x)} \leq \boldsymbol{\epsilon_\xi}\,, \ \ \forall\, \boldsymbol{\xi} \in \Xi \setminus \{\boldsymbol{\xi^*}\} \tag{2.20}$$

$$\boldsymbol{A\,x} \geq \boldsymbol{b} \tag{2.21}$$

$$\boldsymbol{x} \geq \mathbf{0} \tag{2.22}$$

In order to obtain a subset of the Pareto optimal set, we vary the vector of upper bounds $\boldsymbol{\epsilon}$ along each single objective's related Pareto front, performing a new optimization process for each new vector. This iterative process provides a set of Pareto optimal solutions that allow the construction of Pareto fronts concerning all different problem objectives, so that in each iteration we solve the problem with more restraining constraints originated from the non-selected objectives.

More specifically, firstly we determine the maximum and minimum values that each function $\boldsymbol{f_\xi(x), \xi} \in \Xi \setminus \{\boldsymbol{\xi^*}\}$ can achieve, named $\boldsymbol{\epsilon_{\xi_{\mathbf{min}}}}$ and $\boldsymbol{\epsilon_{\xi_{\mathbf{max}}}}$, thereafter we define the stepsize $\boldsymbol{\delta_\xi}$ as the decreasing amount for $\boldsymbol{\epsilon_\xi}$ value in each iteration.

The method then consists in solving the problem through iterations, in which the upper bounds are initially set as $\boldsymbol{\epsilon_\xi} = \boldsymbol{\epsilon_{\xi_{\mathbf{max}}}}$, and at each new iteration their values are decreased by $\boldsymbol{\delta_\xi}$ in order to become more restricted. The iterations finish when $\boldsymbol{\epsilon_\xi}$ reaches $\boldsymbol{\epsilon_{\xi_{\mathbf{min}}}}$.

The Pareto front's shape becomes clearer defined as the value of $\boldsymbol{\delta_\xi}$ is reduced. However, small $\boldsymbol{\delta_\xi}$ values require a greater number of iterations, which can drastically affect the computational time needed for the method to converge. In this sense, part of the whole procedure consists of finding a suitable value for $\boldsymbol{\delta_\xi}$. Still, despite this disadvantage, the method is applicable for problems whose solution space is unknown, which makes it secure and reliable to obtain Pareto optimal solutions.

The aforementioned process is shown in Algorithm 1 of Section 3.3.2, which describes the method application for the problem studied in this dissertation.

Chapter 3

Mathematical Formulations

This chapter proposes a mathematical formulation for the aforementioned problem. In this dissertation, MDI-Patamares' original formulation ([38]) has been modified in order to consider environmental externalities or impact factors related to the operation and expansion of all possible sources into the model's objective function. All the proposed and applied changes are specified in the next sections of this chapter.

3.1 Considered Environmental Impacts

As mentioned in the previous chapter, the original objective function seeks to minimize the expansion cost, which is the sum of the investment cost with the operation cost. Each one of these is composed by different portions whose values differ according to the time period brought to present value by an also defined discount rate. The portions are represented in figure 3.1.

However, as it presents no representation of environmental impacts related to power generation, changes in the formulation were necessary. Therefore, the first step was to decide which environmental aspects would be considered and how they would be implemented.

Power generation affects the environment directly and indirectly in many sorts of way. GHG emissions, water stress, land use, biodiversity and waste generation are few examples. All of them are able to be represented in an optimization model, but for this dissertation only GHG emissions and water consumption were included.

GHG emissions are a major worldwide problem for their contribution to climate change. Moreover, they are an issue for Brazil because the country committed to reduce total emissions under the Paris Agreement. Then, addressing this matter is not only important through an environmental perspective, but also in a political perspective, even though the Brazilian power matrix has little associated emissions when compared to other nations.

In fact, the Brazilian Nationally Determined Contribution - NDC ([77]) - under the Paris Agreement does not present power generation as one of the key sectors for GHG emissions reductions. However, as the document sets emission limits for the nation, it affects power plants investments since thermal power generation may not increase excessively so that the commitment is not breached.

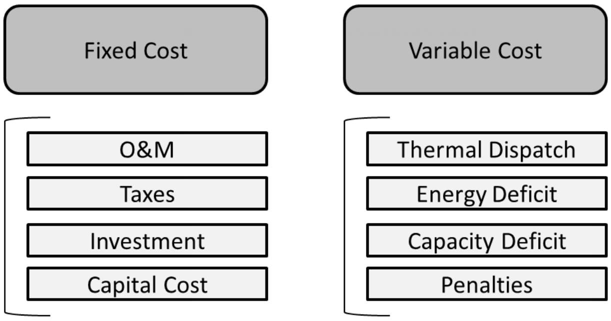

Figure 3.1: Costs considered in Objective Function. Source: adapted from ([38]).

Water resources are important due to the Brazilian Power System specifications. Brazil relies mostly in hydropower generation (Figure 1.2) which reflects the country's access and availability to freshwater. Furthermore, agriculture and cattling are two of the main Brazilian economic activities and both are known for being extremely water intense, requiring great volumes. The nation has faced scarcity episodes and depends on hydrological cycles to sustain its power generation, which means that the model's formulation should somehow address water considerations.

Thus, the adopted approach in the dissertation was to modify MDI-Patamares by turning it into a multi-objective model by considering other objectives that minimize both aforementioned environmental impacts . That is to say, the new multi-objective mathematical formulation comprises GHG emissions and water consumption for electricity generation beyond the system's original expansion and operation costs, therefore seeking for an economic and environmental optimal.

At first, the adopted multi-objective approach was based on minimizing a single objective function composed by the sum of all functions expressed in terms of the same unit, the Weighted Sum Method (Section 2.6.2) . In this sense, the environmental aspects were included into the formulation by means of monetary values, i.e., calculated external costs for GHG emissions and water consumption related to the Brazilian power system's operation and expansion for each generation source.

However, although calculating and using environmental externalities is considered a valid method for impact consideration, the attributed monetary values rely on different methodologies of environmental valuation and may originate distinct values depending on contemplated aspects as well as regional or national regulatory frameworks related to environmental conservation. In regard to this, carbon emissions reduction and water consumption savings would be maximized if the model optimized emission and water volume units rather than their corresponding assigned costs.

Then, the $\boldsymbol{\epsilon}$-Constraint Method was also applied by splitting the objective functions. The first objective is related to the Brazilian power system's operation and investment costs, the second aims to minimize the GHG emissions from operating and expanding the system and the third seeks to minimize water consumption also from both operation and expansion.

Since the original generation expansion problem formulation seeks to find the least expensive investment schedule by minimizing the total expansion cost, the chosen objective for the $\boldsymbol{\epsilon}$-Constraint application also minimizes the costs of operating and expanding the system. The other objectives regarding the environmental aspects were, thus, included in the formulation as constraints limited by their respective calculated values.

Therefore, the next sections present the proposed formulation, elucidating the different comprehended objectives. It also introduces all the sets of constraints, which contain the specific constraints associated to particular energy sources or model aspects.

3.2 Objective Function and Constraints - Weighted Sum Method

3.2.1 Objective Function

The overall structure of the objective function applied in the Weighted Sum Method consists of four main parts: economic costs, emission costs, water consumption costs and other costs. Each one of them is stratified into two minor parts referring to the sources operation and expansion (investment). This division is represented in Figure 3.2.

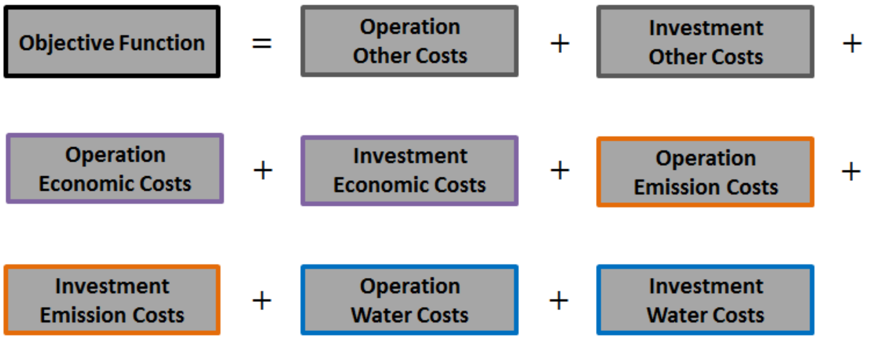

Figure 3.2: Stratification of the Objective Function. Source: the author.

The other costs refer to monetary penalties and transmission grid expansion. The penalties are undesired system inconsistencies that may imply in unrealistic results if not addressed. They consist of slack variables that aim to prevent infeasibility or cycling. As examples, they are used in the model to avoid bidirectional flows in the transmission grid and to penalize violations of minimum hydraulic generation. Others include energy generation deficit and system's capacity deficit, the power deficit. These penalties have specific calculated values which are stated in the original model's formulation ([38, 91]). Their high values intend to inhibit the model from opting for inconsistencies and choose feasible options whenever possible instead. Grid expansion, in its turn, had no environmental impacts associated.

The economic costs are also represented in the original MDI-Patamares' formulation and stand for the occurring charges for the construction and operation of each energy source power plants (Figure 3.1). In opposition, both the emissions and water consumption costs were calculated and introduced in the proposed formulation. These are jointly named environmental costs and, although they might also be considered economic costs, in this work this term is only referring to the embedded market costs. In relation to the included environmental costs, the whole process of gathering and treating data is described in the next chapter, section 4.1.

In order to better understand and monitor the impact of considering the environmental aspects in the GEP problem, a parameter was added multiplying the terms related to emissions and water consumption. By varying the parameter $\boldsymbol{\alpha}$ value in a range from $\mathbf{0}$ to $\mathbf{1}$, it could be possible to evaluate the environmental costs impacts over the expansion results. It also enables the construction of a curve which demonstrates how changing the parameter value affects the total amount of emitted gases and consumed water. Therefore, the model's objective becomes different in every execution depending on the parameter value. Figure 3.3 indicates the final structure of the proposed objective function.

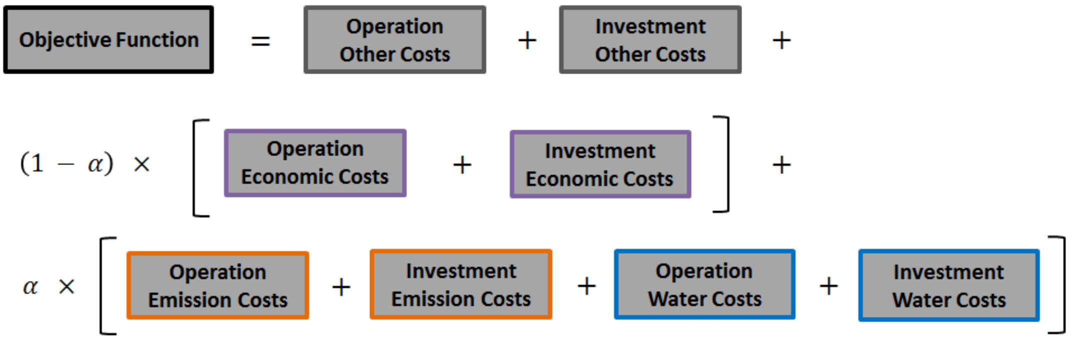

Figure 3.3: Proposed Objective Function - Weighted Sum Method. Source: The author.

By minimizing this new total cost, the model starts to reflect the adopted environmental impacts in the results for each source as they present different externalities concerning their own characteristics. The detailed mathematical formulation of the objective function, with every parameter and decision variable, is introduced later in this chapter, in section 3.2.3.

3.2.2 Constraints

1) Energy Demand Constraint

The first constraint is responsible for ensuring that the sum of energy availability, which stands for generation and exchange, plus the deficit and subtracted from stored energy must be greater than or equal to demand. This constraint must be guaranteed for every submarket, scenario, planning period and load level.

2) Power Demand Constraint

The power demand constraint intend to ensure capacity in order to provide energy at the moment it is required, mainly during demand peaks. As the introduction of intermittent renewable sources and the difficulty in expanding hydroelectric plants with regularization reservoirs have diminished the system's capacity to supply peak demand, this constraint becomes relevant and important by investing in easily dispatchable plants. It results in a capacity investment greater than average electricity necessity.

Generation sources contribution for peak demand is different amongst each other. In fact, this constraint is similar to the first one and the difference relies on summing up the system's total power capacity in the peak load level instead of the supplied energy. For instance, in the optimization model, thermal power plants are considered to contribute with their full capacity, as they are fully dispatchable, hence available to meet maximum instantaneous demand represented as the peak load level. On the other hand, other sources require taking into account their own cycles depending on climate conditions.

Besides being related to the peak load level, this constraint must also be guaranteed for every submarket, scenario and planning period.

3) Availability of Sources and Projects

These constraints are related to generation requirements of the sources and projects. Some are general, applied for every source, and some may be specific. For instance, these constraints include the conditions and generation limits, maximum and minimum, for each scenario, time period and load level.

They also comprise the minimum entrance date constraints, which define when plants are able to start generating electricity for the system, and the ones responsible for maintaining the decided investments, ensuring that there will be no divestment. That is, the installed capacity of a source at time $\boldsymbol{t}$ will be greater than or equal to that at time $\boldsymbol{t-1}$ for continuous variables.

4) System's Representation Constraints

One of the formulation's decision variables represents the possibility of expanding the exchange interconnections between subsystems. This set of constraints guarantees that all energy exchange will be less or equal than the transmission lines' existing maximum limit summed to their invested expansion.

Besides, according to transmission electrical studies from ONS and EPE ([90, 93]), it is possible to establish dynamically maximum limits among the subsystems for sending and receiving electrical energy. Then, the result is additional exchange capacity constraints related to more than one interconnection. These are the exchange groups constraints and they are valid for both energy and power exchanges.

5) Investment Constraints

In terms of binary variables, the decision for each project indicates the period in which the corresponding investment occurs. This variable is an array with a number of spaces equal to the number of periods. It starts receiving a value of "0" in all, remaining the same except in the position corresponding to the period in which the investment will take place. In this specific position the value will be "1" if there is an investment in that project.

Therefore, in order to check if there was an investment in a project during a certain period, we sum the positions of the investment variable from "1" to k, with k being the period of interest. If the result is "1", then it means that the project was invested within the period.

Since it is not possible to build the same project more than once, the investment constraints ensure that the sum of the investment decision variable for each project must always be less than or equal to 1.

6) Additional Constraints

Additional constraints in MDI-Patamares are used to represent energy policies or to emulate some industrial and market conditions, such as maximum or minimum limits for the entry of certain generation sources and adoption of uniform expansion over the horizon. Therefore, they are optional and not necessary for the optimization, which means that their inclusion in the formulation occurs according to the initial data set provided. There are certain types of additional constraints represented in the model, which are described as follows:

- *Step*: Given an initial and final year and minimum and maximum values for the step, the model decides a uniform expansion in this period, that is, in all years during the validity of the constraint, the increase in installed capacity for the chosen project or groups of projects will be the same;
- *Annual Limit*: Defines the installed capacity limit value that a project or group of projects is able to reach in a given year, that is, the maximum power expansion of a project by the given year;
- *Annual Incremental Limit*: Defines the maximum increase that the installed capacity of a project or group of projects may have in a given year in relation to the previous year value, that is, maximum annual increase;
- *Equality*: Defines the value that the installed capacity of a project or group of projects must reach or assigns a value of "1" for the investment variable of a project in a given month and year;
- *Maximum Equality*: Assigns a maximum date for the value of a project's investment variable to equal "1", that is, a deadline for the installation of a given project; and

- *Proportion*: Sets a ratio between two projects from the same source. It is usually used to balance the evolution of installed capacity of a given source between regions, hence, one project may only increase its capacity if the other also increases according to the given ratio.

3.2.3 Mathematical Formulation

The complete mathematical formulation in a mixed integer linear programming (MILP) form is as follows.

Table 3.1: Constants, Sets and Indices.

Item	Description	Item	Description
AI	Power Exchange Groups (ai = 1, 2, ..., AI)	C	Hydrological condition scenarios (c = 1,2, ..., C)
FR	Renewable sources (fr = Small Hydro, Solar PV, Wind, Biomass)	$IJ_{\boldsymbol{AI}}$	Pairs of subsystems which compose the exchange group ai
P	Load levels (p = 1, 2, ..., P)	S	Subsystems (s,i,j = 1, 2, ..., S)
NF	Subsystems which represent fictional nodes in the transmission system	K	Time periods (k = 1, 2, ..., K)
PnB	Load levels with energy storage prohibition for storage technology projects	PnG	Load levels with energy generation prohibition for storage technology projects
Y	Years of planning (y = 0, 1, ..., Y)	$\boldsymbol{MT_r}$	Application month of the additional restriction r
R	Renewable projects (Small Hydro, Solar PV, Wind, Biomass) (r = 1, 2, ..., R)	A	Storage technology projects that are candidates for expansion (a = 1, 2, ..., A)
H	Hydropower projects (h = 1, 2, ..., H)	$\boldsymbol{X_s}$	Subset of plants belonging to the subsystem where X = A, R, H, TE, TP
TE	Existing thermal power plants (te = 1, 2, ..., TE)	TP	Thermal power plants candidates for expansion (tp = 1, 2, ..., TP)
RI	Equality type constraints	RM	Maximum equality type constraints for binary variables
RA	Annual limit type constraints	RL	Annual incremental limit type constraints
RP	Proportion type constraints	RS	Step type constraints
HP	Standard number of hours in a month - 730.5 [hours]	DISC	Discount rate

Table 3.2: Parameters.

Item	**Description**	**Item**	**Description**
$Y_{\boldsymbol{r}}^{\boldsymbol{f}}$	Final year for application of the additional restriction r [MW]	$Y_{\boldsymbol{r}}^{\boldsymbol{i}}$	Initial year for application of the additional restriction r [MW]
$Y_{\boldsymbol{r}}$	Year for application of the additional restriction r [MW]	$CD^{\boldsymbol{P}}$	Penalty for not meeting the capacity constraint [\$/MW]
$CP_{\boldsymbol{s,k,p}}^{\boldsymbol{R}}$	Contribution of type R renewables from subsystem s in period k to load level p	$CD_{\boldsymbol{p}}^{\boldsymbol{E}}$	Penalty for not meeting the demand constraint [\$/MW]
$FC_{\boldsymbol{i,j}}^{\boldsymbol{I}}$	Monthly fixed cost associated with the expansion of one MW of the transmission line that connects subsystem i to subsystem j [\$/MW/month]	$FC_{\boldsymbol{r}}^{\boldsymbol{R}}$	Monthly fixed cost associated with one MW of the renewable source project r [\$/MW/month]
$FC_{\boldsymbol{a}}^{\boldsymbol{A}}$	Monthly fixed cost associated with one MW of the storage technology project project a [\$/MW/month]	$FC_{\boldsymbol{tp}}^{\boldsymbol{TP}}$	Monthly fixed cost associated with one MW of the thermal power project candidate for expansion tp [\$/MW/month]

Continued on next page

Table 3.2 – continued from previous page

Item	**Description**	**Item**	**Description**
$\mathrm{FC}^{\boldsymbol{H}}_{\boldsymbol{h}}$	Monthly fixed cost associated with the hydropower project h [\$/month]	$\mathrm{VC}_{\boldsymbol{te,k}}$	Variable cost of one unit of generation for the existing thermal power plant te in period k [\$/MWh]
$\mathrm{VC}_{\boldsymbol{tp,k}}$	Variable cost of one unit of generation for the invested thermal power plant tp's capacity in period k [\$/MWh]	$\mathrm{DE}_{\boldsymbol{s,k,p}}$	Energy demand in subsystem s, period k and load level p [\$/MW]
$\mathrm{DT}_{\boldsymbol{p}}$	Duration of load level p [%]	$\mathrm{EE}^{\boldsymbol{R}}_{\boldsymbol{s,k}}$	Energy from existing and contracted renewables of type R in subsystem s in period k [MWmonth]
$\boldsymbol{\Phi_{r,k}}$	Capacity factor of renewable project r in period k	$\mathrm{FDISP}_{\boldsymbol{tp}}$	Availability factor of the thermoelectric candidate for expansion tp [%]
FRP	Multiplying factor of the instantaneous maximum demand for operating reserve purposes [%]	$\mathrm{GM}^{\boldsymbol{E}}_{\boldsymbol{s}}$	Minimum hydraulic generation of hydropower plants in the subsystem s [MW]
$\mathrm{GM}^{\boldsymbol{H}}_{\boldsymbol{h}}$	Minimum hydraulic generation of project h [MW]	$\mathrm{INFLEX}_{\boldsymbol{k,te}}$	Inflexibility of the existing thermal power plant te in period k [%]
$\mathrm{INFLEX}_{\boldsymbol{k,tp}}$	Inflexibility of the thermoelectric project tp in period k [%]	$\mathrm{NM}_{\boldsymbol{h}}$	Number of months of motorization of the hydroelectric project h
$\mathrm{LIM}_{\boldsymbol{r,k}}$	Limit of additional constraint r for period k [MW]	$\mathrm{MT}_{\boldsymbol{r}}$	Application month of the additional restriction r
$\mathrm{L}_{\boldsymbol{i,j,k,p}}$	Existing exchange limit between subsystems i and j in period k and load level p [MW]	$\mathrm{L}_{\boldsymbol{ai,k,p}}$	Exchange limit of group ai in period k and load level p [MW]
CI	Penalty applied to power exchanges in order to avoid bidirectional flows [\$/MW]	PGH	Penalty for violation of minimum hydraulic generation [\$/MW]
$\mathrm{MINOp}_{\boldsymbol{te}}$	Minimum start-up period of thermoelectric project te	$\mathrm{MINExp}_{\boldsymbol{r}}$	Minimum period for start-up of the renewable source project r, including construction time
$\mathrm{MIN}\boldsymbol{Exp_{a}}$	Minimum period for start-up of the storage technology project a, including construction time	$\mathrm{MIN}\boldsymbol{Exp_{h}}$	Minimum period for start-up of the hydropower project h, including construction time
$\mathrm{MINExp}_{\boldsymbol{tp}}$	Minimum period for start-up of the thermal power project tp, including construction time	MINExpI	Minimum period for expansion of interconnections between subsystems
$\mathrm{PD}^{\boldsymbol{TE}}_{\boldsymbol{te,k}}$	Available power of the existing thermoelectric plant te in period k [MW]	$\mathrm{PD}^{\boldsymbol{E}}_{\boldsymbol{c,s,k}}$	Available power of hydroelectric plants of the subsystem s in scenario c and period k [MW]
$\mathrm{PD}^{\boldsymbol{H}}_{\boldsymbol{c,h,k}}$	Available power of hydropower project h in scenario c and period k [MW]	$\mathrm{PROB}_{\boldsymbol{c}}$	Occurrence probability of hydrological condition c [%]
$\mathrm{RAT}_{\boldsymbol{rp,k}}$	Ratio for the additional restriction of proportion rp	$\boldsymbol{\Omega^{A}_{a}}$	Performance of the storage technology project a [%]
$\mathrm{SG}^{\boldsymbol{E}}_{\boldsymbol{c,s,k}}$	Monthly hydraulic generation series of hydroelectric plants in subsystem s in scenario c and period k [MWmonth]	$\mathrm{SG}^{\boldsymbol{H}}_{\boldsymbol{c,h,k}}$	Monthly hydraulic generation series of the project h in scenario c and period k [MWmonth]
$\mathrm{STEP}^{\boldsymbol{max}}_{\boldsymbol{rs}}$	Maximum value for the step of constraint rs [MW]	$\mathrm{STEP}^{\boldsymbol{min}}_{\boldsymbol{rs}}$	Minimum value for the step of constraint rs [MW]

Continued on next page

Table 3.2 – continued from previous page

Item	**Description**	**Item**	**Description**
$\text{EMCOP}^{\boldsymbol{TP}}_{\boldsymbol{tp}}$	Emission cost for operating invested thermal power project tp [$/MWh]	$\text{EMC}^{\boldsymbol{TE}}_{\boldsymbol{te}}$	Emission cost for operating existing thermal power plant te [$/MWh]
$\text{EMCEXP}^{\boldsymbol{TP}}_{\boldsymbol{tp}}$	Emission cost for investing in thermal power project tp's capacity [$/month/MW]	$\text{WUCOP}^{\boldsymbol{TP}}_{\boldsymbol{tp}}$	Water consumption cost for operating invested thermal power project tp [$/MWh]
$\text{WUC}^{\boldsymbol{TE}}_{\boldsymbol{te}}$	Water consumption cost for operating existing thermal power plant te [$/MWh]	$\text{WUCEXP}^{\boldsymbol{TP}}_{\boldsymbol{tp}}$	Water consumption cost for investing in thermal power project tp's capacity [$/month/MW]
$\text{EMC}^{\boldsymbol{H}}_{\boldsymbol{h}}$	Emission cost for investing in hydropower project h [$/month/MW]	$\text{WUC}^{\boldsymbol{H}}_{\boldsymbol{h}}$	Water consumption cost for investing in hydropower project h [$/month/MW]
$\text{EMC}^{\boldsymbol{R}}_{\boldsymbol{r}}$	Emission cost for investing in renewable project r's capacity [**$**/month/MW]	$\text{WUC}^{\boldsymbol{R}}_{\boldsymbol{r}}$	Water consumption cost for investing in renewable project r's capacity [**$**/month/MW]
$\text{EMC}^{\boldsymbol{A}}_{\boldsymbol{a}}$	Emission cost for investing in storage project a's capacity [**$**/month/MW]	$\text{WUC}^{\boldsymbol{A}}_{\boldsymbol{a}}$	Water consumption cost for investing in storage project a's capacity [**$**/month/MW]
CB	Energy accumulation cost for storage technology projects [$/MWh]	$\boldsymbol{\alpha}$	Weighting factor for the environmental aspects in the objective function [0.1,1.0]

Table 3.3: Variables.

Item	**Description**	**Item**	**Description**
$\text{b}^{\boldsymbol{A}}_{\boldsymbol{c,a,k,p}}$	Energy accumulation of storage technology project a for scenario c, period k and load level p [MWmonth]	$\text{c}^{\boldsymbol{A}}_{\boldsymbol{a,k}}$	Accumulated installed capacity of storage technology projects of type a that are candidates for expansion in period k [MW]
$\text{c}^{\boldsymbol{R}}_{\boldsymbol{r,k}}$	Accumulated installed capacity of type r renewable projects in period k [MW]	$\text{c}^{\boldsymbol{TP}}_{\boldsymbol{tp,k}}$	Accumulated installed capacity of thermoelectric projects of type tp that are candidates for expansion in period k [MW]
$\text{d}^{\boldsymbol{E}}_{\boldsymbol{c,s,k,p}}$	Energy deficit for scenario c in subsystem s, period k and load level p [MWmonth]	$\text{d}^{\boldsymbol{P}}_{\boldsymbol{c,s,k}}$	Capacity deficit for scenario c in subsystem s and period k [MW]
$\text{c}^{\boldsymbol{I}}_{\boldsymbol{i,j,k}}$	Accumulated expansion of power transmission between subsystems i and j in period k [MW]	$\text{g}^{\boldsymbol{E}}_{\boldsymbol{c,s,k,p}}$	Generation of existing hydropower plants in subsystem s for scenario c in period k and load level p [MWmonth]
$\text{g}^{\boldsymbol{H}}_{\boldsymbol{c,h,k,p}}$	Generation of hydropower plants h for scenario c in period k and load level p [MWmonth]	$\text{g}^{\boldsymbol{TP}}_{\boldsymbol{c,tp,k,p}}$	Generation of thermoelectric plants tp that are candidates for expansion for scenario c in period k and load level p [MWmonth]
$\text{g}^{\boldsymbol{TE}}_{\boldsymbol{c,te,k,p}}$	Generation of existing thermoelectric plants te for scenario c in period k and load level p [MWmonth]	$\text{i}^{\boldsymbol{P}}_{\boldsymbol{c,i,j,k}}$	Power exchange between subsystems i and j for scenario c and period k [MW]
$\text{i}^{\boldsymbol{E}}_{\boldsymbol{c,i,j,k,p}}$	Electricity exchange between subsystems i and j for scenario c, period k and load level p [MWmonth]	$\text{g}^{\boldsymbol{A}}_{\boldsymbol{c,a,k,p}}$	Energy production from storage technology project a for scenario c, period k and load level p [MWmonth]
$\text{step}_{\boldsymbol{rs}}$	Step value of installed capacity for the restriction rs [MW]	$\boldsymbol{\pi}^{\boldsymbol{H}}_{\boldsymbol{h,k}}$	Investment binary variable of hydroelectric project h in period k
$\text{m}^{\boldsymbol{H}}_{\boldsymbol{h,k}}$	Motorization variable of hydroelectric project h in period k [%]	$\text{ghp}^{\boldsymbol{H}}_{\boldsymbol{c,h,k,p}}$	Violation of minimum hydraulic generation of the hydroelectric plant candidate for expansion h for scenario c in period k and load level p [MW]

Continued on next page

Table 3.3 – continued from previous page

Item	Description	Item	Description
$\text{ghp}^{E}_{c,s,k,p}$	Violation of minimum hydraulic generation of existing hydroelectric plants from subsystem s for scenario c in period k and load level p [MW]		

Objective function:

$$
\textbf{Minimize} \sum_{\mathbf{k}\in\mathbf{K}} \frac{\mathbf{1}}{\mathbf{DISC^k}} \cdot \left[
\begin{array}{r}
\sum_{c\in C}\sum_{p\in P} HP\cdot\ PROB_c\cdot\ DT_p\cdot\ \Big(\sum_{s\in S}\Big(d^{E}_{c,s,k,p}\cdot CD^{E}_{p}\Big)+\\
\sum_{a\in A}\Big(b^{A}_{c,a,k,p}\cdot CB\Big)\Big)+\sum_{c\in C}\sum_{i\in S}\sum_{j\in S} CI\cdot PROB_c\cdot\\
\Big(\sum_{p\in P}\Big(i^{E}_{c,i,j,k,p}\Big)+i^{P}_{c,i,j,k}\Big)+\sum_{c\in C}\sum_{p\in P} PGH\cdot PROB_c\cdot\\
\Big(\sum_{s\in S} ghp^{E}_{c,s,k,p}+\sum_{h\in H} ghp^{H}_{c,h,k,p}\Big)+\sum_{c\in C}\sum_{s\in S} CD^{P}\cdot d^{P}_{c,s,k}+\\
\sum_{i\in S}\sum_{j=i}^{S} FC^{I}_{i,j}\cdot c^{I}_{i,j,k}+\\
\\
(1-\alpha)\cdot\Big(\sum_{c\in C}\sum_{p\in P} HP\cdot PROB_c\cdot DT_p\cdot\Big(\sum_{te\in TE}\Big(g^{TE}_{c,te,k,p}\cdot\\
VC_{te,k})+\sum_{tp\in TP}\Big(g^{TP}_{c,tp,k,p}\cdot VC_{tp,k}\Big)\Big)+\sum_{h\in H} FC^{H}_{h}\cdot\sum_{k'=1}^{k}\pi^{H}_{h,k'}+\\
\sum_{r\in R} FC^{R}_{r}\cdot c^{R}_{r,k}+\sum_{tp\in TP} FC^{TP}_{tp}\cdot c^{TP}_{tp,k}+\sum_{a\in A} FC^{A}_{a}\cdot c^{A}_{a,k}\Big)+\\
\\
\alpha\cdot\Big(\sum_{c\in C}\sum_{p\in P} HP\cdot PROB_c\cdot DT_p\cdot\Big(\sum_{te\in TE}\Big(g^{TE}_{c,te,k,p}\cdot\\
EMC^{TE}_{te})+\sum_{tp\in TP}\Big(g^{TP}_{c,tp,k,p}\cdot EMCOP^{TP}_{tp}\Big)\Big)+\sum_{h\in H} EMC^{H}_{h}\cdot\\
\sum_{k'=1}^{k}\pi^{H}_{h,k'}+\sum_{r\in R} EMC^{R}_{r}\cdot c^{R}_{r,k}+\sum_{tp\in TP} EMCEXP^{TP}_{tp}\cdot c^{TP}_{tp,k}+\\
\sum_{a\in A} EMC^{A}_{a}\cdot c^{A}_{a,k}+\sum_{c\in C}\sum_{p\in P} HP\cdot PROB_c\cdot DT_p\cdot\\
\Big(\sum_{te\in TE}\Big(g^{TE}_{c,te,k,p}\cdot WUC^{TE}_{te}\Big)+\sum_{tp\in TP}\Big(g^{TP}_{c,tp,k,p}\cdot WUCOP^{TP}_{tp}\Big)\Big)+\\
\sum_{h\in H} WUC^{H}_{h}\cdot\sum_{k'=1}^{k}\pi^{H}_{h,k'}+\sum_{r\in R} WUC^{R}_{r}\cdot c^{R}_{r,k}+\\
\sum_{tp\in TP} WUCEXP^{TP}_{tp}\cdot c^{TP}_{tp,k}+\sum_{a\in A} WUC^{A}_{a}\cdot c^{A}_{a,k}\Big)
\end{array}
\right] \tag{3.1}
$$

Subject to:

1) Energy Demand Constraints

$$
\begin{array}{r}
CH^{E}_{c,s,k,p}+\sum_{te\in TE_s} g^{TE}_{c,te,k,p}+\sum_{fr\in FR_s}\Big(EE^{fr}_{s,k}\cdot CP^{fr}_{s,k,p}\Big)+\sum_{h\in H_s} g^{H}_{c,h,k,p}+\\
\sum_{tp\in TP_s} g^{TP}_{c,tp,k,p}+\sum_{r\in R_{s,fr}}\Big(c^{R}_{r,k}\cdot\Phi_{r,k}\cdot CP^{fr}_{s,k,p}\Big)+\sum_{a\in A_s}\Big(g^{A}_{c,a,k,p}-b^{A}_{c,a,k,p}\Big)+\\
\sum_{i\in S}\Big(i^{E}_{c,i,s,k,p}-i^{E}_{c,s,i,k,p}\Big)+d^{E}_{c,s,k,p}\geq DE_{s,k,p}\,,\\
c\in C,\ s\in S,\ k\in K,\ p\in P
\end{array} \tag{3.2}
$$

2) Power Demand Constraints

$$\begin{aligned} GH^{E}_{c,s,k,1} + \textstyle\sum_{te\in TE_s} PD^{TE}_{te,k} + \sum_{fr\in FR_s}\left(EE^{fr}_{s,k}\cdot CP^{fr}_{s,k,1}\right) + \sum_{h\in H_s} G^{H}_{c,h,k,1} + \\ \textstyle\sum_{tp\in TP_s}\left(c^{TP}_{tp,k}\cdot FDISP_{tp}\right) + \sum_{r\in R_{s,fr}}\left(c^{R}_{r,k}\cdot \Phi_{r,k}\cdot CP^{fr}_{s,k,1}\right) + \sum_{a\in A_s} G^{A}_{c,a,k,1} + \\ \textstyle\sum_{i\in S}\left(i^{P}_{c,i,s,k} - i^{P}_{c,s,i,k}\right) + d^{P}_{c,s,k} + \geq DE_{s,k,1}\cdot FRP\,, \\ c\in C,\ s\in S,\ k\in K \end{aligned} \tag{3.3}$$

3) Thermal Power Plants Constraints

$$c^{TP}_{tp,k} = 0\,, \qquad tp\in TP,\ k\in\{1..MINExp_{tp}\} \tag{3.4}$$

$$c^{TP}_{tp,k} \geq C^{TP}_{tp,k-1}\,, \qquad tp\in TP,\ k\in\{MINExp_{tp}..K\} \tag{3.5}$$

$$g^{TP}_{c,tp,k,p} \leq c^{TP}_{tp,k}\cdot FDISP_{tp}\,, \qquad c\in C,\ tp\in TP,\ k\in K,\ p\in P \tag{3.6}$$

$$g^{TP}_{c,tp,k,p} \geq c^{TP}_{tp,k}\cdot INFLEX_{k,tp}\,, \qquad c\in C,\ tp\in TP,\ k\in K,\ p\in P \tag{3.7}$$

$$g^{TE}_{c,te,k,p} = 0\,, \qquad c\in C, te\in TE, k\in\{1..MINOp_{te}\}\,, p\in P \tag{3.8}$$

$$g^{TE}_{c,te,k,p} \leq PD^{TE}_{te,k}\,, \qquad c\in C, te\in TE, k\in\{MINOp_{te}..K\}\,, p\in P \tag{3.9}$$

$$g^{TE}_{c,te,k,p} \geq PD^{TE}_{te,k}\cdot INFLEX_{k,te}\,, \qquad c\in C, te\in TE, k\in\{MINOp_{te}..K\}\,, p\in P \tag{3.10}$$

4) Storage Technology Project Constraints

$$c^{A}_{a,k} = 0\,, \qquad a\in A, k\in\{1..MINExp_a\} \tag{3.11}$$

$$c^{A}_{a,k} \geq C^{A}_{a,k-1}\,, \qquad a\in A, k\in\{MINExp_a..K\} \tag{3.12}$$

$$g^{A}_{c,a,k,p} \leq c^{A}_{a,k}\,, \qquad c\in C, a\in A, k\in K, p\in P \tag{3.13}$$

$$b^{A}_{c,a,k,p} \leq c^{A}_{a,k}\,, \qquad c\in C, a\in A, k\in K, p\in P \tag{3.14}$$

$$\sum_{p\in P}\left(g^{A}_{c,a,k,p}\cdot DT_p\right) \leq \Omega^{A}_{a}\cdot\sum_{p\in P}\left(b^{A}_{c,a,k,p}\cdot DT_p\right)\,, \qquad c\in C, a\in A, k\in K \tag{3.15}$$

$$b^{A}_{c,a,k,p} = 0\,, \qquad c\in C, a\in A, k\in K, p\in PnB \tag{3.16}$$

$$g^{A}_{c,a,k,p} = 0\,, \qquad c\in C, a\in A, k\in K, p\in PnG \tag{3.17}$$

5) Renewable Sources Projects Constraints

$$c^{R}_{r,k} = 0\,, \qquad r\in R,\ k\in\{1..MINExp_r\} \tag{3.18}$$

$$c^{R}_{r,k} \geq C^{R}_{r,k-1}\,, \qquad r\in R,\ k\in\{MINExp_r..K\} \tag{3.19}$$

6) Electricity Exchange between Subsystems and Exchange Groups Constraints

$$c^I_{i,j,k} = 0\,, \qquad i,j \in S,\ k \in \{1..MINExpI\} \tag{3.20}$$

$$c^I_{i,j,k} \geq C^I_{i,j,k-1}\,, \qquad i,j \in S,\ k \in \{MINExpI..K\} \tag{3.21}$$

$$c^I_{i,j,k} = C^I_{j,i,k}\,, \qquad i,j \in S,\ k \in \{MINExpI..K\} \tag{3.22}$$

$$i^E_{c,i,j,k,p} \leq L_{i,j,k,p} + c^I_{i,j,k}\,, \qquad c \in C,\ i,j \in S,\ k \in K,\ p \in P \tag{3.23}$$

$$\sum_{i,j \in IJ_{AI}} i^E_{c,i,j,k,p} \leq LA_{ai,k,p} + \sum_{i,j \in IJ_{AI}} c^I_{i,j,k}\,, \qquad c \in C,\ ai \in AI,\ k \in K, p \in P \tag{3.24}$$

$$\sum_{i,j \in IJ_{AI}} i^P_{c,i,j,k} \leq LA_{ai,k,1} + \sum_{i,j \in IJ_{AI}} c^I_{i,j,k}\,, \qquad c \in C,\ ai \in AI,\ k \in K \tag{3.25}$$

$$\sum_{j \in S} i^E_{c,j,i,k,p} - \sum_{j \in S} i^E_{c,i,j,k,p} = 0\,, \qquad c \in C,\ i \in NF,\ k \in K, p \in P \tag{3.26}$$

$$\sum_{j \in S} i^P_{c,j,i,k} - \sum_{j \in S} i^P_{c,i,j,k} = 0\,, \qquad c \in C,\ i \in NF,\ k \in K \tag{3.27}$$

7) Hydropower Plants Constraints

$$\pi^H_{h,k} = 0\,, \qquad h \in H,\ k \in \{1..MINExp_h\} \tag{3.28}$$

$$\sum_{k=MINExp_h}^{K} \pi^H_{h,k} \leq 1\,, \qquad h \in H \tag{3.29}$$

$$\sum_{p \in P} \left(g^H_{c,h,k,p} \cdot DT_p \right) \leq \sum_{k'=1}^{k} \left(\pi^H_{h,k'} \cdot SG^H_{c,h,k} \right)\,, \qquad c \in C,\ h \in H,\ k \in K \tag{3.30}$$

$$m^H_{h,k'} \leq \frac{1}{NM_h}\,, \qquad h \in H,\ k \in K \tag{3.31}$$

$$\sum_{k'=1}^{k} m^H_{h,k'} \leq \sum_{k'=1}^{k} \pi^H_{h,k'}\,, \qquad h \in H,\ k \in K \tag{3.32}$$

$$g^H_{c,h,k,p} \leq PD^H_{c,h,k} \cdot \sum_{k'=1}^{k} m^H_{h,k}\,, \qquad c \in C,\ h \in H,\ k \in K,\ p \in P \tag{3.33}$$

$$g^H_{c,h,k,p} + ghp^H_{c,h,k,p} \geq GM^H_h \cdot \sum_{k'=1}^{k} m^H_{h,k'}\,, \qquad c \in C,\ h \in H,\ k \in K,\ p \in P \tag{3.34}$$

$$\sum_{p \in P} \left(g^E_{c,s,k,p} \cdot DT_p \right) \leq SG^E_{c,s,k}\,, \qquad c \in C,\ s \in S,\ k \in K \tag{3.35}$$

$$g^E_{c,s,k,p} \leq PD^E_{c,s,k}\,, \qquad c \in C,\ s \in S,\ k \in K,\ p \in P \tag{3.36}$$

$$g^E_{c,s,k,p} + ghp^E_{c,s,k,p} \geq GM^E_s\,, \qquad c \in C,\ s \in S,\ k \in K,\ p \in P \tag{3.37}$$

8) Additional Constraints

$$\boldsymbol{c^X_{x,k} - c^X_{x,k-12} = step_{rs}\,, \qquad rs \in RS, k \in \left\{MT_{rs}/Y^i_{rs}, .., MT_{rs}/Y^f_{rs}\right\}, x \in \{R, TP\}} \tag{3.38}$$

$$\boldsymbol{STEP^{min}_{rs} \geq step_{rs} \geq STEP^{max}_{rs}\,, \qquad rs \in RS} \tag{3.39}$$

$$\boldsymbol{c^X_{x,k} \leq LIM_{ra,k}\,, \qquad ra \in RA, k \in \left\{1/Y^i_{ra}, .., 12/Y^f_{ra}\right\}, x \in \{R, TP, A\}} \tag{3.40}$$

$$\boldsymbol{c^X_{x,k} - c^X_{x,k-12} \leq LIM_{rl,k}\,, \qquad rl \in RL, k \in \left\{1/Y^i_{rl}, .., 12/Y^f_{rl}\right\}, x \in \{R, TP, A\}} \tag{3.41}$$

$$\boldsymbol{c^X_{x,MT_{ri}/Y_{ri}} = LIM_{ri}\,, \qquad ri \in RI, x \in \{R, TP, A\}} \tag{3.42}$$

$$\boldsymbol{\pi^H_{h,MT_{ri}/Y_{ri}} = 1\,, \qquad ri \in RI^H} \tag{3.43}$$

$$\boldsymbol{\sum_{k=1}^{MT_{rm}/Y_{rm}} \pi^H_{h,k} = 1\,, \qquad rm \in RM} \tag{3.44}$$

$$\boldsymbol{c^X_{x1,k} = RAT_{rp,k} \cdot c^X_{x2,k}\,, \qquad rp \in RP, k \in \left\{1/Y^i_{ra}, .., 12/Y^f_{ra}\right\}, x \in \{R, TP\}} \tag{3.45}$$

3.3 Objective Function and Constraints - ϵ-Constraint Method

3.3.1 Objective Function

Similarly to the previous method, in the case of the ϵ-Constraint, the objective function consists of the operation economic costs summed with the investment economic costs and the other costs involved. However, no environmental aspects are considered. In resume, the objective function is presented in Figure 3.4.

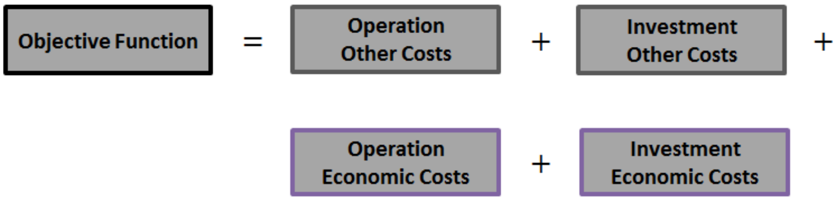

Figure 3.4: Proposed Objective Function - ϵ-Constraint Method. Source: The author.

Therefore, the model's objective function refers to the original formulation of the expansion problem, which relies in its economic nature. In other words, the reason for this option considers the economic perspective that guides the official generation expansion planning in Brazil of attending the estimated energy demand increase in the future with the least costly investment schedule.

The parts related to emissions and water consumption were turned into constraints in which these impacts are not included in terms of external costs, but in terms of their original measuring units, as previously explained. In this sense, the adopted procedure to calculate their limiting values is described in the next subsection (3.3.2).

3.3.2 Constraints

The formulation used in the ϵ-Constraint Method involves the exact same constraints applied to the Weighted Sum Method besides the environmental objectives turned into constraints. In this sense, all equations introduced in the constraint part of section 3.2.3 are included with the only existing difference being these two mentioned equations.

In order to calculate their limiting values, the following procedure was conducted. The maximum values for GHG emissions and water consumption are reached when the model has no environmental aspects considered. Since there is no motivation or restriction for the model to reduce environmental impacts, the decision will be solemnly based on economic cost minimization. As the environmental and economic objectives compete with each other, minimizing exclusively the costs incurs in elevated levels of GHG emissions and water consumption. Therefore, the first step was to execute the model with no environmental objectives in order to determine their maximum limits.

Similarly, the minimum limiting values are reached for each environmental objective when they are defined in the formulation with no other objectives. In view of this, the following steps were to execute the model one time only considering the minimization of GHG emissions as the adopted objective and one time considering only the minimization of water consumption. For both executions, the model had no economic restriction and the total expansion cost got as expensive as it was necessary to avoid the emission of GHG or to save water while still respecting the existing technical constraints that were maintained in the formulation.

Regarding the bounding values, they differ according to the number of applied hydrological series. The original model uses ten different hydrological series that contemplate possible hydropower affluent energy in the reservoirs. However, the higher the number of series the longer it lasts for the model to end the execution. Since the ϵ-Constraint is an iterative method that consists of reexecuting the model multiple times altering the restraining limits, the number of hydrological series directly affects the method's feasibility. Thus, bounding values were reached for the case of one, two and five series applied, so that the respective ones could be used depending on the adopted number.

Finally, after these model executions all required maximum and minimum values were defined, allowing the application of the $\boldsymbol{\epsilon}$-Constraint Method by setting the objective function as the minimization of the operation and investment economic costs and by including the two new constraints referring to both chosen environmental aspects.

In resume, the new included limiting constraints are defined as shown in Figure 3.5 and Figure 3.6:

1) GHG Emissions in Operation and Investment Constraint

Figure 3.5: GHG Emissions Constraints - $\boldsymbol{\epsilon}$-Constraint Method. Source: The author.

2) Water Consumption in Operation and Investment Constraint

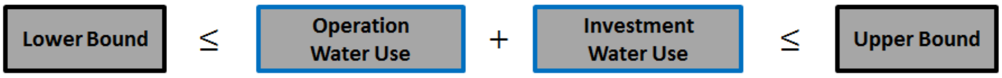

Figure 3.6: Water Consumption Constraints - $\boldsymbol{\epsilon}$-Constraint Method.
Source: The author.

In the actual formulation, Figure 3.5 and Figure 3.6 are translated in terms of $\boldsymbol{\epsilon}_{\boldsymbol{\xi}}$ for each model execution, in which $\boldsymbol{\epsilon}_{\boldsymbol{\xi}_{em}}$ stands for the limiting parameter related to the emissions bound and $\boldsymbol{\epsilon}_{\boldsymbol{\xi}_{wu}}$ stands for the limiting parameter related to the water consumption bound, as both constraints require distinct values. In the $\boldsymbol{\epsilon}$-Constraint Method, each bound vary within its minimum and maximum value, as shown in Algorithm 1, which returns the Optimal Pareto front $\boldsymbol{P}$.

The provided solutions from all the model executions are used to compose the Optimal Pareto front, after discarding the dominated solutions. Next section presents the mathematical representation of the adopted $\boldsymbol{\epsilon}$-Constraint formulation of the problem.

Algorithm 1: ϵ-Constraint Method

```
$P \leftarrow \emptyset$ ;
$\epsilon_{\xi_{max_{em}}} \leftarrow$ upper bound emissions ;
$\epsilon_{\xi_{max_{wu}}} \leftarrow$ upper bound water consumption ;
$\epsilon_{\xi_{min_{em}}} \leftarrow$ lower bound emissions ;
$\epsilon_{\xi_{min_{wu}}} \leftarrow$ lower bound water consumption ;
$\delta_{em} \leftarrow$ defined decreasing value for emissions;
$\delta_{wu} \leftarrow$ defined decreasing value for water consumption;
$\epsilon_{\xi_{em}} \leftarrow \epsilon_{\xi_{max_{em}}}$ ;
$\epsilon_{\xi_{wu}} \leftarrow \epsilon_{\xi_{max_{wu}}}$ ;
while $\epsilon_{\xi_{em}} \geq \epsilon_{\xi_{min_{em}}}$ do
    while $\epsilon_{\xi_{wu}} \geq \epsilon_{\xi_{min_{wu}}}$ do
        $Model(\epsilon_{\xi_{em}}, \epsilon_{\xi_{wu}})$;
        $Update(P)$;
        $\epsilon_{\xi_{wu}} \leftarrow \epsilon_{\xi_{wu}} - \delta_{wu}$;
    $\epsilon_{\xi_{wu}} \leftarrow \epsilon_{\xi_{max_{wu}}}$ ;
    $\epsilon_{\xi_{em}} \leftarrow \epsilon_{\xi_{em}} - \delta_{em}$;
Discard dominated solutions$(P)$ ;
return $P$ ;
```

3.3.3 Mathematical Formulation

Apart from the constraints introduced in Section 3.2.3, the new objective function and added constraints, which use the extra parameters from Table 3.4, are presented next.

Table 3.4: Extra Parameters for ϵ-Constraint Method.

Item	**Description**	**Item**	**Description**
EMFOP^{TP}_{tp}	Emission factor for operating invested thermal power project tp [tCO_{2eq}/MWh]	EMFOP^{TE}_{te}	Emission factor for operating existing thermal power plant te [tCO_{2eq}/MWh]
$\mathrm{EMFEXP}^{TP}_{tp}$	Emission factor for investing in thermal power project tp's capacity [tCO_{2eq}/month/MW]	EMFEXP^{H}_{h}	Emission factor for investing in hydropower project h [tCO_{2eq}/month]

Continued on next page

Table 3.4 – continued from previous page

Item	**Description**	**Item**	**Description**
EMFEXP_{r}^{R}	Emission factor for investing in renewable project r's capacity [tCO_{2eq}/month/MW]	EMFEXP_{a}^{A}	Emission factor for investing in storage project a's capacity [tCO_{2eq}/month/MW]
WUFOP_{tp}^{TP}	Water consumption factor for operating invested thermal power project tp [L/MWh]	WUFOP_{te}^{TE}	Water consumption factor for operating existing thermal power plant te [L/MWh]
WUFEXP_{tp}^{TP}	Water consumption factor for investing in thermal power project tp's capacity [L/month/MW]	WUFEXP_{h}^{H}	Water consumption factor for investing in hydropower project h [L/month]
WUFEXP_{r}^{R}	Water consumption factor for investing in renewable project r's capacity [L/month/MW]	WUFEXP_{a}^{A}	Water consumption factor for investing in storage project a's capacity [L/month/MW]

Objective function:

$$\textbf{Minimize} \sum_{\mathbf{k} \in \mathbf{K}} \frac{\mathbf{1}}{\mathbf{DISC^k}} \left[\begin{array}{r} \sum_{c\in C} \sum_{p\in P} HP \cdot\ PROB_c \cdot\ DT_p \cdot\ \Bigl(\sum_{s\in S} \bigl(d_{c,s,k,p}^{E} \cdot CD_{p}^{E}\bigr) + \\ \sum_{a\in A} \bigl(b_{c,a,k,p}^{A} \cdot CB\bigr)\Bigr) + \sum_{c\in C} \sum_{i\in S} \sum_{j\in S} CI \cdot PROB_c \cdot \\ \Bigl(\sum_{p\in P} \bigl(i_{c,i,j,k,p}^{E}\bigr) + i_{c,i,j,k}^{P}\Bigr) + \sum_{c\in C} \sum_{p\in P} PGH \cdot PROB_c \cdot \\ \Bigl(\sum_{s\in S} ghp_{c,s,k,p}^{E} + \sum_{h\in H} ghp_{c,h,k,p}^{H}\Bigr) + \sum_{c\in C} \sum_{s\in S} CD^{P} \cdot d_{c,s,k}^{P} + \\ \sum_{i\in S} \sum_{j=i}^{S} FC_{i,j}^{I} \cdot c_{i,j,k}^{I} + \\ \sum_{c\in C} \sum_{p\in P} HP \cdot PROB_c \cdot DT_p \cdot \Bigl(\sum_{te\in TE} \bigl(g_{c,te,k,p}^{TE} \cdot \\ VC_{te,k}\bigr) + \sum_{tp\in TP} \bigl(g_{c,tp,k,p}^{TP} \cdot VC_{tp,k}\bigr)\Bigr) + \sum_{h\in H} FC_{h}^{H} \cdot \sum_{k'=1}^{k} \pi_{h,k'}^{H} + \\ \sum_{r\in R} FC_{r}^{R} \cdot c_{r,k}^{R} + \sum_{tp\in TP} FC_{tp}^{TP} \cdot c_{tp,k}^{TP} + \sum_{a\in A} FC_{a}^{A} \cdot c_{a,k}^{A} \end{array} \right] \tag{3.46}$$

Subject to:

1) GHG Emissions in Operation and Investment Constraint

$$\begin{array}{r} \sum_{k\in K} \Bigl[\sum_{c\in C} \sum_{p\in P} HP \cdot PROB_c \cdot DT_p \cdot \\ \Bigl(\sum_{te\in TE} \bigl(g_{c,te,k,p}^{TE} \cdot EMFOP_{te}^{TE}\bigr) + \\ \sum_{tp\in TP} \bigl(g_{c,tp,k,p}^{TP} \cdot EMFOP_{tp}^{TP}\bigr)\Bigr) + \\ \sum_{h\in H} EMFEXP_{h}^{H} \cdot \sum_{k'=1}^{k} \pi_{h,k'}^{H} + \\ \sum_{r\in R} EMFEXP_{r}^{R} \cdot c_{r,k}^{R} + \sum_{tp\in TP} EMFEXP_{tp}^{TP} \cdot c_{tp,k}^{TP} + \\ \sum_{a\in A} EMFEXP_{a}^{A} \cdot c_{a,k}^{A}\Bigr] \leq \epsilon_{\xi_{em}} \end{array} \tag{3.47}$$

2) Water Consumption in Operation and Investment Constraint

$$\begin{aligned}\boldsymbol{\textstyle\sum_{k\in K}\Big[\sum_{c\in C}\sum_{p\in P} HP\cdot PROB_c\cdot DT_p\cdot}\\ \boldsymbol{\Big(\textstyle\sum_{te\in TE}\Big(g^{TE}_{c,te,k,p}\cdot WUFOP^{TE}_{te}\Big)+}\\ \boldsymbol{\textstyle\sum_{tp\in TP}\Big(g^{TP}_{c,tp,k,p}\cdot WUFOP^{TP}_{tp}\Big)\Big)+}\\ \boldsymbol{\textstyle\sum_{h\in H} WUFEXP^{H}_{h}\cdot\sum_{k'=1}^{k}\pi^{H}_{h,k'}+}\\ \boldsymbol{\textstyle\sum_{r\in R} WUFEXP^{R}_{r}\cdot c^{R}_{r,k}+}\\ \boldsymbol{\textstyle\sum_{tp\in TP} WUFEXP^{TP}_{tp}\cdot c^{TP}_{tp,k}+}\\ \boldsymbol{\textstyle\sum_{a\in A} WUFEXP^{A}_{a}\cdot c^{A}_{a,k}\Big]\le\epsilon_{\xi_{wu}}}\end{aligned}\tag{3.48}$$

Chapter 4

Computational Experiments

Based on the mathematical formulations proposed in the previous chapter, here it is introduced the input data, the created instances and their corresponding results. All the data acquisition and processing is described, highlighting the new information not included in the original model, which guides it towards a power generation investment schedule solution with lower GHG emissions and water consumption.

4.1 Data Acquisition and Processing

According to section 3.1, this dissertation focus in GHG emissions and water consumption from all the existing environmental impacts concerning power generation. In order to implement these aspects in quantitative values, the concepts of carbon footprint and water footprint were applied, which refer to life cycle considerations ([85]).

Some power generation technologies are emissions-free or have a null water consumption along their processes, hence being considered environmental-friendly. However, they might have higher resources depletion and emissions when considering their whole life cycle, from material extraction until decommissioning and end-of-use disposal. A more sustainable solution involves an overall reduction in the environmental impacts, thus it is important to analyze other aspects rather than the electricity generation itself for a comprehensive approach.

Therefore, the carbon footprint values for each source used in this work account for direct and indirect emissions related to the construction and operation of the power plants ([85]). Similarly, water footprint measures consider the virtual rainwater that evaporated during the production process - green water footprint -, and the consumed surface and groundwater - blue water footprint - ([47]). There is also the volume of wastewater generated during the plant construction and operation phases - grey water footprint - ([47]), but this one was not considered in this work analysis.

Total water footprint varies depending on the power source. Biomass production requires the daily irrigation volume for the crops to grow while solar panels need constant cleaning since dust and other small particles prevent the photovoltaic effect from happening. Thermoelectric power plants may use large volumes of water for cooling depending on the technology and hydropower reservoirs have their considerable losses due to evaporation. In this sense, in terms of power expansion planning, every generation option has a different relationship with water availability and scarcity that is relevant to address in optimization models.

Water footprint is a broad concept and calculation methodologies deal with regional complexities related to the resource. Some important works have been conducted over this matter. Among them, there is AWARE-LCA ([11]), a framework providing indicators for water use impact assessment focusing on scarcity. In resume, it quantifies remaining available water per area once the demand of humans and aquatic ecosystems has been met and then verifying potential water scarcity according to original demand when another use arises ([11]). The provided global indicators resulted from years of study and represent a robust assessment based on life cycle analysis.

However, since this dissertation aims to discuss environmental trade-offs between power generation sources, applied water footprint factors derive from specific papers over this topic. Therefore, by using values found in the literature, the environmental factors and costs - GHG emissions and water consumption - for each source were properly calculated separated between operation and expansion.

Besides the added environmental information, the other necessary data comes from the original MDI-Patamares input spreadsheet from PDE ([91]). This spreadsheet is available for download at PDE's website ([37]) with the other model files, more precisely in the section related to the third chapter. The next subsections present the performed calculations for the distinct groups of power generation sources.

4.1.1 Thermal Power Source

Thermal power plants are represented in terms of capacity investment and energy production. Both are decision variables which differentiate thermal expansion from thermal operation, respectively. In other words, investing in thermal capacity does not necessarily imply in proportional thermal generation increase because these are distinct decisions for the model, with different conditions, prices and, consequently, environmental impacts.

That is to say that activating thermal power plants for electricity generation incurs in direct emissions from fossil fuels and water consumption for cooling and cleaning purposes, whilst investing in power capacity expansion is related to indirect emissions and virtual water consumption from the materials extraction and construction of the power plants. Therefore, the model incorporates separate environmental costs for operation and expansion concerning all the possible thermal power sources - fossil fuels and biomass.

Regarding the direct GHG emissions from thermal power operation, the implemented factors were presented in Table 2.2. As previously mentioned, the volume of emissions per unit of electrical energy generated for each fossil fuel are adapted from [100]. Yet, biomass emission factor comes from [3], which states that carbon footprint for electricity from biomass is normally lower than that of the least carbon intensive thermal fossil source, but not null.

Biomass emission factor values may vary between extensive ranges because it depends on feedstock and main purpose. For this dissertation, it is assumed that existing thermal power plants fueled by biomass in Brazil are actually a way of harnessing energy from other activities' waste as electricity generation is not the main objective of crop production. Considering this premise and the fact that bioelectricity in Brazil comes from different feedstocks, the representative emission factor adopted in this work was **75.00** gCO$_{\boldsymbol{2eq}}$/kWh ([3]).

Subsequent to collecting all required emission factors in a common unit, the next step was to transform them into environmental costs in order to add them in the objective function. The assumed externality value was US\$15.00/tCO$_{\boldsymbol{2eq}}$, the same adopted in [100], which represents a more conservative scenario than applying higher carbon prices. The used currency conversion rate from US dollars to Brazilian reais was the calculated mean between each daily value extracted from the Brazilian Central Bank for the January-February period 2020 - R$**4.24**/US$.

By having all the emission factors multiplied by the externality value and the conversion rate, the environmental costs for the operation of thermal plants are achieved. These costs are presented in Table 4.1. New plants with more efficient technologies present smaller values, but the ones presented in Table 4.1 are valid for the purposes of this dissertation of testing the proposed methodology and to investigate whether and how they are capable of altering the power generation expansion investment schedule.

Table 4.1: Emission Costs for Thermal Generation. Source: the author, based on [3, 100].

Unit	**Coal**	**Fuel Oil**	**Natural Gas**	**Diesel**	**Biomass**
tCO_{2eq}/MWh	1.21	1.01	0.57	0.72	0.08
R$/MWh	76.79	64.16	36.24	45.97	4.76

In relation to water consumption, the consumed volumes were also separated between operation and investment (expansion). For the operation of thermal power plants, the adopted volume per unit of produced electricity was the average value stated in [74], which defines 485 m^3/TJ_e for coal and oil, hence also adopted for diesel and fuel oil, and 267 m^3/TJ_e for natural gas. For biomass plants the considered factor was the same as for coal and oil because it was assumed that the water volume used for plant's cooling and cleaning would fluctuate in a proximate range.

Still, the actual values are highly dependent on the implemented generation technology. For instance, a thermal power plant with a wet cooling tower consumes more water than one with a dry cooling tower due to evaporation. On the contrary, when once-through cooling is applied, the related water consumption is low. Water consumption, however, is not the same as water use, which means that a plant may be a not intense consumer, but use a relevant total amount of water.

Once more, it was necessary to transform the water volumes into use costs in order to also add them in the objective function. However, finding a common externality value for water footprint is not trivial since environmental valuation of water resources depends mostly on each nation's water availability, access and hydrological conditions. In the Brazilian case the value variability would even be regional due to its large territorial extension with different climate types.

In [4], the consumption of water in the energy supply expansion in Brazil is analyzed, establishing the deep relationship between electricity generation and water consumption in the Brazilian power sector. In this sense, [4] discusses the inclusion of a water cost and uses the value of US$1500/1000 m^3 for all the existing regions, which results from a review over the topic and considers energetic and non-energetic consumptive users. Therefore, this value was also adopted in this work and multiplied by the water consumption factors and the currency conversion rate. Table 4.2 presents these factors and final consumption costs included in the model. Again, although the presented values may differ substantially according to the considered technology, they are still valid for the purposes of this dissertation.

Table 4.2: Water Consumption Costs for Thermal Generation. Source: the author, based on [4, 74].

Unit	**Coal**	**Fuel Oil**	**Natural Gas**	**Diesel**	**Biomass**
L/MWh	1745.99	1745.99	961.19	1745.99	1745.99
R$/MWh	11.09	11.09	6.11	11.09	11.09

Regarding power generation expansion, the GHG emissions and water consumption may refer to materials' extraction, transportation and plants' construction. In terms of emissions, [116] states that construction, decommissioning and waste disposal of coal-fired plants have negligible emissions, but the ones relating to coal mining and transportation lie between 50 and 300gCO$_{\boldsymbol{2eq}}$/kWh. Regarding natural gas-fired plants, upstream and downstream GHG emissions range between 60 and 130gCO$_{\boldsymbol{2eq}}$/kWh ([116]).

The only existing investment options concerning thermal power capacity in the version of MDI-Patamares applied for PDE 2029 ([91]) are coal, natural gas and wood chip because other bioenergy sources are considered renewable projects ([37]). Although wood chip is not a fossil fuel, this dissertation adopted a premise of its emissions factor for expansion being similar to the minimum values presented above. Therefore, considering that total emissions from thermal generation are mostly due to the operation of power plants, the included value for investing in any of the options was the same, 60gCO$_{\boldsymbol{2eq}}$/kWh.

Then, it was possible to calculate the costs using the US$15.00/tCO$_{\boldsymbol{2eq}}$ externality price. However, thermal generation capacity is expanded in terms of a fixed cost per unity of installed power of a given project and per month - R$/MW.month -, in which this total amount of power increase for each project is decided for each time period by the solver. Thus, the emission factors were converted into tCO$_{\boldsymbol{2eq}}$/MW.month using **730.5** as the number of hours in a month, as originally established in MDI-Patamares' input spreadsheet. The resulting factors and costs are presented in Table 4.3.

Table 4.3: Emission Costs for Thermal Investment. Source: the author, based on [116].

Unit	**Coal**	**Natural Gas**	**Wood Chip**
tCO$_{\boldsymbol{2eq}}$/MW.month	43.83	43.83	43.83
R$/MW.month	2,784.34	2,784.34	2,784.34

The factors related to water consumption for the investment of thermal power plants were also obtained by [74]. In this case, the considered water footprint relates to fuel supply and construction phases. The minimum and maximum values for coal and natural gas are the sum of their respective minimum and maximum values in both phases, so that the mean could be calculated. The implemented water consumption factors consist in this result.

Since wood chip comes mostly from timber of pre-existing forests and electricity generation was not the original reason for deforestation, its factor should not account for necessary water in growth stage and the selected value was the same as for natural gas.

Total water consumption costs for each thermal source available for expansion in PDE 2029 ([91]) were then obtained by multiplying the defined factors to the water externality price and the currency conversion rate, with results shown in Table 4.4.

Table 4.4: Water Use Consumption for Thermal Investment.
Source: the author, based on [74].

Unit	**Coal**	**Natural Gas**	**Wood Chip**
L/MW.month	931,362.52	49,466.14	49,466.14
R$/MW.month	25,057.00	1,330.82	1,330.82

4.1.2 Hydropower Source

In relation to hydropower plants, their costs are completely related to capacity expansion because their energy generation is considered to be cost-free, with their investment being the only binary decision variables in the model. That is to say that hydroelectrical plants have fixed costs as the decision is based on including or not a certain project into the system rather than determining the optimal amount of power to be invested for every time period.

Given these circumstances, this source's emission and water consumption impacts needed to be specifically calculated in terms of monetary unit for every individual project available for investment during their whole lifetime and then added to their economic costs in order to be correctly addressed.

According [100], GHG emissions concerning hydropower generation comprehends native vegetation removal of reservoir area, avoided carbon sequestration due to the vegetation that no longer exists and methane emissions also from the flooded areas. In this sense, all these emission categories were calculated for each project and summed up to represent each plant's total volume of emissions.

Initially, the mean flooded area per unit of power information for each Brazilian subsystem from Table 2.1 was used to estimate the average total inundated extension of all hydroelectric projects available ([37]), in regard to the specific subsystem they would be located whether invested. The total flooded areas allowed the quantification of the distinct related emissions described above through the factors presented in [100] in terms of biomes, here introduced in Table 4.5.

Table 4.5: Mean Net Emissions for Hydropower Expansion per Brazilian Biome. Source: the author, adapted from [100].

Biome	**Emission Factor (tCO_{2eq}/ha)**	**Avoided Sequestration (tCO_{2eq}/ha.year)**
Amazônia	132.30	0.77
Mata Atlântica	123.60	0.72
Cerrado	56.10	0.33
Pantanal	63.00	0.37
Caatinga	24.90	0.14
Pampa	24.90	0.14

Every Brazilian subsystem encompasses more than one biome, which means that their respective factors should be weighted averages considering the percentage of land occupation by the existing biomes in each subsystem. Although the factors introduced in Table 4.5 may present large deviation when applied to specific regions because each biome is a complex system, they are still representative as average values.

In order to define the subsystems in terms of biomes, information about their total area and every Brazilian macro region territorial extension was obtained from the official Brazilian Institute of Geography and Statistics - *IBGE*.

Based on [53, 54], Table 4.6 presents total area for the Brazilian macro regions, while Table 4.7 contains the total area of each biome and its share from Brazilian total territory. This data allied to a figure that demonstrates the location of the Brazilian biomes, Figure 4.1, enabled the calculation of Table 4.8, which refers to sets of weights for all the Brazilian subsystems as they correlate to the national macro regions division.

Table 4.6: Brazilian Macro Region Territorial Areas. Source: the author, adapted from [53].

Macro Region	**Area (km^2)**
North	3,850,509.94
Northeast	1,552,167.01
Southeast	924,565.48
South	576,736.82
Central-West	1,606,316.67

Table 4.7: Brazilian Biomes Territorial Areas. Source: the author, adapted from [54].

Biome	**Area (km^2)**	**Brazilian Share (%)**
Amazônia	4,196,943.00	49.29
Mata Atlântica	1,110,182.00	13.04
Cerrado	2,036,448.00	23.92
Pantanal	150,355.00	1.76
Caatinga	844,453.00	9.92
Pampa	176,496.00	2.07

Figure 4.1: Brazilian Biomes. Source: [54].

Table 4.8: Brazilian Biomes Share in Each Subsystem. Source: the author.

Biome	**South (%)**	**SE/CW[1](%)**	**Northeast (%)**	**North (%)**
Amazônia	-	24.03	-	93.20
Mata Atlântica	69.40	21.04	11.44	-
Cerrado	-	48.99	34.16	6.80
Pantanal	-	5.94	-	-
Caatinga	-	-	54.40	-
Pampa	30.60	-	-	-

[1] SE/CW stands for Southeast/Central-West, a subsystem uniting both regions.

Next, the GHG factors from Table 4.5 were converted into new ones related to the Brazilian subsystems using the resulted weights in order to be applicable in the case of the hydropower projects available for expansion in the proposed model, according to the available options in PDE ([37]). Table 4.9 presents the actual factors.

Therefore, since all the individual available projects are introduced in [37] with the subsystem they belong to, their total GHG emissions from native vegetation removal as well as total avoided captured carbon were estimated after calculating each respective flooded area with Table 2.1. In the case of carbon sequestration, given that the values also depend on the projects' lifetime, they were multiplied by the total amount of years each one is active during the planning horizon in view of their earliest investment period, another specific characteristic of every individual plant from [37]. The results are shown in Table 4.10.

Table 4.9: Mean Net Emissions for Hydropower Expansion per Brazilian Subsystem. Source: the author, based on [100].

Subsystem	**Emission Factor (tCO_{2eq}/km^2)**	**Avoided Sequestration (tCO_{2eq}/km^2.year)**
Southeast/Central-West	8,902.27	52.02
South	9,339.78	54.25
Northeast	4,684.92	27.13
North	12,711.84	74.01

Nevertheless, GHG emissions from methane emissions from the flooded areas are still missing. In fact, [100] states that there is no consensus in terms of estimating emissions originated from reservoirs, but he opted for considering the median of indicators provided by an official report of the Brazilian government in his work. Since the median value was calculated based on existing hydropower plants in Brazil, it was also applied in this dissertation. Then, it was adopted a methane emissions factor of 105.83 tCO_2/km^2.year, which represents total anaerobic decomposition of reservoirs ([100]).

Similarly to total avoided sequestration of carbon, the methane factor multiplied by the estimated total flooded area and number of active years for every individual project originated the GHG emissions related to the existence of the reservoirs. The resulting values are also in Table 4.10, as well as total overall emissions for each hydropower project available for investment, composed by the sum of all three possible sources and divided by the number of active periods in order to reach a value per month as required by the objective function. A fixed monthly cost is also a strategy that helps preventing the end of the world effect, by which an optimization model tends to place greater emphasis on the final values of the finite period as it understands that the represented system only exists until the last planning moment and no longer than that.

As the last step, since the model's objective function also requires environmental impacts in terms of monetary values, the external costs resulted from the total GHG emissions values for the projects multiplied by US\$15.00/t$CO_{\boldsymbol{2eq}}$ and converted to Brazilian currency. These final values are also in Table 4.10.

In terms of water consumption in hydropower generation, total volumes are directly related to water resources management and climate conditions. Therefore, energy related water footprint studies usually focus in a specific country or region within a country. That is the case of [41], which calculates the water footprint of certain hydropower units of a Brazilian power generation company using LCA. The work considers blue, green and gray footprints standing for consumption in each existing process from extraction, construction and operation of the plants, as well as generated wastewater. It also considers the amounts of water in transportation and in the used electricity.

In fact, reservoirs in Brazil are not only planned for power purposes, but also for many different uses contemplated under each region's necessity. They are fundamental for the nation's overall water management as they regularize major outflows of water bodies, ensuring water availability in dry seasons and preventing major floods in wet seasons. The volumes maintained in the reservoirs are necessary for irrigation and general supply water catchments, as well as for sustaining fishing activities, rivers' navigability and even population amusement, as previously mentioned.

In this sense, calculating water footprint factors for reservoirs of hydropower plants in Brazil is complex as they change form region to region not only due to the different uses, but also due to the different hydrological regimes. Even the process of assigning a monetary value for water consumption represents a simplification because the external costs of using water are higher in catchment basins where it is more sparse and the occurring uses are more likely to be stressed. Besides, the regularization property of reservoirs might even count as a positive externality of hydropower generation, although this benefit not necessarily applies for this case of study as the possible candidate plants for expansion are run-of-river based and their smaller reservoirs do not contribute for regularization.

Therefore, in this dissertation only water consumption related to evaporation in reservoirs during their lifetime operation is considered since plants' construction phase presents very little contribution for overall water footprint. As for thermal power generation, [74] also indicates water footprint factors concerning hydroelectric plants and, specifically for Brazil, it states that blue and green water footprint related to this source's electricity and heat production ranges from 15,000 to 20,000 $m^{\mathbf{3}}$/TJ ([74]).

Table 4.10: GHG Emission Factors and Costs for Each Available Hydropower Project. Source: the author, based on [100].

Project's Name	**Power (MW)**	**Flooded Area ($\mathbf{km^2}$)**	**Emissions ($\mathbf{tCO_{2eq}}$)**	**Avoided Sequestration ($\mathbf{tCO_{2eq}}$)**	**Reservoir Emissions ($\mathbf{tCO_{2eq}}$)**	**Total Emissions ($\mathbf{tCO_{2eq}}$/month)**	**Total Costs (R$/month)**
ALTA FLORESTA	127.80	100.96	898,809.93	5,251.79	10,684.81	914,746.53	58,110,096.40
APERTADOS	139.00	113.98	1,064,519.78	48,952.52	95,494.82	12,725.97	808,428.67
BEM QUERER	650.00	630.50	8,014,815.12	276,083.76	394,794.41	122,333.71	7,771,358.92
BURITI QUEIM	142.00	112.18	998,677.70	17,019.68	34,626.69	30,009.26	1,906,365.21
CASTANHEIRA	140.00	110.60	984,611.82	45,545.63	92,662.98	11,819.16	750,822.93
COMISSARIO	140.00	114.80	1,072,178.19	49,304.70	96,181.83	12,817.52	814,244.71
COUTO MAGALH	150.00	118.50	1,054,941.23	6,164.07	12,540.86	1,073,646.16	68,204,338.50
DAVINOPOLIS	80.00	63.20	562,635.32	26,026.08	52,950.28	6,753.81	429,041.68
ERCILANDIA	87.10	71.42	667,048.00	30,674.57	59,838.84	7,974.33	506,576.53
FORMOSO	342.00	270.18	2,405,266.01	83,153.31	169,176.13	37,430.92	2,377,833.00
FOZ PIQUIRI	93.20	76.42	713,764.34	16,238.67	31,677.81	16,205.97	1,029,499.14
FOZ DO XAXIM	63.20	51.82	484,011.87	8,200.15	15,996.56	14,520.25	922,411.63
ITAGUAÇU	92.00	72.68	647,030.62	14,807.47	30,125.92	14,722.64	935,268.86
ITAPIRANGA	724.60	594.17	5,549,287.98	126,250.42	246,284.79	125,996.24	8,004,024.43
JATOBA	1,650.00	1,600.50	20,345,299.92	463,928.40	663,408.58	456,864.61	29,022,735.84
MARANHAO BAI	125.00	98.75	879,117.69	20,118.84	40,931.96	20,003.58	1,270,745.74
MIRADOR	80.00	63.20	562,635.32	9,588.55	19,508.00	16,906.62	1,074,008.57
P GALEANO	81.00	63.99	569,668.27	13,037.01	26,523.91	12,962.32	823,443.24
PARANA	90.00	71.10	632,964.74	10,787.12	21,946.50	19,019.95	1,208,259.64
PORTEIRAS 2	86.00	67.94	604,832.97	13,841.76	28,161.19	13,762.47	874,273.07
SANTO ANTÔNIO	84.30	69.13	645,604.44	10,937.86	21,337.18	19,367.99	1,230,368.68
SAUDADE	61.40	50.35	470,226.72	7,966.60	15,540.96	14,106.69	896,140.42
TABAJARA	400.00	388.00	4,932,193.92	198,612.80	284,012.44	65,238.79	4,144,352.54
ITAOCARA I	150.00	118.50	1,054,941.23	6,164.07	12,540.86	1,073,646.16	68,204,338.50
TELEM BORBA	118.00	96.76	903,693.05	41,556.82	81,067.54	10,803.34	686,291.97

However, since Brazil is focused in hydropower generation with several plants spread across the national territory in different climate conditions, the adopted water footprints were based in [104], another study that estimates water consumption in the country for existing reservoirs of distinct sizes and regional locations which are solely used for the purpose of hydroelectricity production.

One of the occurring issues in Brazil is that many of its hydropower generation comes from run-of-river plants and, despite the fact that they also have small reservoirs, it is hard to compare them with large ones. In fact, according to [91], projects available for investment are mostly run-of-river type due to social and environmental restrictions. In that case, using the data stated in [104], proportional water consumption factors were calculated and applied for the projects concerning their power capacity. Then, Table 4.11 present the relevant used information from [104].

Table 4.11: Water Footprint of Some Brazilian Hydropower Plants. Source: the author, adapted from [104].

Plant's Name	**Reservoir Area (km^2)**	**Installed Capacity (MW)**	**Water Consumption (m^3/MWh)**
Água Vermelha	673.63	1,396.20	87.01
Itaipu	1,049.56	7,000.00	23.96
Porto Primavera	2,976.98	1,540.00	305.60
Emborcação	485.08	1,192.00	67.19
Balbina	4,437.72	250.00	2,613.79
Barra dos Coqueiros	25.30	90.00	51.60
Castro Alves	6.21	130.00	6.46
Ilha dos Pombos	3.71	187.00	3.33
Sobradinho	4,380.79	1,050.30	854.82
Xingó	58.94	3,162.00	3.81

In addition, Table 4.12 introduces the estimated proportional values. Given that there is a higher number of available projects with installed capacities lower or equal than 150 MW, their water consumption factors were assigned within defined ranges. Yet, the few projects with installed capacities higher than 150 MW had proportional estimations directly assigned to them based on the calculated water footprints for the small capacity plants instead of values from Table 4.11 in order to avoid overdimensioning. Also, the ones with a less than 100 MW difference between them received the same values.

Table 4.12: Estimated Water Footprint for Available Hydropower Projects . Source: the author, based on [104].

Installed Capacity (MW)	**Water Footprint (L/MWh)**
61 - 91	3,330.00
92 - 120	4,895.00
121 - 150	6,460.00
342	17,226.67
400	17,226.67
650	31,223.33
725	31,223.33
1650	71,060.00

After defining the amount of water consumed by each hydropower project per unit of electrical energy produced, it was necessary to convert the factors into monetary costs per month period due to the model's time discretization. In order to do that, first the water footprints were transformed into L/MWmonth using the number of hours in a month used in PDE [37]. After, every individual project's mean monthly generation over the whole time horizon, also from [37], was multiplied by this converted factor, resulting in water consumption values in L/month.

Finally, the monthly water footprint factors were then changed into external costs using the same water externality price applied in the previous section: US\$1500/1000 m^3 [4], properly converted into Brazilian currency per litre. Table 4.13 presents all this information, including the name and power capacity of each available project for expansion according to PDE [37], the calculated estimates for flooded area and the final results inserted into the model's objective function formulation.

Table 4.13: Water Consumption Factors and Costs for Each Available Hydropower Project. Source: the author, based on [4, 104].

Project's Name	**Power (MW)**	**Flooded Area (km^2)**	**Water Consumption (L/MWmonth)**	**Mean Monthly Generation (MWmonth/month)**	**Final Water Consumption (L/month)**	**Total Costs (R$/month)**
ALTA FLORESTA	127.80	100.96	4,719,030.00	58.48	275,990,077.26	1,753,251.80
APERTADOS	139.00	113.98	4,719,030.00	81.39	384,104,915.23	2,440,061.04
BEM QUERER	650.00	630.50	22,808,645.00	336.28	7,670,032,693.45	48,724,572.99
BURITI QUEIM	142.00	112.18	4,719,030.00	85.10	401,592,988.63	2,551,155.60
CASTANHEIRA	140.00	110.60	4,719,030.00	97.80	461,519,630.17	2,931,844.99
COMISSARIO	140.00	114.80	4,719,030.00	75.45	356,032,570.95	2,261,728.95
COUTO MAGALH	150.00	118.50	4,719,030.00	108.29	511,038,298.12	3,246,416.78
DAVINOPOLIS	80.00	63.20	2,432,565.00	43.95	106,908,281.14	679,144.48
ERCILANDIA	87.10	71.42	2,432,565.00	54.33	132,160,839.76	839,563.63
FORMOSO	342.00	270.18	12,584,080.00	166.18	2,091,185,002.01	13,284,440.93
FOZ PIQUIRI	93.20	76.42	3,575,797.50	59.62	213,193,745.70	1,354,332.46
FOZ DO XAXIM	63.20	51.82	2,432,565.00	34.51	83,947,945.78	533,286.88
ITAGUAÇU	92.00	72.68	3,575,797.50	64.23	229,658,027.97	1,458,923.29
ITAPIRANGA	724.60	594.17	22,808,645.00	374.39	8,539,398,277.03	54,247,296.10
JATOBA	1,650.00	1,600.50	51,909,330.00	982.40	50,995,627,540.78	323,954,313.56
MARANHAO BAI	125.00	98.75	4,719,030.00	72.47	341,973,324.36	2,172,416.32
MIRADOR	80.00	63.20	2,432,565.00	58.73	142,855,095.61	907,499.85
P GALEANO	81.00	63.99	2,432,565.00	56.16	136,609,956.10	867,827.04
PARANA	90.00	71.10	2,432,565.00	45.73	111,245,422.53	706,696.56
PORTEIRAS 2	86.00	67.94	2,432,565.00	52.15	126,847,427.07	805,809.70
SANTO ANTÔNIO	84.30	69.13	2,432,565.00	45.89	111,623,774.61	709,100.07
SAUDADE	61.40	50.35	2,432,565.00	36.55	88,921,124.09	564,879.44
TABAJARA	400.00	388.00	12,584,080.00	244.34	3,074,779,843.30	19,532,815.68
ITAOCARA I	150.00	118.50	4,719,030.00	93.00	438,875,692.76	2,787,997.34
TELEM BORBA	118.00	96.76	3,575,797.50	78.91	282,168,012.77	1,792,497.70

4.1.3 Renewable and Storage Power Sources

Optimization models created for solving the GEP problem often do not include any sort of environmental impact for renewable sources. Indeed, electricity generation from renewables have zero or little direct GHG emissions. However, through a life cycle perspective, they have GHG emissions related to their materials extraction, transportation and construction phases. The same is applicable for water consumption, but, in that case, some sources might even require freshwater during their operational processes. Therefore, for the purpose of this work, carbon and water footprints were considered for these generation options in order to give a proper signal over their benefits, even though some of the values are considerably insignificant when compared to conventional sources of power.

The renewable sources available for expansion in MDI-Patamres are biomass, biogas, solar photovoltaics, wind onshore wind offshore and small hydro. Most of their respective carbon footprints were obtained from [3], which reviewed several publications related to LCA of renewable electricity and heat generation in order to estimate mean factors for these sources in terms of total GHG emissions throughout life cycle per unit of generated energy.

According to [3], offshore wind has the lowest mean life cycle GHG emissions factor, which is 13.00 ± 5.20 gCO_{2eq}/kW, followed by onshore wind with a mean value of 34.20 gCO_{2eq}/kWh. Solar PV, in contrast, presents an average estimate of 91.10 gCO_{2eq}/kWh when adopting c-Si systems as the considered technology ([3]). Small hydro plants as run-of-river schemes were assigned a mean value of 45.90 gCO_{2eq}/kWh ([3]). For biomass, it was used the same value of 75.00 gCO_{2eq}/kWh as in for the generation of biomass-fueled existing power plants (Section 4.1.1).

However, [3] does not specify an emissions factor for power generation plants runinng on biogas. This source is only considered in a broader group of waste treatment technologies. Therefore, the adopted value was obtained after some calculations based on data from [10] for large scale biogas systems. Regarding the most recent biogas panorama in Brazil, [23] affirms that 80.00% of existing small local scale plants for energetic purposes generate biogas from agriculture and cattle raising, while 12.00% refers to industry and 8.00% to municipal organic waste and domestic wastewater - sewage.

By adopting a premise that biogas plants connected to SIN will run mainly on crops, sewage and municipal organic waste, a mean value between CO_2 and CH_4 emissions per energy unit was estimated by converting both into CO_{2eq}, which defines the incorporated biogas carbon footprint as approximately 14.99 gCO_{2eq}/MJ. Table 4.14

presents all the final GHG emission factors for renewable sources, properly converted to MWh.

Table 4.14: Estimated GHG Emission Factors for Available Renewable Sources.
Source: the author, adapted from [3, 10].

Source	**Emission Factor ($\mathbf{tCO_{2eq}/MWh}$)**
Offshore wind	0.02
Onshore Wind	0.03
Solar PV	0.09
Small Hydro	0.05
Biomass	0.08
Biogas	0.05

Rewewables in MDI-Patamares are invested in terms of projects' capacity increase. All the different sources are divided into specific expansion options which determine their subsystem location and distinguishing characteristics. For instance, some sources may have cost discounts under certain conditions related to government energy policies or industry stimulation. Then, in this case, there might be more than one project related to the same source: one with the normal cost and one with the discount.

All these projects are distinct investment options represented as continuous variables and the model will increase their capacity in order to reach the optimal solution. Therefore, each available project is described in [37] with its monthly cost per unit of invested power and its monthly capacity factor. After converting the emission factors from Table 4.14 to MWmonth, the mean capacity factor was calculated for every individual renewable option and the multiplication of both values resulted in the projects' estimations of total emissions per unit of power per month.

Once more, the calculated emission factors were transformed into external costs using the defined externality price US\$15.00/$tCO_{\boldsymbol{2eq}}$ and the currency conversion value to Brazilian Reais in order to be incorporated in the model's objective function. Table 4.15 presents the final values for every individual renewable project capable of receive investments. The presented capacity factor values are the ones adopted by PDE [37].

The factors related to water consumption in the life cycle of electricity generation from renewables were calculated following the same steps. Some of the values comes from [74], the same used for thermal power generation. In this case, for each individual source, a mean value between the maximum and the minimum water footprint factors was adopted, resulting in 154.70 m^3/TJe for solar photovoltaics and 6.10 m^3/TJe for onshore and offshore wind.

Table 4.15: Total GHG Emission Factors and Costs for Each Available Renewable Project. Source: the author, based on [3, 10].

Project's Name	**Emissions (tCO_2/MWmonth)**	**Mean Capacity Factor**	**Emissions (tCO_2/MW.month)**	**Total Costs (R$/MW.month)**
Biomass	54.79	0.29	15.80	1,003.48
Solar Northeast	66.55	0.25	16.57	1,052.49
Solar Southeast	66.55	0.25	16.61	1,055.13
Solar Northeast Discounted	66.55	0.25	16.57	1,052.49
Solar Southeast Discounted	66.55	0.25	16.61	1,055.13
Onshore Wind South	24.98	0.38	9.60	609.73
Onshore Wind Northeast	24.98	0.47	11.85	752.81
Small Hydro 1 Southeast	33.53	0.45	15.16	963.25
Small Hydro 2 Southeast	33.53	0.45	15.16	963.25
Small Hydro 3 Southeast	33.53	0.45	15.16	963.25
Small Hydro 1 South	33.53	0.54	17.96	1,140.75
Small Hydro 2 South	33.53	0.54	17.96	1,140.75
Small Hydro 3 South	33.53	0.54	17.96	1,140.75
Biogas	39.10	0.80	31.28	1,987.29
Offshore Wind Southeast	13.30	0.47	6.27	398.33
Offshore Wind South	13.30	0.53	7.08	449.79
Offshore Wind Northeast	13.30	0.62	8.18	519.59
Offshore Wind North	13.30	0.32	4.27	271.44

However, the remaining renewable sources are more likely to have water related impacts depending on the investment location. As previously mentioned, due to Brazilian hydrological cycles and other water uses, water footprints concerning small hydro, biomass and biogas plants are directly related to the nation's particularities.

In view of this, the considered factor for small hydro plants is proportional to the ones applied for hydropower generation, contemplating their smaller potency. Actually, in Brazil, small hydroelectrical plants' installed capacity must be less or equal to 30 megawatts (MW) ([91], which led the estimated value to be approximately 1,637.70 L/MWh, based on Table 4.12.

Biomass water consumption, for instance, depends on certain conditions such as climate and crop type. General values range significantly due to this reason and it is prudent to seek factors related to the studied area. Therefore, this work considers that electricity generation from biomass in Brazil comes mostly from sugarcane bagasse and it was adopted an estimation of this crop's water footprint specifically for Brazil published in a quantitative assessment ([47]): 25.00 m^3/GJe.

Regarding biogas plants, it is difficult to account for the water footprint related to the organic matter that originated the biogas. In this case, the value included in the model was 1,700.00 L/MWh ([43]), which refers to direct water consumption in biogas-steam systems.

Table 4.16 unites all the above adopted water consumption factors for renewable sources, properly converted to litres per unit of produced energy.

Table 4.16: Estimated Water Consumption Factors for Available Renewable Sources. Source: adapted from [43, 47, 74].

Source	**Water Consumption Factor (L/MWh)**
Offshore wind	21.96
Onshore Wind	21.96
Solar PV	556.92
Small Hydro	1,637.70
Biomass	89,928.06
Biogas	1,700.00

The same process as for GHG emissions calculation was then applied using each project's capacity factor and again the resulting factors were transformed into external costs using the defined water consumption externality price US$1500/1000 $\mathbf{m^3}$ converted to litres and to Brazilian currency. Table 4.17 presents the final values for every individual renewable project capable of receive investments.

Finally, there are the storage options. These available projects for expansion consist of batteries and pumped-storage reservoirs. In the model they are not represented as electricity generation sources, but as options able to accumulate energy produced by other sources and release it whenever need be. In this sense, model's decision for pumped-storage refers to energy storage capacity rather than new power units.

Since pumped-storage's investment is also inserted into the model as continuous decision variables referring to the option's total installed capacity, the considered GHG emissions and water consumption factors have the same values as small hydropower plants, since both are hydro sources with the difference that pumped-storage plants are able to choose between accumulate or dispatch energy in every planning period.

Table 4.17: Total Water Consumption Factors and Costs for Each Available Renewable Project. Source: the author, based on [43, 47, 74].

Project's Name	**Water Consumption (L/MWmonth)**	**Mean Capacity Factor**	**Water Consumption (L/MW.month)**	**Total Costs (R$/MW.month)**
Biomass	65,692,446.04	0.29	18,940,534.47	120,321.45
Solar Northeast	406,826.81	0.25	101,282.92	643.41
Solar Southeast	406,826.81	0.25	101,537.19	645.02
Solar Northeast Discounted	406,826.81	0.25	101,282.92	643.41
Solar Southeast Discounted	406,826.81	0.25	101,537.19	645.02
Onshore Wind South	16,041.65	0.38	6,162.99	39.15
Onshore Wind Northeast	16,041.65	0.47	7,609.19	48.34
Small Hydro 1 Southeast	1,196,343.44	0.45	541,017.22	3,436.86
Small Hydro 2 Southeast	1,196,343.44	0.45	541,017.22	3,436.86
Small Hydro 3 Southeast	1,196,343.44	0.45	541,017.22	3,436.86
Small Hydro 1 South	1,196,343.44	0.54	640,712.33	4,070.18
Small Hydro 2 South	1,196,343.44	0.54	640,712.33	4,070.18
Small Hydro 3 South	1,196,343.44	0.54	640,712.33	4,070.18
Biogas	1,241,850.00	0.80	993,480.00	6,311.17
Offshore Wind Southeast	16,041.65	0.47	7,565.69	48.06
Offshore Wind South	16,041.65	0.53	8,543.03	54.27
Offshore Wind Northeast	16,041.65	0.62	9,868.88	62.69
Offshore Wind North	16,041.65	0.32	5,155.52	32.75

Environmental impacts linked to batteries are mostly related to the material's extraction process, modules production and discard due to their hazardousness in terms of heavy metals contamination. The adopted GHG emissions factor was the sum of values for raw materials phase and production phase considering a lithium iron phosphate battery, resulting in 28.40 $\text{kgCO}_{\boldsymbol{2eq}}/1000\text{kWh}$, according to [66].

Water consumption of batteries are also associated with raw material extraction and production phases. According to [66], lithium iron batteries have a water footprint in the production phase of 0.02 $\text{m}^{\mathbf{3}}/1000\text{kWh}$. However, unfortunately no value was found for raw materials extraction and processing phases, although they probably account for most of the water consumption, and only 0.02 $\text{m}^{\mathbf{3}}/1000\text{kWh}$ was considered.

Table 4.18 presents the factors' values for GHG emissions and water consumption for the possible storage options.

Table 4.18: Estimated GHG Emissions and Water Consumption Factors for Available Storage Options. Source: the author, based on [66].

Source	**GHG Emissions Factor ($\mathbf{tCO_{2eq}}$/MWh)**	**Water Consumption Factor (L/MWh)**
Pumped-storage Hydropower	45.90	1,637.70
Battery	28.40	0.02

Once more, by using each storage project's efficiency defined for PDE [37], the resulting factors were properly converted and then turned into external costs using the defined externality prices for emissions and water consumption as well as transformed to the Brazilian currency. Table 4.19 presents the final values for every possible storage project.

Table 4.19: Total GHG Emissions and Water Consumption Factors and Costs for Each Available Storage Project. Source: the author, based on [66].

Project's Name	**Emissions (tCO_{2eq}/MWmonth)**	**Water Consumption (L/MWmonth)**	**Efficiency Factor**	**Emissions (tCO_{2eq}/MW.month)**	**Water Consumption (L/MW.month)**	**Emissions Costs (R$/MW.month)**	**Water Consumption Costs (R$/MW.month)**
Pumped-storage Southeast	33.53	1,196,343.44	0.75	25.15	897,257.58	1,597.52	5,699.91
Pumped-storage South	33.53	1,196,343.44	0.75	25.15	897,257.58	1,597.52	5,699.91
Pumped-storage Paraná	33.53	1,196,343.44	0.75	25.15	897,257.58	1,597.52	5,699.91
Battery Southeast	20.75	14,610.00	0.90	18.67	13,149.00	1,186.13	83.53
Battery Northeast	20.75	14,610.00	0.90	18.67	13,149.00	1,186.13	83.53

4.2 Instances

In terms of experiments, two sets of instances were created and optimized. For the Weighted Sum method application, each set is composed of 11 cases, all derived from the official dataset created and provided by EPE for PDE 2029 ([37]). They consist of altering the alpha value that multiplies the objective function (section 3.2.1) from 0.0 to 1.0. Every individual instance has an increase in this parameter of 0.1, completing the 11 cases in each set.

For the $\boldsymbol{\epsilon}$-Constraint method application, the same instance is executed several times with a different limiting bound. Then, there is an instance representing the official case from PDE 2029 ([37]) and another representing the alternative case.

The difference between the two sets relies on the defined additional constraints, previously addressed in the third chapter (section 3.2.2). The sections below describe these two major groups.

4.2.1 Group 1 - Basic Model

The first group maintains the exact original additional constraints presented in the input data spreadsheet [37] from PDE 2029 ([91]), representing energy policies which limit the expansion of some sources or define a minimum expansion for them. Their inclusion into the proposed model restrains the search space and, thus, the important influences of GHG emissions and water consumption to reach the optimal decision might not be fully explored.

For the Weighted Sum method application, the instances created within this set are:

- *1-0.0*: Environmental objectives multiplied by $(\boldsymbol{\alpha = 0.0})$ and economic objectives multiplied by $(\boldsymbol{1 - \alpha = 1.0})$ with all additional constraints;
- *1-0.1*: Environmental objectives multiplied by $(\boldsymbol{\alpha = 0.1})$ and economic objectives multiplied by $(\boldsymbol{1 - \alpha = 0.9})$ with all additional constraints;
- *1-0.2*: Environmental objectives multiplied by $(\boldsymbol{\alpha = 0.2})$ and economic objectives multiplied by $(\boldsymbol{1 - \alpha = 0.8})$ with all additional constraints;
- *1-0.3*: Environmental objectives multiplied by $(\boldsymbol{\alpha = 0.3})$ and economic objectives multiplied by $(\boldsymbol{1 - \alpha = 0.7})$ with all additional constraints;
- *1-0.4*: Environmental objectives multiplied by $(\boldsymbol{\alpha = 0.4})$ and economic objectives multiplied by $(\boldsymbol{1 - \alpha = 0.6})$ with all additional constraints;

- *1-0.5*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.5}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.5}$) with all additional constraints;
- *1-0.6*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.6}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.4}$) with all additional constraints;
- *1-0.7*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.7}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.3}$) with all additional constraints;
- *1-0.8*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.8}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.2}$) with all additional constraints;
- *1-0.9*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.9}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.1}$) with all additional constraints; and
- *1-1.0*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{1.0}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.0}$) with all additional constraints.

In order to calculate the limiting values for this instance in the $\boldsymbol{\epsilon}$-Constraint method application, the model was executed considering one, two and five hydrological series out of the ten used series in PDE [37], so the correct bounds could be used depending on the adopted number of series. The reached lower and upper bound values for the emissions and water consumption limiting constraints are presented in Table 4.20 and Table 4.21.

Table 4.20: Group 1 - GHG Emissions Constraint Lower and Upper Bounds. Source: the author.

Series	**Lower Bound - $\boldsymbol{\epsilon_{\xi_{min}}}$ ($\mathbf{tCO_{2eq}}$)**	**Upper Bound - $\boldsymbol{\epsilon_{\xi_{max}}}$ ($\mathbf{tCO_{2eq}}$)**
1	203,296,653	625,415,691
2	259,818,201	799,136,892
5	292,674,033	828,780,885

Table 4.21: Group 1 - Water Consumption Constraint Lower and Upper Bounds. Source: the author.

Series	**Lower Bound - $\boldsymbol{\epsilon_{\xi_{min}}}$ (L)**	**Upper Bound - $\boldsymbol{\epsilon_{\xi_{max}}}$ (L)**
1	2,284,793,902,551	3,325,385,328,017
2	2,358,309,130,495	4,335,434,742,536
5	2,398,757,402,270	4,350,145,344,257

The applied additional constraints for this group of instances are in Table 4.22.

Table 4.22: Group 1 - Included Additional Constraints from PDE 2029. Source: the author, adapted from [91].

Available Project	Constraint Type	Year	Value
Biomass	Annual Limit	2028	5,292
Biomass	Annual Limit	2033	8,224
Biomass	Step	2023 - 2033	150 ; 500
Onshore Wind South ; Northeast	Proportion	2023 - 2033	1 ; 4
Onshore Wind South ; Northeast	Annual Incremental Limit	2023 - 2033	3,000
Biogas	Step	2023 - 2033	0 ; 30
Solar Southeast ; Northeast	Proportion	2023 - 2033	1 ; 4
Solar Southeast ; Northeast	Step	2023 - 2033	1,000 ; 2,000
Small Hydro 1 ; 2 ; 3 Southeast	Annual Limit	2033	1,527
Small Hydro 1 ; 2 ; 3 South	Annual Limit	2033	823
Small Hydro Southeast ; South	Step	2023 - 2033	0 ; 300
Battery	Annual Limit	2033	10,000
Battery	Annual Incremental Limit	2024 - 2033	1,000
Wood Chip	Step	2024 - 2033	50 ; 100
Coal	Annual Incremental Limit	2026 - 2033	500
Coal	Annual Limit	2029	1,000
Coal	Annual Limit	2033	3,000
Pre-salt Natural Gas	Annual Incremental Limit	2026 - 2033	1,000
Pre-salt Natural Gas	Annual Limit	2029	3,000

4.2.2 Group 2 - Basic Model with Modified Additional Constraints

In order to properly observe how the added environmental aspects affected the model's decision, the second set was formed by removing or modifying the existing additional constraints. Basically, the ones that established hard limits or low steps for the expansion of renewable sources were eased, while the ones necessary for solution's consistency were kept.

For the Weighted Sum method application, the instances in this set are:

- *2-0.0*: Environmental objectives multiplied by ($\boldsymbol{\alpha = 0.0}$) and economic objectives multiplied by ($\boldsymbol{1 - \alpha = 1.0}$) with modified additional constraints;

- *2-0.1*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.1}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.9}$) with modified additional constraints;
- *2-0.2*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.2}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.8}$) with modified additional constraints;
- *2-0.3*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.3}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.7}$) with modified additional constraints;
- *2-0.4*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.4}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.6}$) with modified additional constraints;
- *2-0.5*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.5}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.5}$) with modified additional constraints;
- *2-0.6*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.6}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.4}$) with modified additional constraints;
- *2-0.7*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.7}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.3}$) with modified additional constraints;
- *2-0.8*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.8}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.2}$) with modified additional constraints;
- *2-0.9*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{0.9}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.1}$) with modified additional constraints; and
- *2-1.0*: Environmental objectives multiplied by ($\boldsymbol{\alpha} = \mathbf{1.0}$) and economic objectives multiplied by ($\mathbf{1} - \boldsymbol{\alpha} = \mathbf{0.0}$) with modified additional constraints.

As in the previous set, the model was executed considering one, two and five hydrological series out of the ten used series in PDE ([37]) for the $\boldsymbol{\epsilon}$-Constraint method application. The resulting lower and upper bound values for the emissions and water consumption limiting constraints are presented in Table 4.23 and Table 4.24.

Table 4.23: Group 2 - GHG Emissions Constraint Lower and Upper Bounds. Source: the author.

Series	**Lower Bound - $\epsilon_{\xi_{min}}$ ($\mathbf{tCO_{2eq}}$)**	**Upper Bound - $\epsilon_{\xi_{max}}$ ($\mathbf{tCO_{2eq}}$)**
1	148,489,394	418,053,447
2	181,147,579	536,082,584
5	191,057,516	569,111,132

Table 4.24: Group 2 - Water Consumption Constraint Lower and Upper Bounds. Source: the author.

Series	**Lower Bound -** $\epsilon_{\xi_{min}}$ **(L)**	**Upper Bound -** $\epsilon_{\xi_{max}}$ **(L)**
1	187,849,591,827	960,806,838,045
2	226,567,432,857	1,359,537,783,648
5	235,160,774,461	1,390,405,054,127

The applied additional constraints for this group of instances are in Table 4.25.

Table 4.25: Group 2 - Included Additional Constraints. Source: the author.

Available Project	**Constraint Type**	**Year**	**Value**
Biomass	Annual Limit	2033	15,000
Onshore Wind South ; Northeast	Annual Limit	2033	60,000
Biogas	Annual Limit	2033	5,000
Small Hydro 1 ; 2 ; 3 Southeast	Annual Limit	2033	6,000
Small Hydro 1 ; 2 ; 3 South	Annual Limit	2033	3,000
Offshore Wind Southeast	Annual Limit	2033	20,000
Offshore Wind South	Annual Limit	2033	20,000
Offshore Wind Northeast	Annual Limit	2033	20,000
Offshore Wind North	Annual Limit	2033	20,000
Battery	Annual Limit	2033	20,000
Wood Chip	Annual Limit	2033	15,000
Coal	Annual Limit	2033	15,000
Pre-salt Natural Gas	Annual Limit	2033	15,000

The intention of the above selected constraints with their respective values was to set a maximum amount of capacity expansion for each project in order to avoid concentration in a single source and also to provide freedom for the model to choose between a wider range than the original additional constraints from PDE ([37]). Although most of these limit values exceed real feasibility, they aim to provide an indicator of preferable generation options according to the model.

4.3 Computational Results - Weighted Sum Method

The optimization problem presented in Section 3.2.3 was coded in Python 3.7 and solved using the CPLEX solver v.12.1. All experiments were performed on a computer with an

Intel i7 processor 4700MQ CPU @ 2.4 GHz and 16 GB DDR3L of RAM memory, under Windows 8.1 x64 operating system.

In terms of hydropower generation, the ten hydrological series used in PDE ([91]) require a more robust processing capacity. Therefore, in order to be able to solve the model with this machine configuration, five hydrological series were considered in the Weighted Sum method application. All original ten series are equally distributed and representative, which means that the adopted five were randomly sorted out of the existing ones with no resulting bias for the model.

Although only five hydrological series were used, the results for instance *1-0.0* are still comparable with the original expansion schedule provided by EPE ([91]) because the additional constraints considerably restrain the solution space and no differences were observed in the results, hence this instance is the reference scenario.

4.3.1 Economic Costs versus Environmental Costs

After executing the proposed model for all instances, the results were collected and transformed into graph charts. One of the most relevant analysis is how the economic costs and the environmental costs from objective function behaved as the alpha parameter increased.

In this sense, Figure 4.2 provides a comparison among total economic cost and total environmental cost taking ($\boldsymbol{\alpha} = \mathbf{0.0}$) as the base level for the first set of instances. The horizontal axis presents the adopted alpha weight values for the environmental objectives, while the vertical axis corresponds to the difference between the final costs of the referring instance and the base level.

The results demonstrate that whenever the original additional constraints are maintained, environmental costs slightly decrease as alpha increases. On the contrary, total economic costs increase alongside alpha. This was expected because as the environmental objectives start to become more significant, more expensive sources are invested since they are more likely to reduce overall GHG emissions and water consumption. In addition, when the environmental objectives' total weight is at least **70%** and the economics' is **20%**, the economic curve escalates substantially while the environmental one does not have a proportional reduction, indicating a point from which little improvements become more financially costly.

Instance ($\boldsymbol{\alpha} = \mathbf{0.0}$) represents the official expansion schedule proposed in PDE 2029 ([91]) for the nation's power capacity increase until 2029. Therefore, Figure 4.2 indicates that environmental gains in terms of GHG emissions reduction and water consumption for power generation are possible, i.e., the Brazilian energy matrix have opportunities for environmental costs reduction.

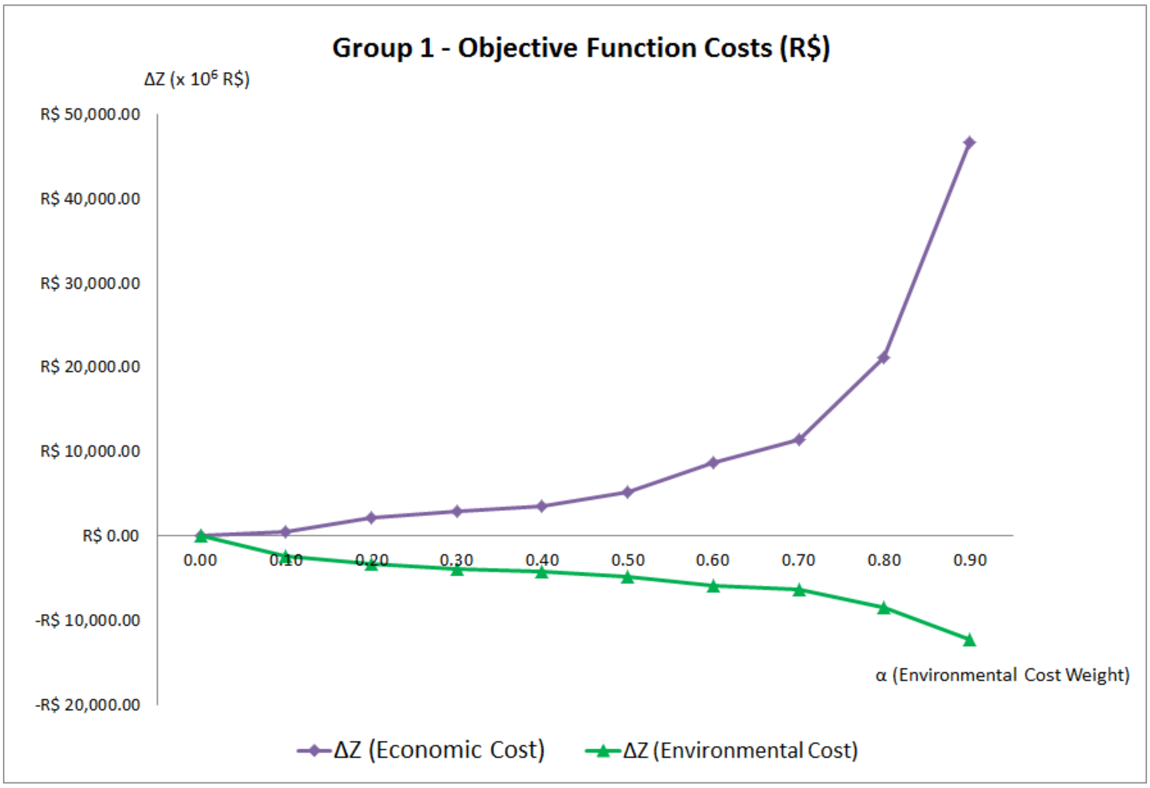

Figure 4.2: Total Economic and Environmental Costs - Group 1. Source: the author.

However, the economic objectives represent the operation and investment total costs. In order to understand how each individual curve behave, another graph chart was prepared. Figure 4.3 provides a comparison among total operation cost, total investment (expansion) cost and total environmental cost, considering again ($\boldsymbol{\alpha = 0.0}$) as the base level for the first set of instances.

From Figure 4.3 it is possible to observe that operation economic costs increase for ($\boldsymbol{\alpha \leq 0.4}$), while investment economic costs remain with low increment. However, starting from ($\boldsymbol{\alpha = 0.4}$), this behaviour reverses and both environmental and operation economic costs reduce as alpha continues to increase, while investment economic costs rise. Since thermal power plants operation is one of the most impacting activities, with low alpha values the model prefers to adjust the operation and investment of these plants, generating energy with more efficient technologies and also burning fuels with lower GHG emissions and water consumption. For ($\boldsymbol{\alpha \geq 0.4}$) the model understands that investing in more expensive sources that reduce the need for thermal operation is more interesting in terms of emissions and water consumption.

Moreover, for ($\boldsymbol{\alpha} \geq \mathbf{0.6}$), operation costs become smaller than in the instance with no environmental consideration ($\boldsymbol{\alpha} = \mathbf{0.0}$), i.e., it reduces to lower levels than the operation cost of PDE 2029 ([91]). In the proposed formulation, both environmental functions are weighted equally. Thus, when the problem is being solved, there is no differentiation between both impacts and one may increase as long as the total environmental cost diminishes. In this sense, a reduction in overall operation cost indicates less activation of thermal power plants, but this does not necessarily imply in diminishing water consumption and GHG emissions concomitantly.

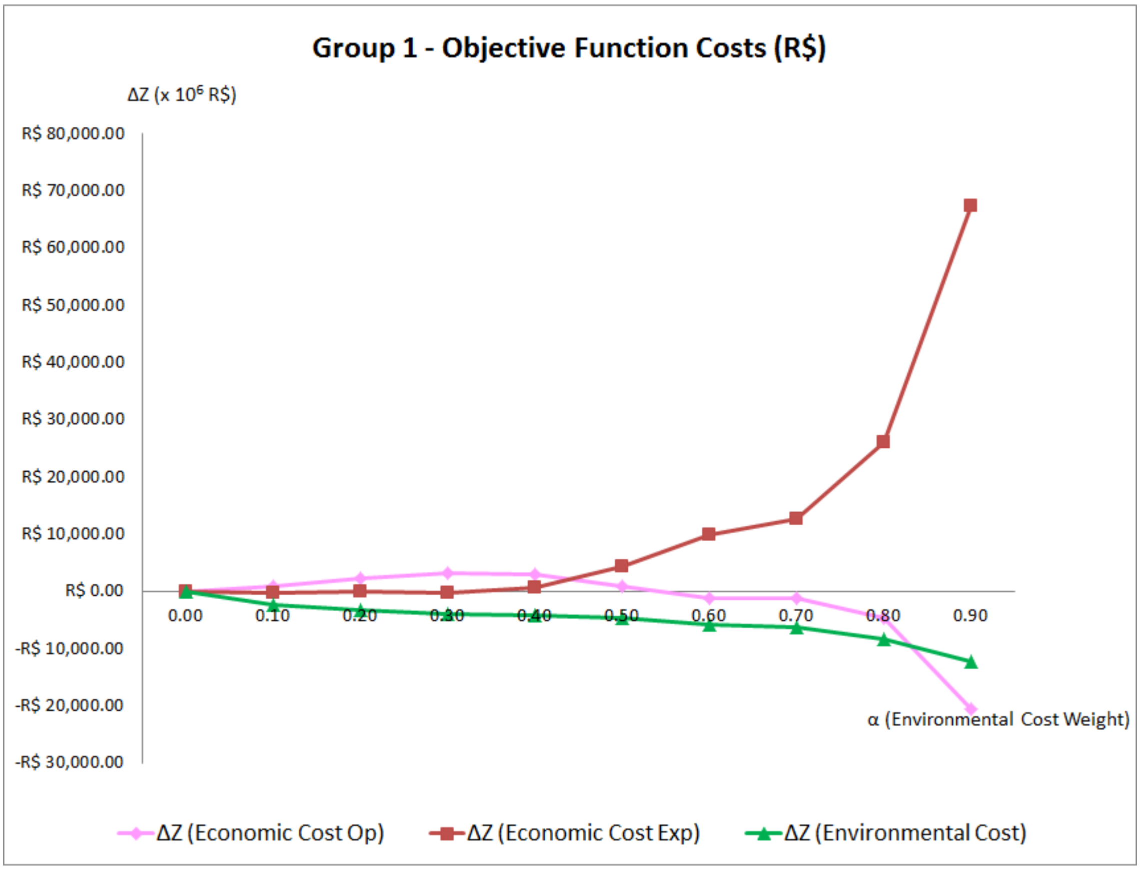

Figure 4.3: Total Operation, Investment and Environmental Costs - Group 1. Source: the author.

The same analysis is applied for the instances of the second group. Figure 4.4 presents the total economic and environmental costs for the instances with modified additional constraints. The resulting solutions show that the economic cost grows similarly to the first group's instances and, at the same time, the environmental costs start to decrease more significantly only when ($\boldsymbol{\alpha} \geq \mathbf{0.6}$). However, environmental costs for Group 2 decrease at a slower pace, with less reduction in each instance when compared to instances of Group 1. These results are plausible because, since the additional constraints are more flexible and do not restrain the solution space as much as in the first group, the first instance already provides an investment schedule and operation decisions with less environmental impacts than the first set, influencing the other instances' results.

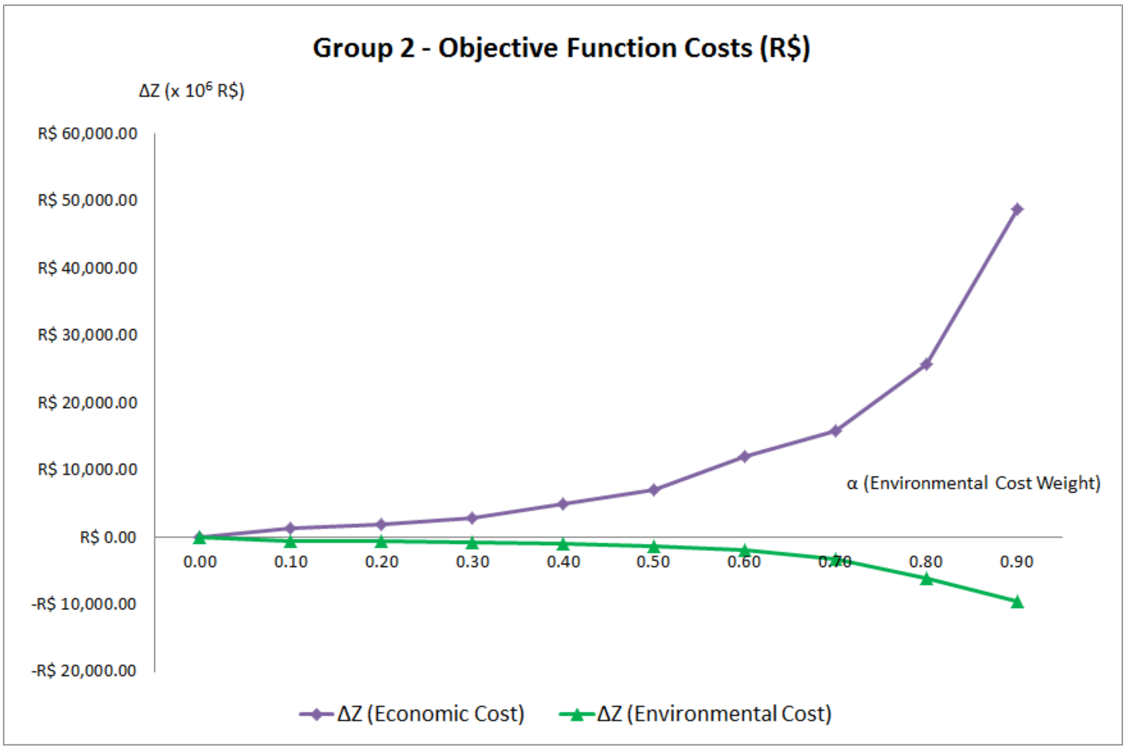

Figure 4.4: Total Economic and Environmental Costs - Group 2. Source: the author.

Figure 4.5 corroborates with this idea because it shows that the economic curves behave different than in 4.3. Although the operation economic curve still has a small rise for ($\boldsymbol{\alpha} \leq \mathbf{0.4}$), the increase in the investment costs is already relevant since the first instance. Starting from ($\boldsymbol{\alpha} = \mathbf{0.4}$) operation costs decrease considerably, while investment costs grow faster due to the necessity of more expensive sources in order to achieve better environmental outcomes.

At the beginning, for both groups the model opted for sustaining the operation of thermal plants, instead of deactivating them. These have an important task in the system, which is providing dispatchable energy during peak demands because generating electrical energy with renewables requires back up sources. However, for both cases, when ($\boldsymbol{\alpha} \geq \mathbf{0.5}$) the solver starts to value expensive options that are able to provide this service to the system and also cause less environmental impacts.

Still, the curves' patterns are similar in both sets of instances, signaling that the environmental aspect affects the energy generation decision problem. Whenever the focus is on sustainability, the optimal investment schedules might diverge from the ones officially adopted by the power planning agency, as they do not consider carbon and water footprints in the model. The challenge is to find a feasible trade off that results in environmental benefits without extensively penalizing overall cost.

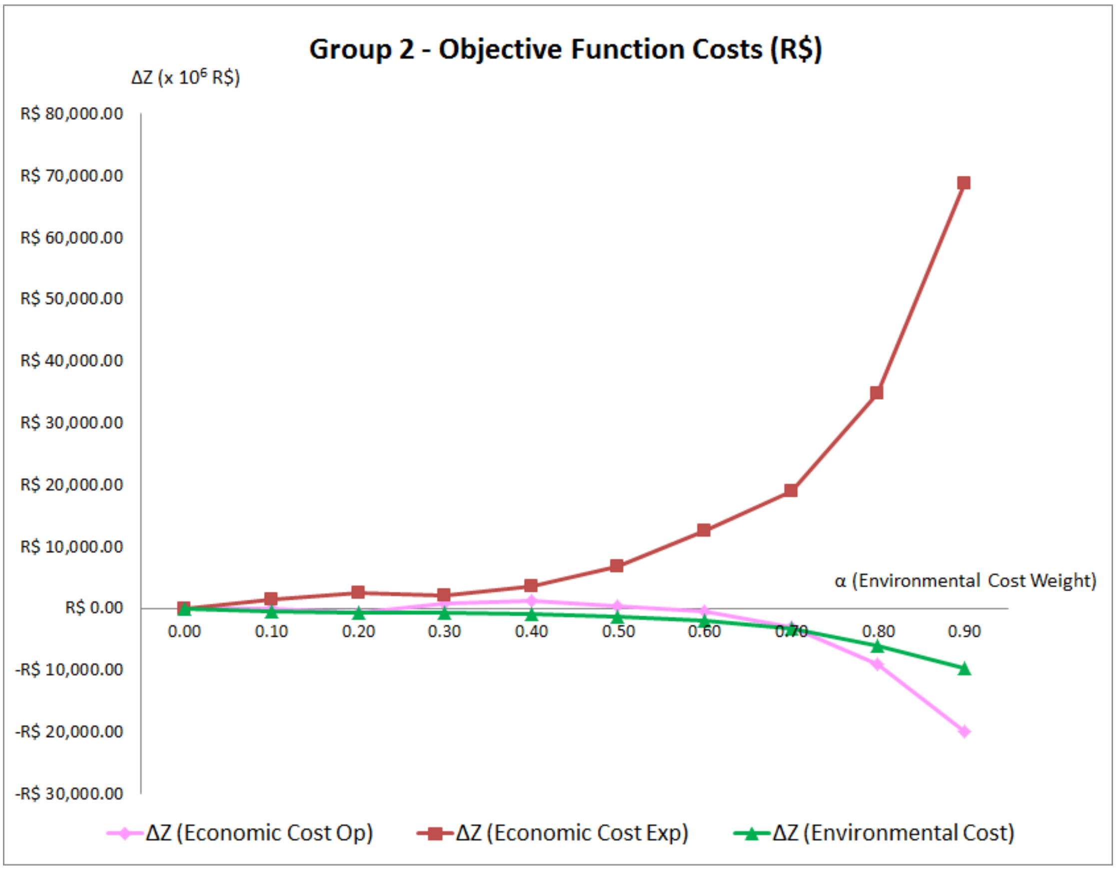

Figure 4.5: Total Operation, Investment and Environmental Costs - Group 2. Source: the author.

Besides the economic and environmental objectives, there are the other costs in the objective function, discussed in Section 3.2.1. As mentioned previously, they consist of monetary penalties and of transmission grid's capacity expansion costs, which is included in this group because there were no environmental impacts considered for this option. Thus, in order to validate the results, it is important to check whether these values vary among the instances' outcomes.

As it is possible to observe in Figure 4.6, energy deficit values had slight variations between all the instances. In other words, in general, the model chose to invest in new projects rather than increasing deficits. In fact, power deficit decreases, implying in more security for the system's infrastructure as less lack of power is noticed. Since power deficit values drop and energy deficit values remain constant, total other costs also reduce.

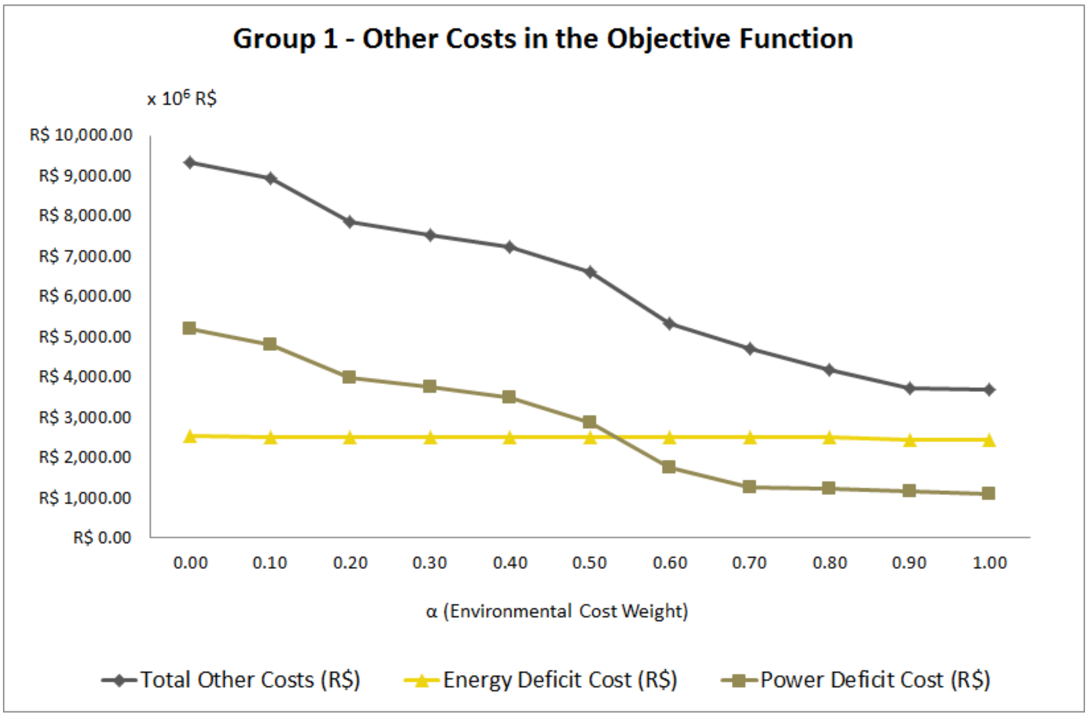

Figure 4.6: Other Costs rather than Economic and Environmental - Group 1. Source: the author.

Therefore, as the environmental aspect becomes more relevant, the deficit related to total power capacity in the system diminishes. The same happens for instances of the second group, in which the reduction is even more significant. In relation to the energy deficit curve, it also remained approximately flat as the first group's. The other costs' total also decreased with the increase of environmental objectives' weight.

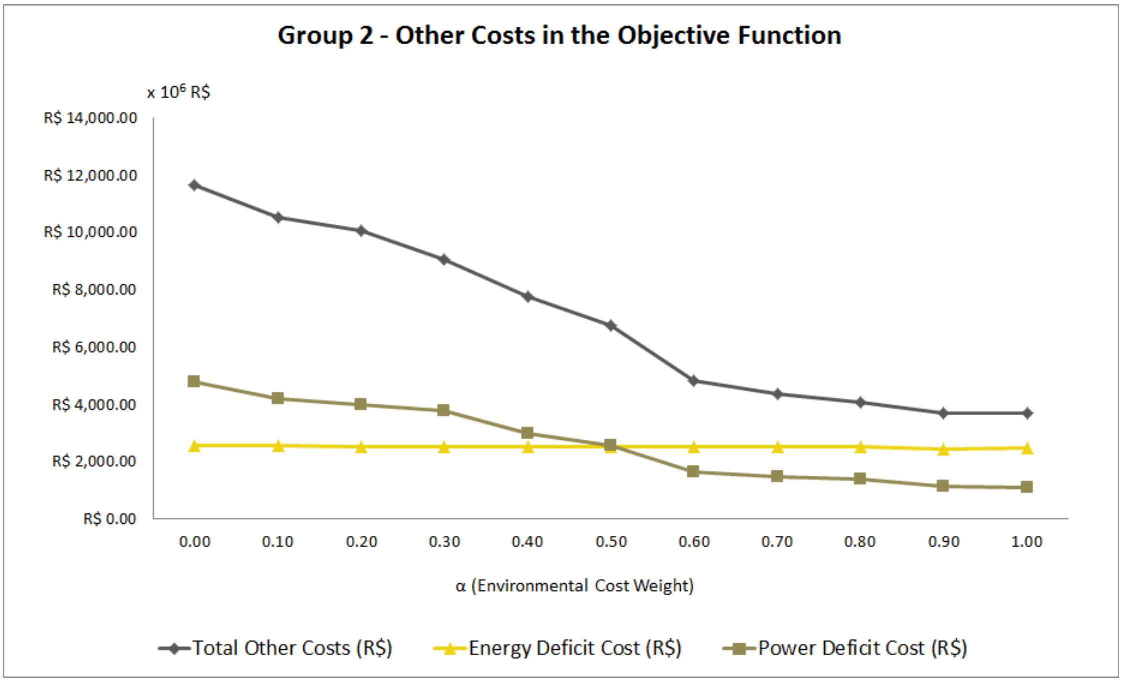

Figure 4.7: Other Costs rather than Economic and Environmental - Group 2. Source: the author.

4.3.2 Total GHG Emissions and Water Consumption

The graph charts presented in last section demonstrate that total environmental costs decrease as their weight increases in the objective function. However, as previously stated, the environmental objectives are treated jointly and the overall reduction affects differently GHG emissions and water consumption. One impact may increase for the reduction of the other, depending on the solver's decisions. Then, it is important to compare both aspects in order to understand their separate patterns.

In this sense, Figure 4.8 exhibits the curves referring to the difference between total GHG emissions costs and total water consumption costs for each instance of the first set considering ($\boldsymbol{\alpha} = \mathbf{0.0}$) as the base level. In addition, the total environmental costs' curve is also included in order to demonstrate that the overall reduction in the environmental impacts reflects distinct decreasing possibilities for both analyzed aspects. Nonetheless, although these curves do not behave equally, it is possible to observe that both impact costs curves diminish as the environmental objectives become more significant.

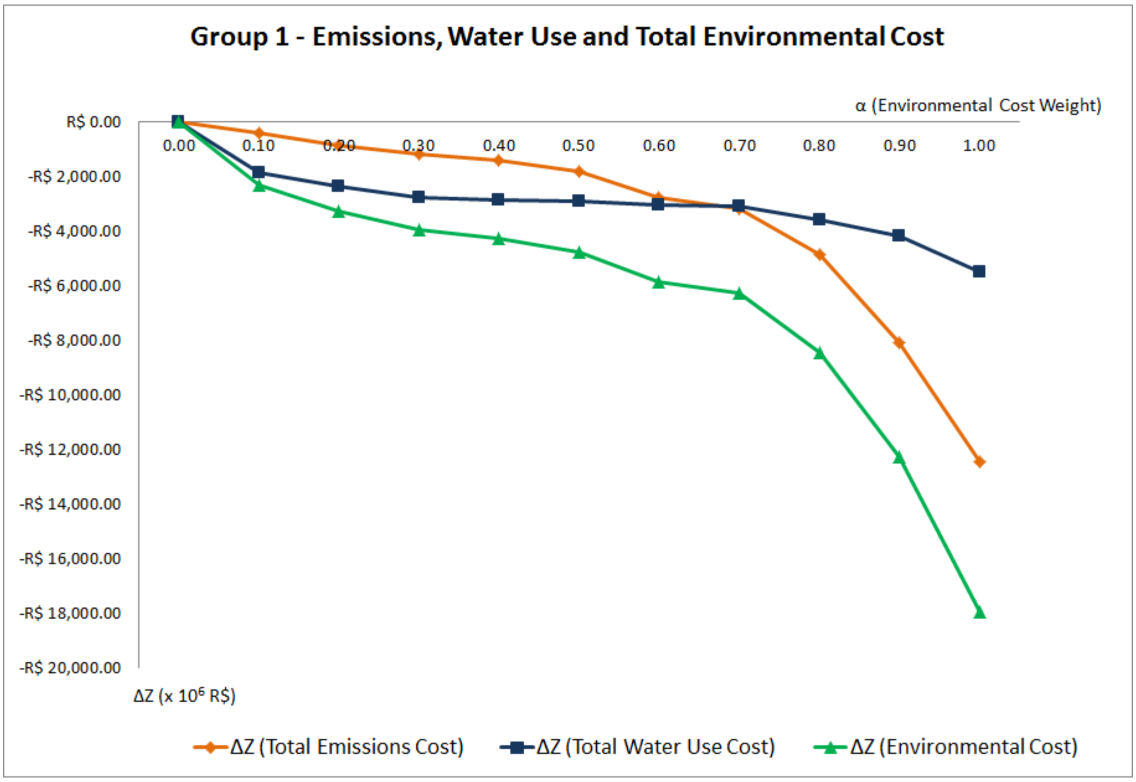

Figure 4.8: Total GHG Emissions, Water Consumption and Environmental Costs - Group 1. Source: the author.

According to the information above, the model initially preferred to reduce total water consumption as soon as the alpha parameter started to increase, while GHG emissions had less expressive reductions at the beginning. In other words, there is a trade-off between the costs of these two impacts in a sense that, for instances with original additional constraints, best environmental cost reduction was achieved through diminishing water consumption for the first instances.

However, this situation inverts for ($\boldsymbol{\alpha \geq 0.6}$) when there is no much space left for decreasing water consumption and, since economic costs became less relevant than the environmental ones, the solver found better solutions by significantly decreasing GHG emissions as well.

The opposite occurs for instances of the second group. Figure 4.9 reveals that, in the case of modified additional constraints, the model decided to reduce GHG emissions and increase water consumption in order to reach the maximum environmental cost decrease. Since this set of instances includes more renewable power capacity already with ($\boldsymbol{\alpha = 0.0}$), when no environmental objectives are considered, as the environmental weight starts to increase, there are not many possible solutions that respect all the constraints and promote high environmental cost reduction.

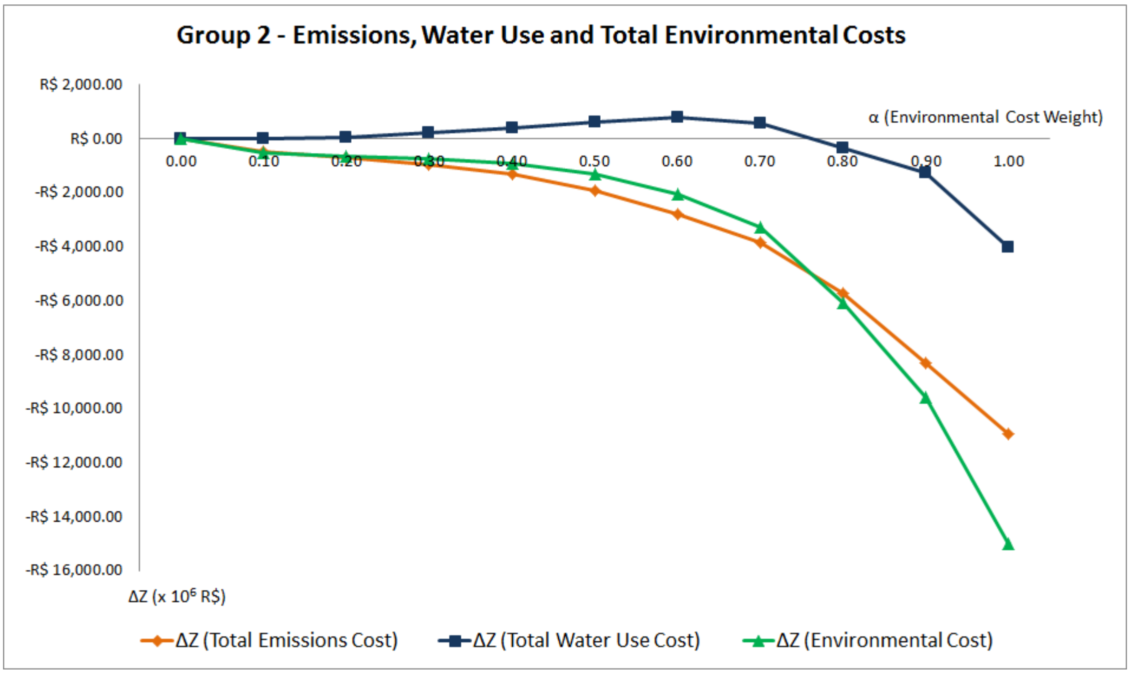

Figure 4.9: Total GHG Emissions, Water Consumption and Environmental Costs - Group 2. Source: the author.

Therefore, total environmental cost continues to diminish in every instance, but actually water consumption increases for ($\boldsymbol{\alpha \leq 0.6}$) so that GHG emissions are able to be reduced and affect total environmental cost. Water consumption only decays below the first instance level when ($\boldsymbol{\alpha \geq 0.8}$). Still, it is important to state that, as this set already provides more sustainable optimal solutions from the start, total overall environmental cost savings are below the values for the first group, which provides more possibilities in terms of lessening environmental impacts.

Nonetheless, analyzing environmental costs curves does not actually give a proper signal on how the impacts are lowering from instance to instance. In fact, it is essential to evaluate GHG emissions and water consumption regarding their corresponding measuring units, i.e, their quantities. The next presented graph charts aim to represent this information.

Regarding GHG emissions, Figure 4.10 indicates the carbon reduction pathway throughout the instances of the first group as the alpha parameter value rises. As previously stated, total emissions costs remained decreasing at a slow path while ($\boldsymbol{\alpha \leq 0.5}$). Thus, more significant GHG emissions decrease only begins at ($\boldsymbol{\alpha = 0.6}$) when there is a **12%** reduction when comparing with the first instance. For the last case, when no economic costs are considered ($\boldsymbol{\alpha} = \mathbf{1.0}$) and the objective function is completely focused in lowering the total environmental cost, total emissions reduction is approximately **60%** in relation to the official indicative expansion schedule from EPE [91].

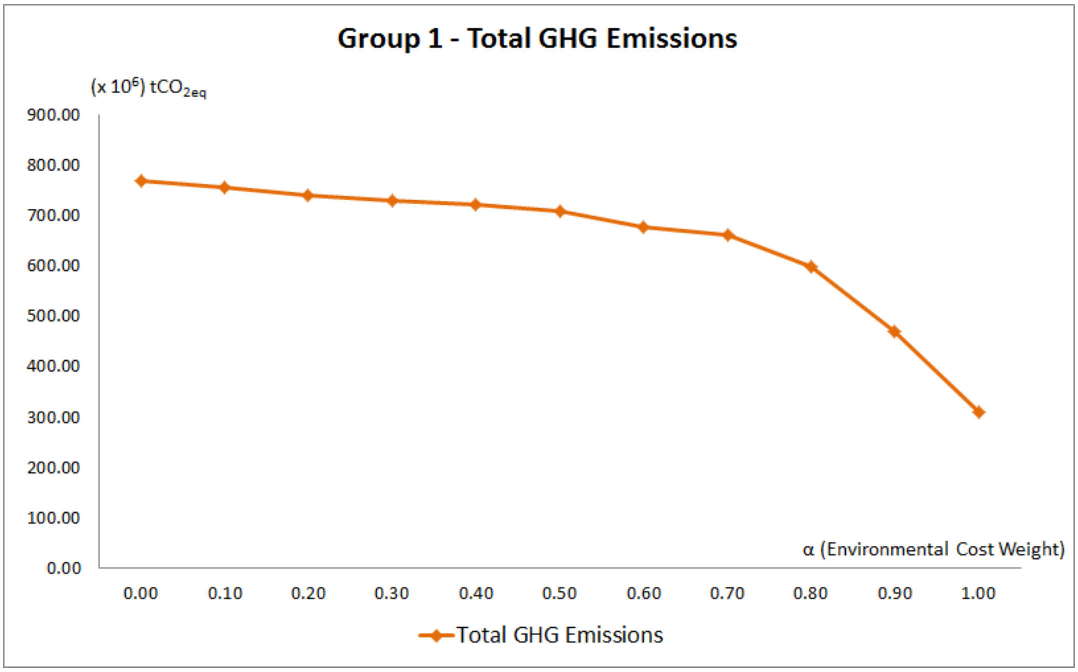

Figure 4.10: Total GHG Emissions per Instance - Group 1. Source: the author.

In relation to the second group's instances, GHG emissions decay is steeper, with values decreasing faster than when compared to the first group's, as previously mentioned. In this case, reduction begins to become even more significant at ($\boldsymbol{\alpha} = \mathbf{0.5}$) when there is approximately a **11%** drop from the initial instance level of emissions.

For the last instance of the modified additional constraints group, overall emissions decrease when ($\boldsymbol{\alpha} = \mathbf{1.0}$) - no economic costs considered - was almost **63%**, which means that the solution emitted less than half of the base level. Yet, it is relevant to note that, as the second group already provides less environmental impacting results since the first instance, overall GHG reduction achieved by the second group is less than first group's in terms of absolute value.

A scenario where economic costs are ignored is not feasible due to project financing. Then, under the established conditions, when the environmental costs weight the same as the economic costs, instance ($\boldsymbol{\alpha} = \mathbf{0.5}$), the total GHG emissions avoidance is approximately **62** $\mathrm{MtCO}_{\mathbf{2}\boldsymbol{eq}}$ for the first set of instances and **61** $\mathrm{MtCO}_{\mathbf{2}\boldsymbol{eq}}$ for the second, noting that environmental costs are not only related to emissions.

The same analysis for water consumption demonstrates that, for the same instance

($\boldsymbol{\alpha} = \mathbf{0.5}$), total water saving is around **967** billion L when looking at the first group, but for the second there is a consumption increase of approximately **259** billion L. This water footprint rise enabled optimal overall cost reduction by focusing on emissions decrease, as mentioned above. In other words, the invested projects concerned mainly available sources that present low values for carbon footprint, despite being water intense, because the trade-off between both impacts represented costs was beneficial.

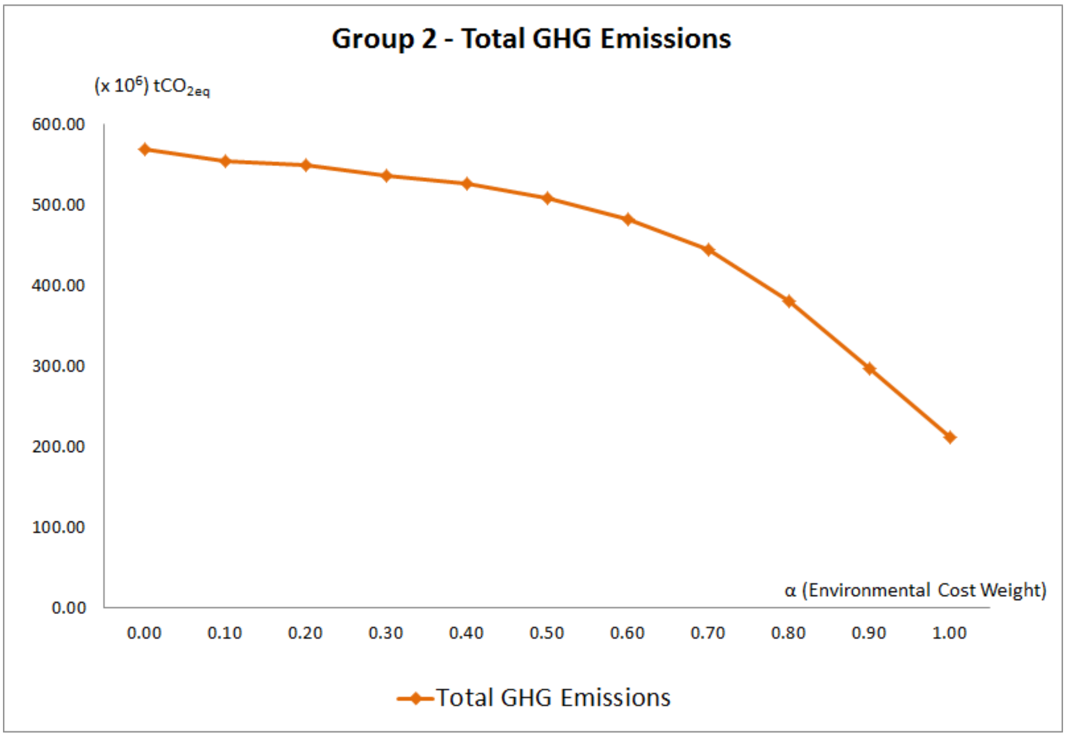

Figure 4.11: Total GHG Emissions per Instance - Group 2. Source: the author.

The next pictures present the water consumption impacts according to solver's decisions. Figure 4.12 shows the water consumption curve for the group with original additional constraints maintained. The initial drop when the environmental objectives start to be considered in the formulation corroborates with the idea that the model preferred to adjust thermal generation in order to be more efficient as not a as noticeable drop in GHG emissions occurred.

Right after the initial large depletion, the curve stabilizes and the next instances present little water consumption variation, although the values continue to decrease. Only when ($\boldsymbol{\alpha} \geq \mathbf{0.8}$) the solver finds possibilities of more significant reductions. The opposite happens for the instances of the second group. Figure 4.13 indicates that there was no initial drop, but, actually, the water consumption increased until ($\boldsymbol{\alpha} \geq \mathbf{0.6}$), when it starts to drop. However, it is important to note from Figure 4.13 that second group's water consumption initiates at a much lower volume than the first's.

The increase in water consumption allowed the model to diminish GHG emissions, resulting in an overall environmental cost decrease. This trade-off between both adopted environmental aspects indicates an expansion of bioenergy thermal power plants, as it will be explored in the next section.

Since the modified additional constraints resulted in a more sustainable power expansion from the beginning, when the environmental objectives were not even accounting in the model ($\boldsymbol{\alpha = 0.0}$), as soon as the alpha parameter started to increase, there was already not much space for water footprint reduction when economical costs remained high. All these results directly reflect the model's investment schedules proposed over the planning horizon. Therefore, the next section aims to address the indicated generation expansions.

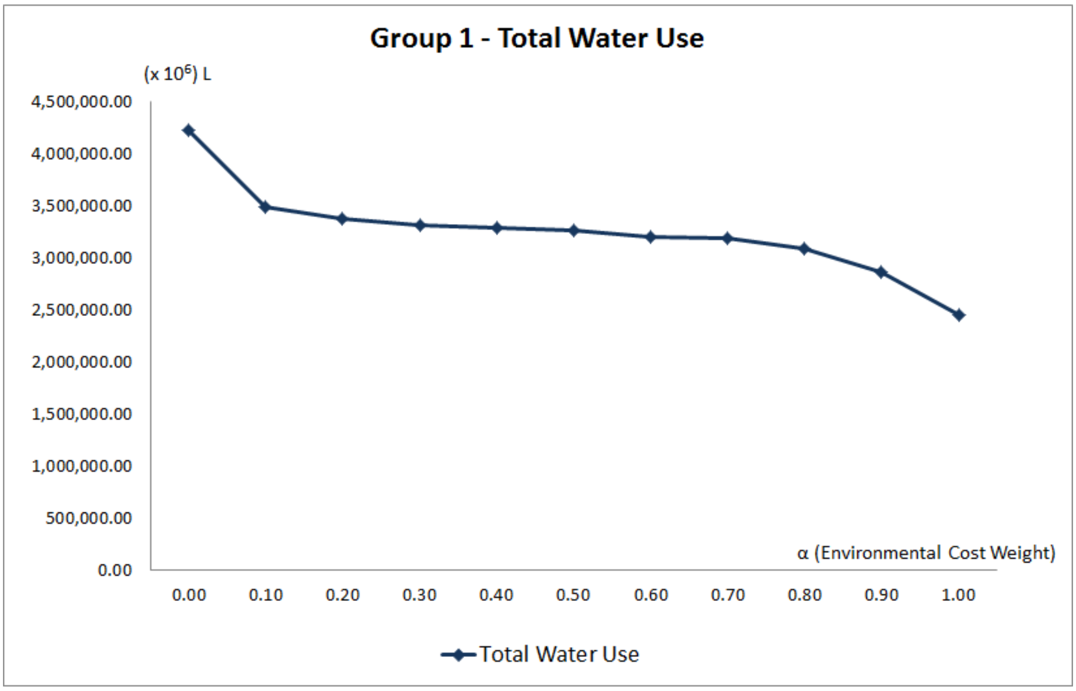

Figure 4.12: Total Water Consumption per Instance - Group 1. Source: the author.

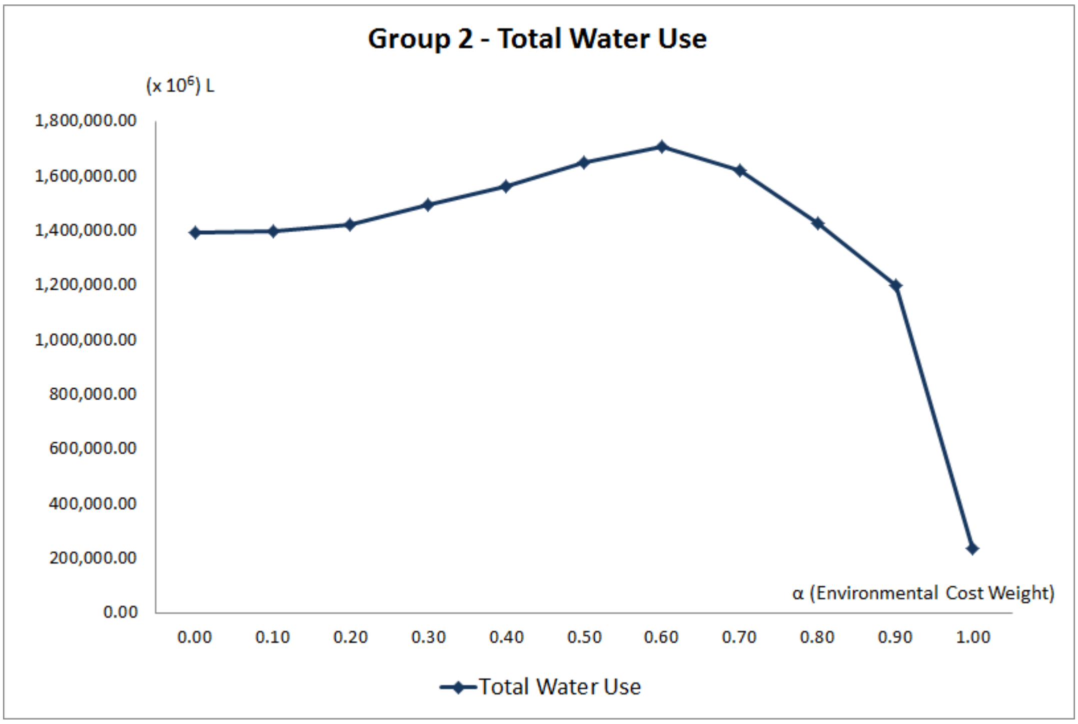

Figure 4.13: Total Water Consumption per Instance - Group 2. Source: the author.

4.3.3 Indicated Generation Expansion

Figure 4.14 provides a comparison between the expansion results for the first group. It contains the total amount of power invested at the end of the planning period for each source opted by the model and for each instance in the group. All available sources for expansion are represented in the figure, even if any of them has not received any capacity investment in all instances.

The horizontal axis presents the electricity generation sources that were invested. BIOENERGY stands for the sum of biomass - mostly sugarcane bagasse -, biogas and wood chip. In terms of thermal sources, FNG CC stands for Flexible Natural Gas in combined cycle, representing power plants which are flexible for activation and deactivation. Similarly, FNG OC stands for Flexible Natural Gas in open cycle, a preferable option for attending peak demands. The difference among WIND and OFF WIND is that WIND accounts for onshore wind farms, whilst OFF WIND refers to offshore wind farms. Concerning solar energy, only the photovoltaic technology is considered as an expansion option.

Regarding the results for the first group, the graphic demonstrates that when keeping PDE's original set of additional constraints ([37, 91]), there is no much space for variations among the most common sources. Since onshore wind energy expansion must be restrained in order to fit in the step and annual limit constraints, the model opted to invest in solar energy and offshore wind as the alpha parameter increased. Although solar technology has been presenting reduced costs in every Brazilian auction, MDI-Patamares still adopt a conservative scenario with higher costs, which turn solar PV into an expensive alternative when compared to others. This is the reason why solar energy capacity grows as the economic costs become less significant to overall costs.

Figure 4.14 also indicates that the model expanded large amounts of thermal power generation even in instances with increasing environmental relevance than in the base instance ($\boldsymbol{\alpha = 0.0}$). However, the decreasing GHG emissions levels reveal that thermoelectric plants were, in general, less activated or activated with more efficient fuels, even though natural gas installed capacity increase. For instance, the first three instances invested in expanding coal thermal generation, but this decision was not carried along by the other instances.

In fact, as renewables increase their installed capacity, total thermal power also needs to increase due to peak demand reasons. These renewable sources do not contribute for maximum instantaneous demand and the model must also meet the power constraint. Thus, thermoelectric plants are invested because they are easily dispatchable, but they are not operated until necessary.

Pre-salt stands for thermoelectric power plants running on natural gas from Brazilian pre-salt oil basins, while retrofit columns represent the opportunity of retrofitting old or inefficient thermal generators. Retrofit expansion is significant for most of the instances because it is a less costly option for thermal expansion. However, as the environmental aspects become more relevant, pre-salt natural gas power plants become unattractive due to their higher costs when comparing with the other cited natural gas options, not fueled by pre-salt gas.

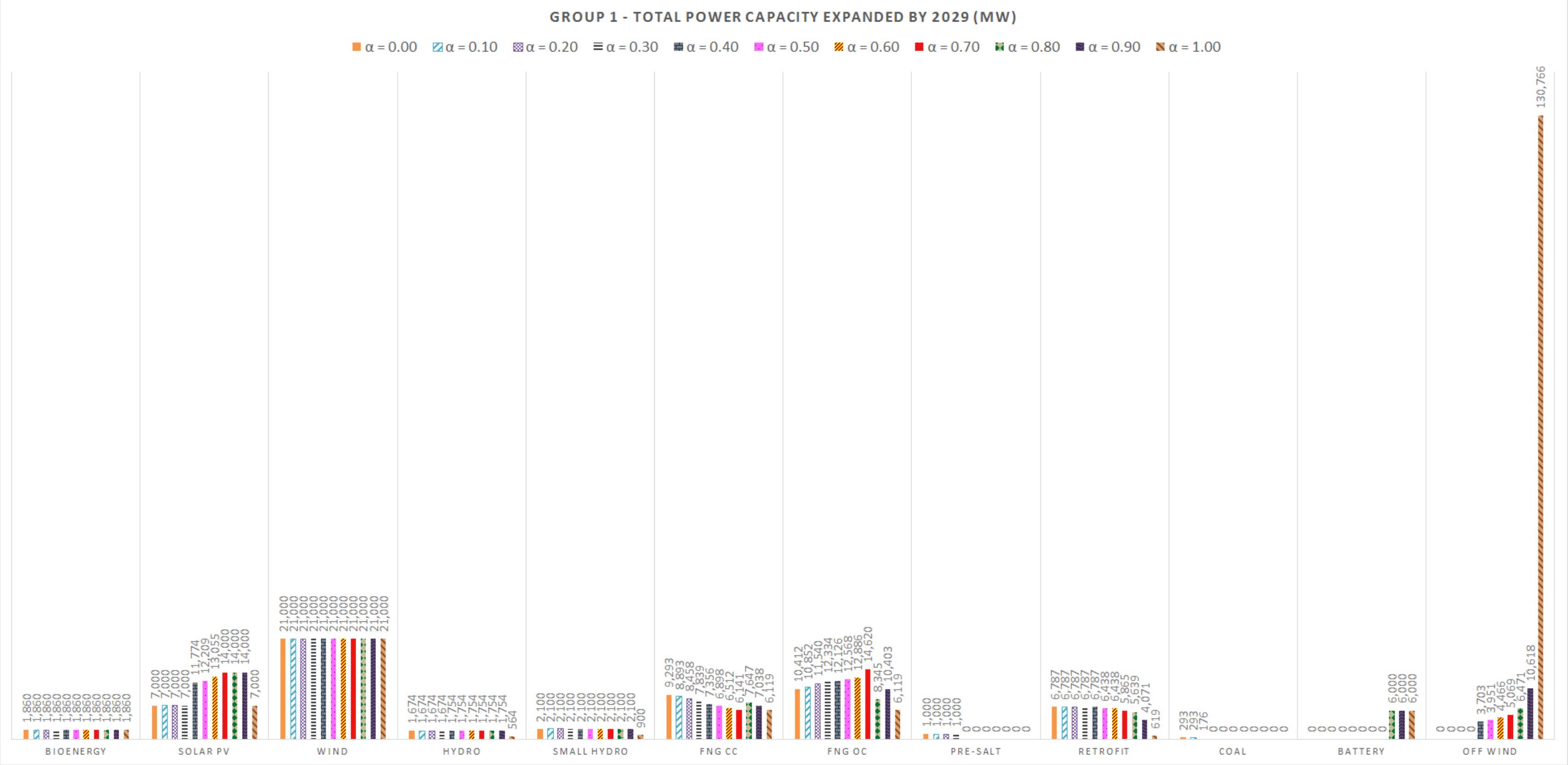

Figure 4.14: Total Capacity Expansion per Source by 2029 (MW) - Group 1. Source: the author.

When assessing the results for other sources, it is possible to observe that the model chose to invest in the maximum expansion capacity of small hydro and onshore wind for all the instances besides the last one in the case of small hydro. This fact indicates that the model perceives those options as interesting possibilities in terms of energy and power supply in oppose to their environmental impacts.

Similarly, large hydropower plants also remained almost constant, with a small growth of only 100 MW as the alpha parameter increased due to the source's high carbon and water footprints. These sources were only substituted in the final instance because the economic costs became irrelevant and the solver was capable of investing in batteries and offshore wind, whose environmental impacts considered in the model are lower, but their economic costs make them unlikely options to be invested.

Regarding bioenergy capacity, Figure 4.14 demonstrates that there was no variation between the results for all the instances. In this sense, Figure 4.15 splits total bioenergy generation capacity investment for each instance in terms of the available sources. It shows that wood chip and biogas expansions reached their maximum limit over all the instances, while biomass also carried the same amount, but its invested value was the minimimum according to the biomass step additional constraint.

From all the bioenergy sources, biomass is the one which incorporates the highest water footprint value, while the one related to biogas is also expressive, but lower than biomass, and wood chip is considered to have a low water consumption factor in the model due to its origin. Therefore, as the alpha parameter increases, the model continues to value biogas and wood chip sources, while biomass was only invested due to the source's lower bound.

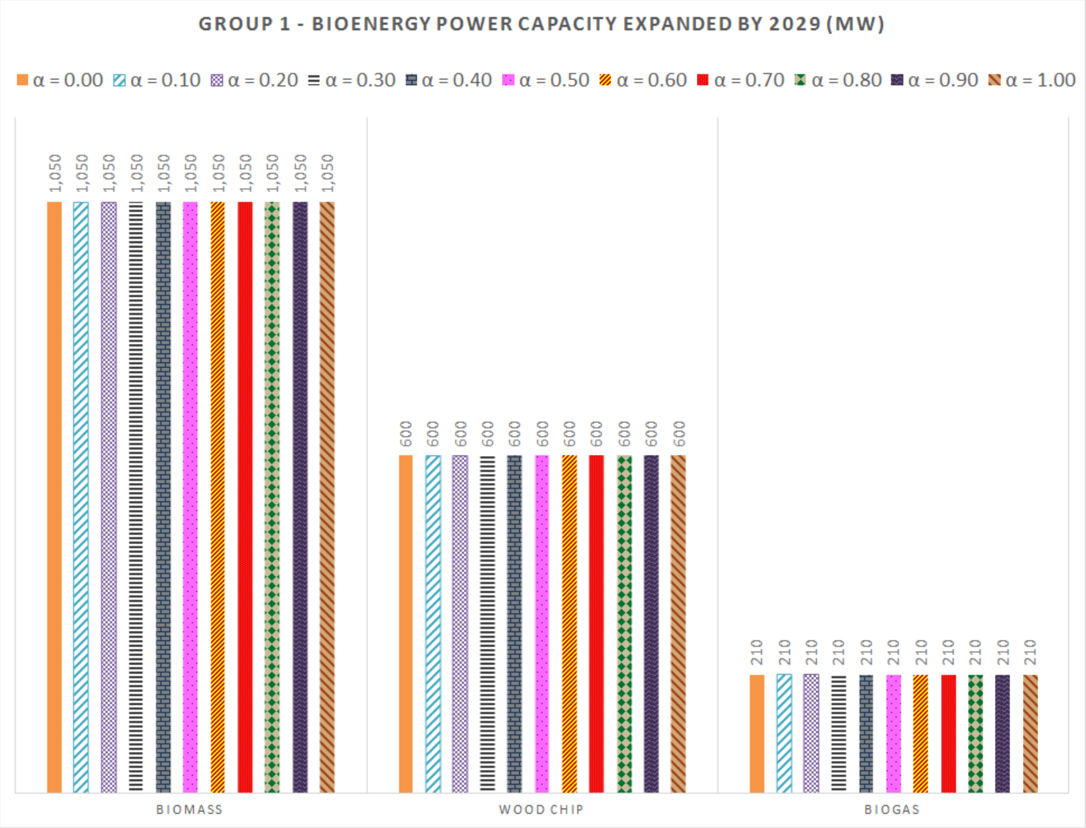

Figure 4.15: Total Bioenergy Capacity Expansion per Source by 2029 (MW) - Group 1. Source: the author.

As the environmental costs become more important to the objective function than the economic costs, the model starts investing in offshore wind and battery. Battery's expansion reached the upper bound as soon as the source became feasible because its GHG emissions and water consumption are low and it contributes to power capacity due as it stores energy, then being perceived as an interesting option.

Offshore wind, on the other hand, has no limiting constraints attached in the formulation and, since economic costs are not accounted when ($\boldsymbol{\alpha} = \mathbf{1.0}$), the required energy demand is able to be fulfilled with this source as long as the necessary amount of not intermittent sources also receive investments to attend maximum instantaneous demand constraint as well.

In relation to the second group of instances, the results differ, but some similarities are observed. Figure 4.16 reveals that the investment decision also focused in wind power. Since this source's limit was extended, the model was able to expand it to the detriment of solar PV. It is a reasonable decision because wind capacity expansion is less economic costly than solar and wind source has a little contribution to peak demands, while solar PV is considered to have null contribution in the formulation. In the first set of instances, solar PV had a minimum expansion per year as a Brazilian energy policy, but as this lower bound was removed, the model opted for not expanding it because it is still expensive besides having a relative high carbon footprint.

Also, by doubling total maximum investment in onshore wind capacity and removing the annual incremental limit, the model was able to increase this source freely, expanding what the solver perceived as the capacity needed for each year. In this sense, there was no need for offshore wind power in most years. As a result, offshore wind was only invested in the last instance, when no economic costs are considered.

Nevertheless, wind's intermittence and little contribution to generation during peak demands according to the model data ([37]) requests the investment in easily dispatchable and available sources. This is the reason why thermal power plants also increase, considering the ones running on biomass. In terms of fossil fuels, open cycle thermal power capacity investment starts to increase after several decreasing instances for two cases with elevated environmental weights, while combined cycle diminishes. The first one is indicated to supply peak demands because its respective plants activate and generate faster, hence being used preferably whenever necessary.

The above statement is corroborated by the fact that bioenergy capacity expansion also increases as the environmental weight rises. When considering that the additional constraints limiting expansion of the thermal power project running on wood chip were modified in order to increase its maximum annual limit, it is reasonable to expect that overall operation cost would stay stable in average while emissions would decrease since this source's related emissions factor is the lowest from all considered thermal projects' fuels. In fact, that is exactly what is represented in Figure 4.17. It shows that as economic weight reduces, wood chip investment increases.

Moreover, total biogas capacity expansion is also significant, mainly for instances with higher alpha parameter value. Biomass, however, was not invested in any of the instances due to its elevated water footprint. For the last instance, both wood chip and biogas had no capacity expansion because offshore wind became the most interesting renewable source for investment besides onshore wind.

Although the model opted for no capacity investment of biomass thermal power plants, in reality this source will continue to expand in order to supply power for sugarcane production and to make a valuable use out of the bagasse.

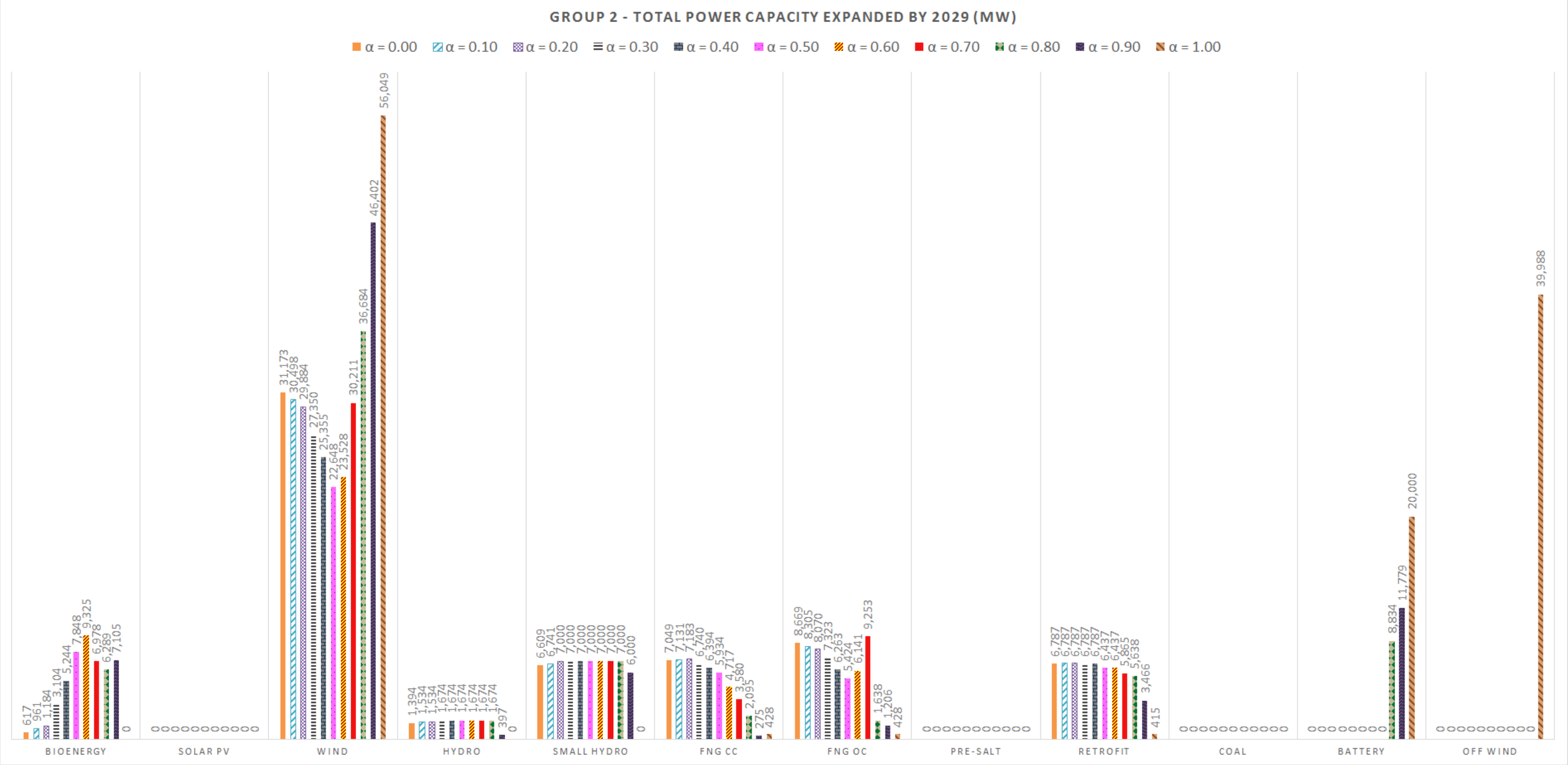

Figure 4.16: Total Capacity Expansion per Source by 2029 (MW) - Group 2. Source: the author.

The bioenergy increase united with Figure 4.9 and Figure 4.13 explains why water consumption increases for ($\boldsymbol{\alpha} \mathbf{<= 0.6}$) when comparing to the base level. Instance ($\boldsymbol{\alpha} \mathbf{= 0.6}$) has the highest biogas investment and it starts do decrease afterwards. Although biogas' water footprint is expressive, the source becomes relevant because it attends the power demand constraint due to its dispatchability property and it contributes for GHG emissions decrease with feasible economic costs, compensating the water consumption costs. However, for ($\boldsymbol{\alpha} \mathbf{> 0.6}$), the environmental weight in the objective function covers the economic weight and the impacts on water becomes more relevant.

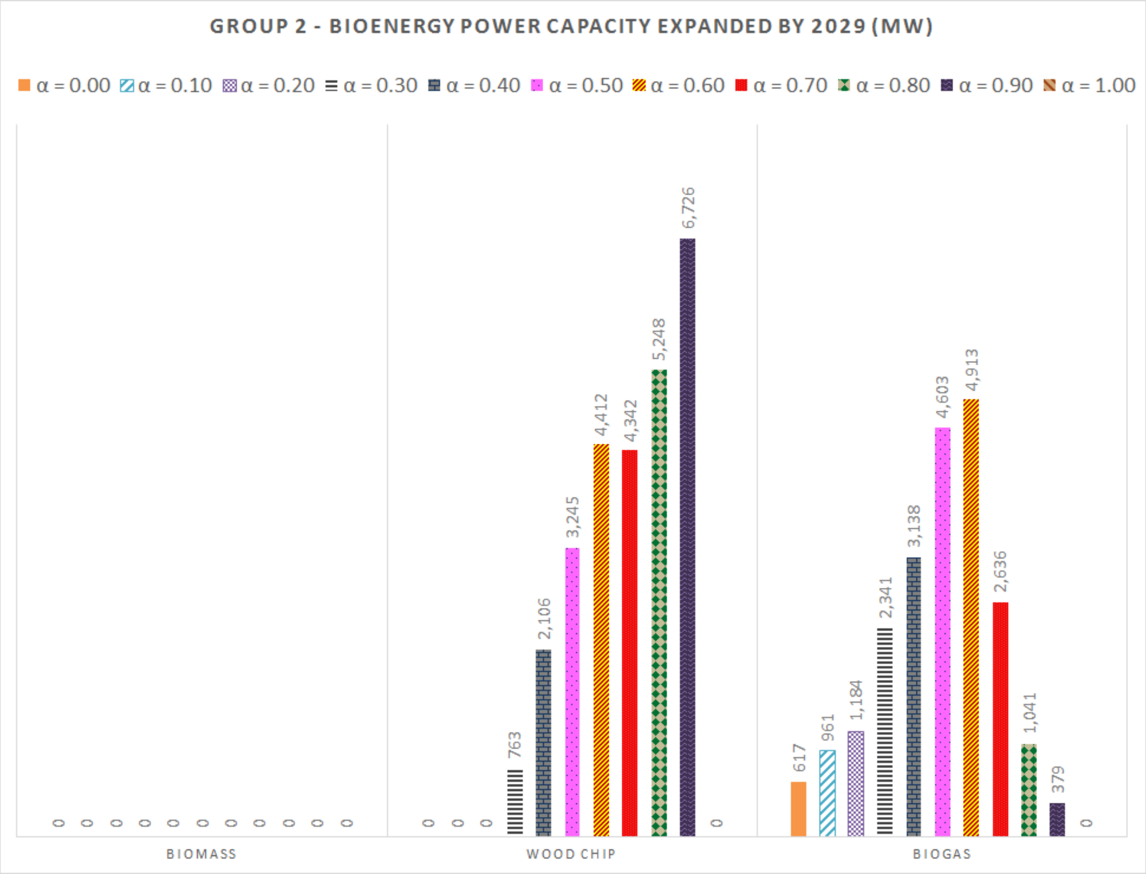

Figure 4.17: Total Bioenergy Capacity Expansion per Source by 2029 (MW) - Group 2. Source: the author.

In terms of the other sources, hydropower capacity expansion has a little increase. Large hydropower plants expand around 300 MW when compared to the base instance and stabilizes because it depends on projects' minimum date and the option presents significant environmental impacts. Small hydropower capacity also maintained a close range of capacity expansion values for most of the instances and decayed in the two last ones. In fact, small hydropower reaches the upper bound, indicating that this source could have had higher investments if there was no limitation because its trade-off between economic costs and environmental costs is pertinent.

The alpha parameter controls each objective function's weight. However, it is also important to understand the decision with no weighting, when all objectives have their original costs. Figure 4.18 and Figure 4.19 compare the results for both sets of instances. Regarding the group with the same additional constraints as PDE ([37]), it is possible to note by Figure 4.18 that there are no major significant differences when comparing to the instance ($\boldsymbol{\alpha} = \mathbf{0.5}$). This result was expected because both define the same weighting for the economic and environmental costs related to the system's operation and expansion investment, beside the fact that the solution space is strongly restrained.

Some difference in power expansion exists for solar and thermal sources. These are explained considering the other costs which are also related to expanding the transmission grid. For the instance with no alpha parameter, investments in natural gas and solar power were higher because they are better supported by transmission expansion as there are no differentiating weights. In other words, when all full costs are applied, the model understands that increasing solar PV for energy demand and, consequently, thermal plants to ensure power and dispatchability is interesting because the possibility of increasing transmission capacity between the subsystems has the same importance in the objective function, enabling the system to exchange more energy whenever necessary.

When conducting the same analysis for instances of the second group, in which the additional constraints were modified, the situation changes. Figure 4.19 shows that the instance with no alpha parameter shares roughly no similarities with case ($\boldsymbol{\alpha} = \mathbf{0.5}$). In fact, the no alpha instance reveals that as energy and power deficit costs, as well as the costs for expanding the transmission grid, equally compete with operation and investment economic and environmental costs, the model prefers to invest in less costly and impacting options because they are able to be supported by an expansion in the system's transmission capacity.

As an example, onshore wind is the most feasible option when considering both economic and environmental aspects, but the source is limited to Brazilian Northeast and South regions due to resource availability. Therefore, it would be necessary to invest in additional generation options in other regions in order to attend the demand, reason why there is considerable expansion of bioenergy thermal plants in the instance ($\boldsymbol{\alpha} = \mathbf{0.5}$) from the second group.

However, when all weights are removed, the model understands that investing in the increase of transmission capacity is a preferable solution because it can expand more the onshore wind source and also meet the overall required energy through exchange with other regions as long as there are fast and easily activated plants in the system. And that explains the investment rise in open-cycle natural gas thermal power plants, which are mostly responsible for providing this service.

Either way, both figures demonstrate that considering environmental aspects in the objective function, whether applying weights or not, changes the decision of power sector expansion. As previously mentioned, instance ($\boldsymbol{\alpha} = \mathbf{0.0}$) in the first group stands for the original indicative expansion plan from EPE ([91]) and, by adding costs related to GHG emissions and water consumption, the results indicate reduction in thermal power expansion that is non-related with power security purposes and increase in Solar PV. These are important outcomes to assure the importance of including sustainability into the official planning models.

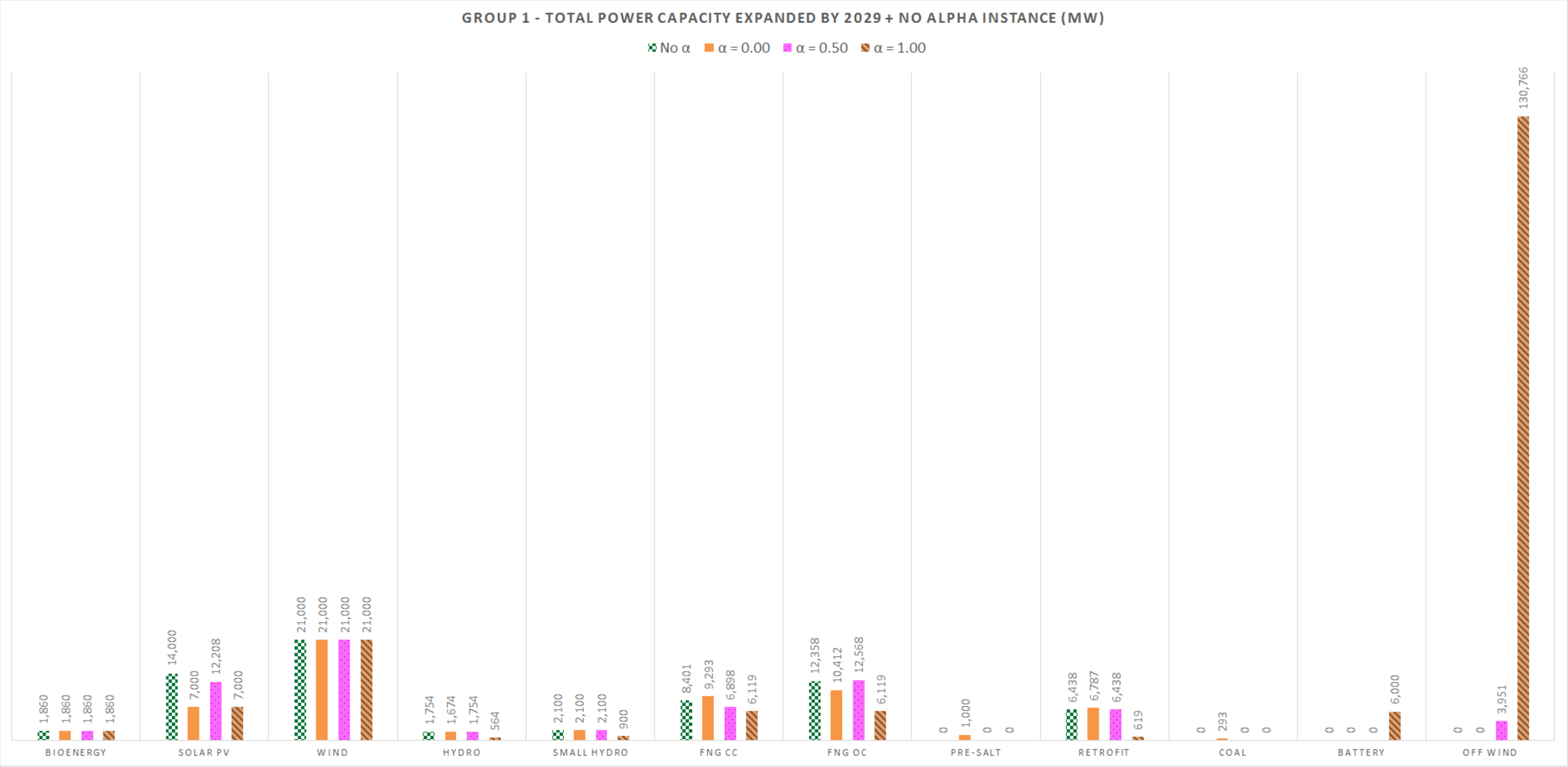

Figure 4.18: Group 1 - Total Capacity Expansion per Source by 2029 (MW) including no alpha instance. Source: the author.

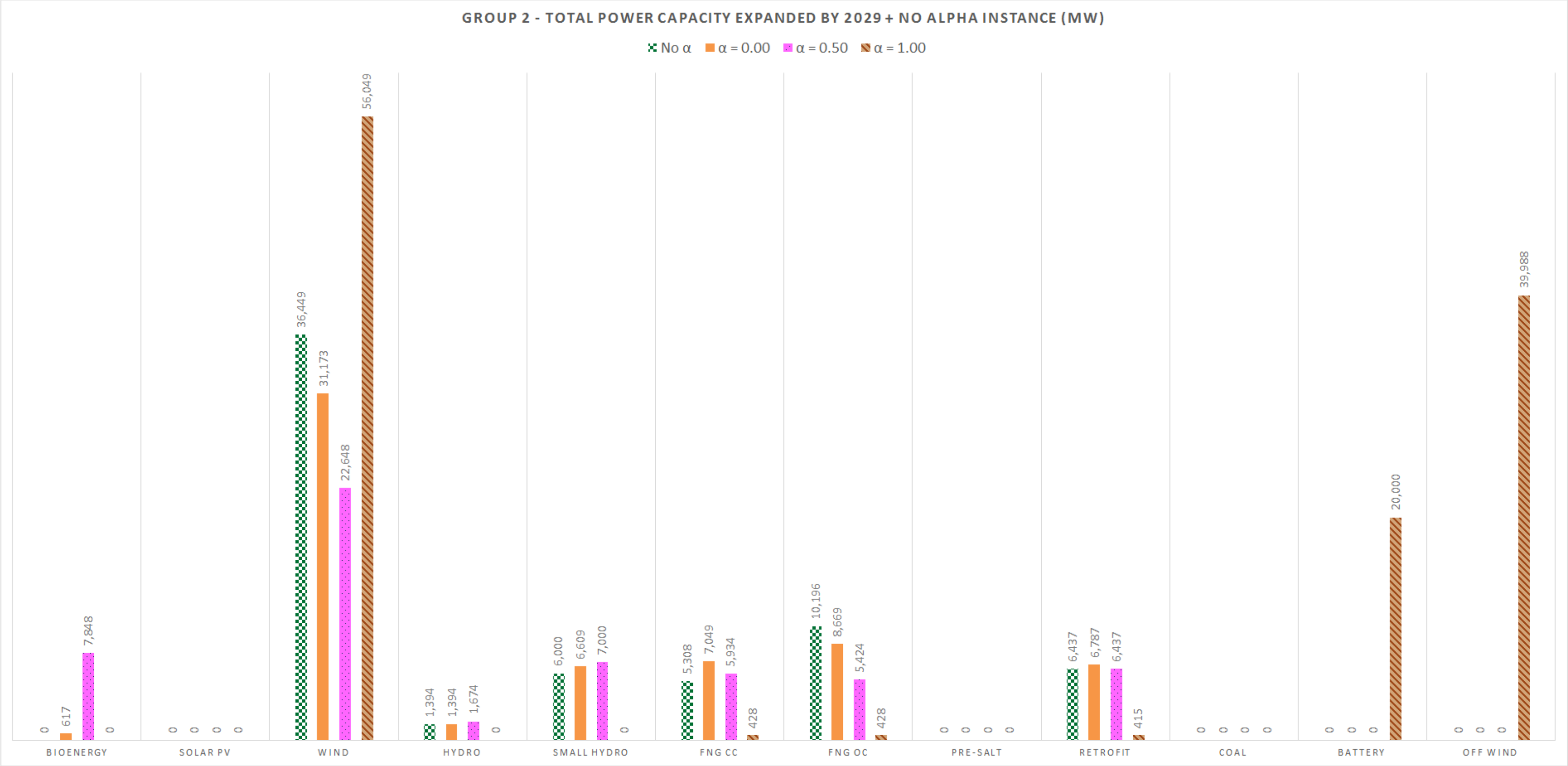

Figure 4.19: Group 2 - Total Capacity Expansion per Source by 2029 (MW) including no alpha instance. Source: the author.

For more information about the results, all the above commented costs as well as total emissions and water consumption values are presented in Appendix A.

4.4 Computational Results - $\boldsymbol{\epsilon}$-Constraint Method

The optimization problem presented in Section 3.3.3 was also coded in Python 3.7 and solved using the CPLEX solver v.12.1, but in a distinct environment. Since this is an iterative method and it consists of executing the model several times, the hardware configuration directly impacts the method performance. Thus, the experiments were performed in a server with an AMD 3960x 24c/48t and 128 GB DDR4.

In addition, the number of used hydrological series also affects the total execution time. In this sense, for the $\boldsymbol{\epsilon}$-Constraint method application two different series were considered instead of five. Both numbers were tested and an execution applying two hydrological series lasted for 22 hours, while the five hydrological series execution was not finished even after 48 hours.

The decreasing parameter that controls the number of executed iterations ($\boldsymbol{\delta}$) was defined considering ten iterations from the upper bound to the lower bound. Thus, for each instance the model was solved a hundred times altering the limiting bounds in the environmental-related constraints, according to algorithm 1 on Section 3.3.2. The required steps are presented in Equations (4.1) and (4.2).

$$\boldsymbol{\delta_{em}} = \frac{\boldsymbol{\epsilon_{\xi_{max_{em}}} - \epsilon_{\xi_{min_{em}}}}}{\mathbf{10}} \tag{4.1}$$

$$\boldsymbol{\delta_{wu}} = \frac{\boldsymbol{\epsilon_{\xi_{max_{wu}}} - \epsilon_{\xi_{min_{wu}}}}}{\mathbf{10}} \tag{4.2}$$

These values were determined considering that they offer a feasible trade-off between execution time and number of solutions, as they provide a total of a hundred optimal results for each instance.

Among all the optimal results, the non-dominated Pareto-optimal solutions, described in Section 2.6, were selected in order to build the Optimal Pareto-front. In this context, all the results obtained from the $\boldsymbol{\epsilon}$-Constraint method application and the consequent analyses are then presented in the next sections.

4.4.1 Economic Objective versus Environmental Objectives

As previously mentioned, in view of the original expansion problem, the adopted objective function consists of minimizing the total cost of expansion while the environmental aspects are incorporated as constraints. Therefore, the first relevant results are how each of both considered environmental impacts relate to the overall resulting costs.

In this sense, Figure 4.20 presents the two-dimensional Pareto front concerning emissions and the expansion cost for the instance with all original additional constraints from PDE (Section 4.2.1). From all the obtained optimal results from the model executions, the curve was created by discarding all the dominated solutions. Since it is a minimization problem, the non-dominated solutions are the ones closest located to where the axes begin, expressing the lowest possible emissions and costs.

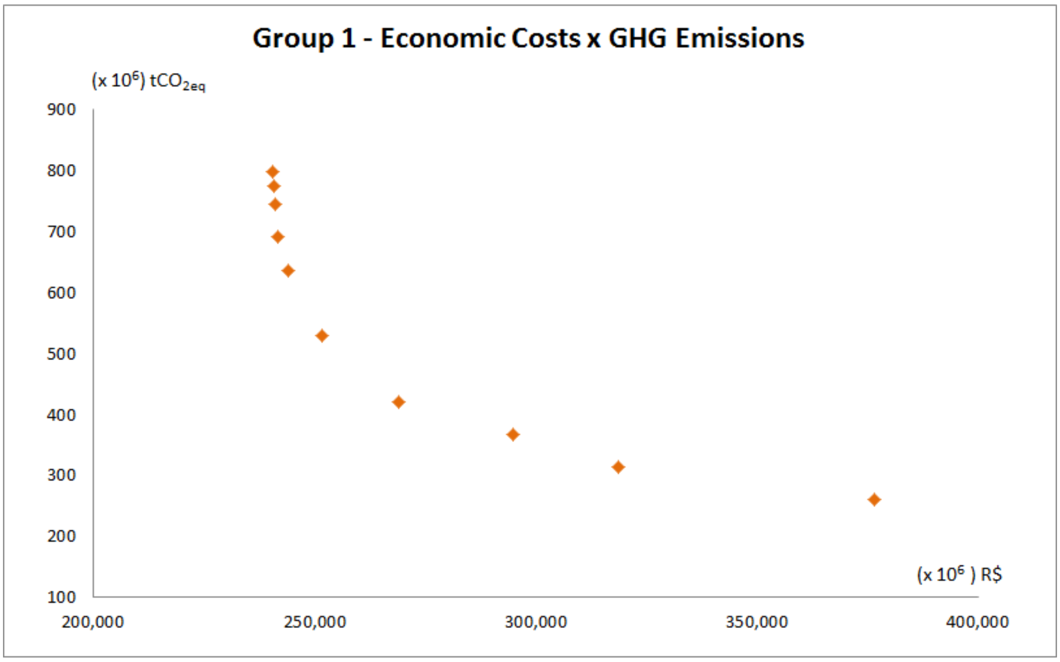

Figure 4.20: Pareto-front formed by Economic Objective and GHG Emissions Objective - Group 1. Source: the author.

Figure 4.20 reveals that approximately 100 $MtCO_{2eq}$ is able to be avoided without major increases in total expansion expense. However, reaching higher emissions reductions require a significant growth in the total cost. In order to achieve a decrease of 500 $MtCO_{2eq}$, the cost rises more than R$ 50 billion. In addition, GHG emission levels lower than 300 $MtCO_{2eq}$ become not financially beneficial as the cost starts to escalate in exchange for minor emissions reductions.

Similarly, Figure 4.21 demonstrates the results for the other environmental objective concerning the minimization of water consumption. Although the curve presents a similar pattern, it is possible to observe that higher water consumption reductions are able to achieved with feasible cost increases, when comparing to GHG emissions.

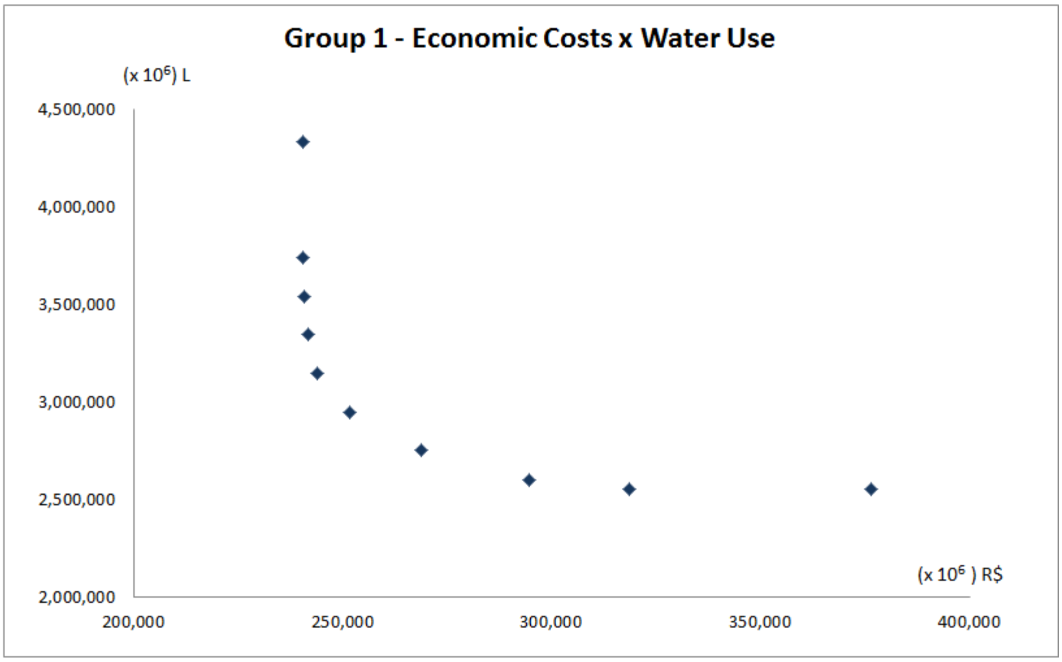

Figure 4.21: Pareto-front formed by Economic Objective and Water Consumption Objective - Group 1. Source: the author.

In this case, for the instance with the exact same additional constraints from PDE [37], approximately 1.2 trillion liters of virtual water consumption may be reduced maintaining the total expansion expense in a similar range. In this sense, the Pareto-front indicates that higher water volume reductions require a more significant cost increase. Yet, when the total water consumption level reaches approximately 2.5 trillion liters, the cost elevation starts to become unbearable since it leads to only marginal decrements in the expansion's virtual water consumption.

One aspect concerning the number of non-dominated solutions refers to the strongly restrained solution space. The possibility of deciding for new investment configurations depends on the additional constraints. As PDE ([91]) defines limiting constraints for the expansion options (Section 4.2.1) due to the sources' inherent characteristics in terms of operation and capacity, most of the solutions from the model executions are dominated, hence excluded from the Pareto-front.

In this regard, finding non-dominated solutions in the instance with modified additional constraints (Section 4.2.2) tends to be less challenging, since the applied changes aimed to flexibilize the solution space. Still, the other sets of constraints in the formulation are kept unaltered and the possibilities remain restricted in terms of ensuring energy and power supply. This explains why the next graphs referring to the instance with modified additional constraints present a few more non-dominated solutions for the same number of model executions.

Figure 4.22, as aforementioned, reveals the resulting Pareto-front concerning GHG emissions and costs for the instance with modified additional constraints. Similarly to the previous instance, Figure 4.22 also indicates that to diminish emissions the overall cost needs to increase, as expected for conflicting objectives. However, in this case the curve presents a different shape. After reaching 200 $MtCO_{2eq}$ of reduction in GHG emissions, the additional cost increment to continue decreasing the emissions begins to grow faster when comparing to the other instance (Figure 4.20).

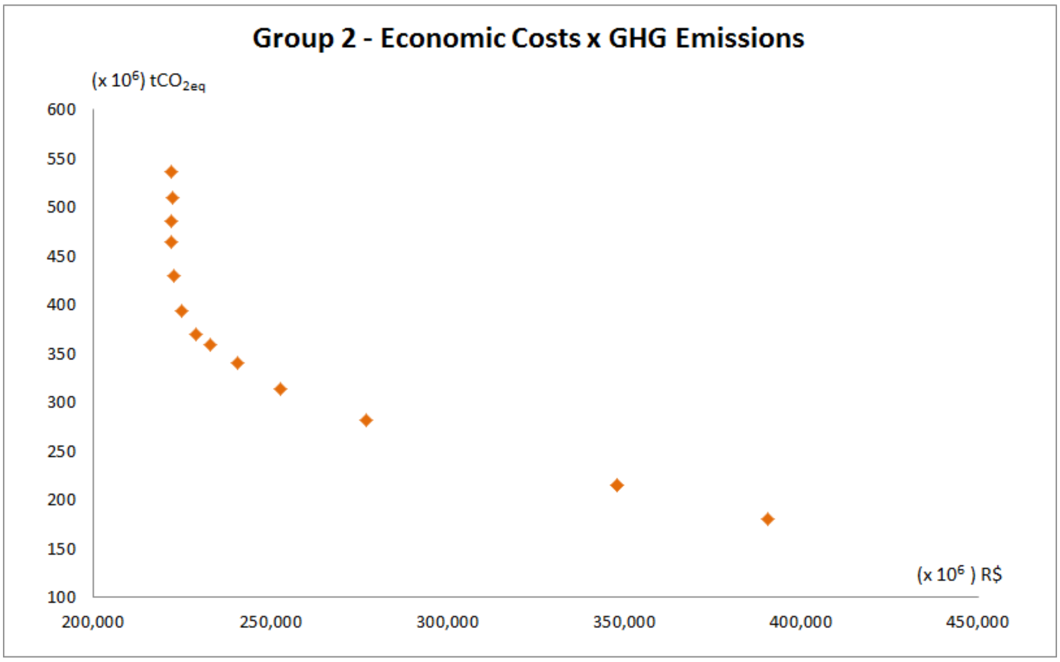

Figure 4.22: Pareto-front formed by Economic Objective and GHG Emissions Objective - Group 2. Source: the author.

Although in this case it is also possible to avoid 100 $MtCO_{2eq}$ with small cost impact, the situation is distinct. Since this instance includes modified additional constraints that enable the model to invest more power capacity in renewable sources, the results are naturally less intense in emissions and water than the previous instance's. In fact, decreasing up to 200 $MtCO_{2eq}$ in this instance is less costly than the same amount in the instance that maintains PDE's additional constraints, as observed from Figure 4.22. In view of this gap, it is demonstrated that easing the limiting values of additional constraints not only automatically result in less environmental impacting investment schedules, but also allow less expensive emissions reductions.

In terms of water consumption, Figure 4.23 indicates that the same behavior occurs. However, the adopted additional constraints already promote an expansion with a much smaller volume. Then, the overall reduction in quantity is less expressive than the achieved by the first instance. Still, the curve pattern's reveals the possibility of reducing approximately 0.4 trillion liters with little variation on total expansion cost.

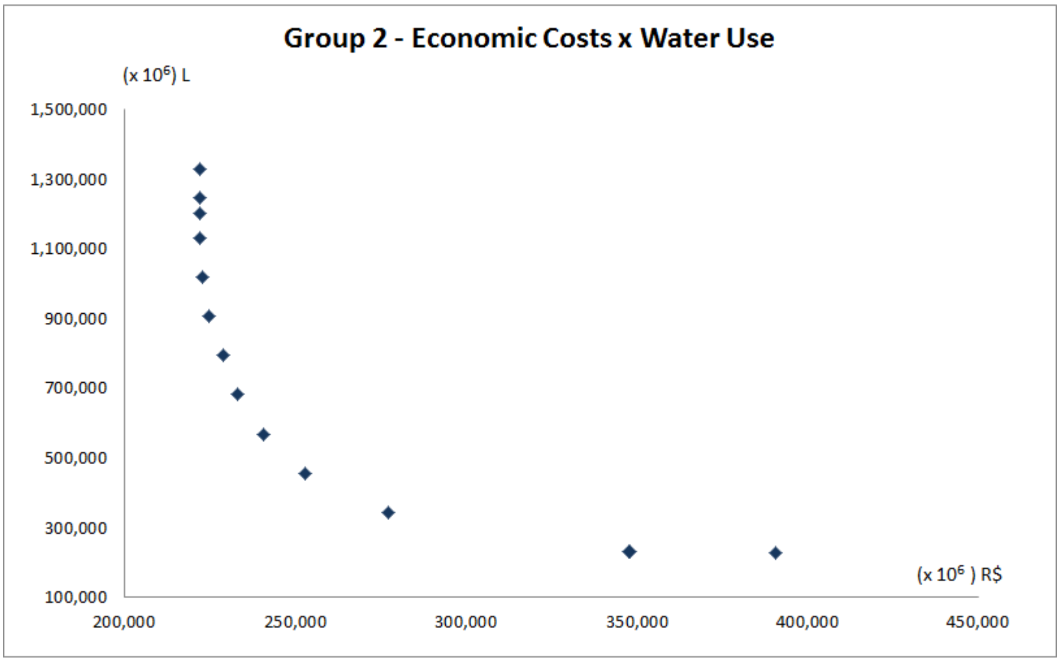

Figure 4.23: Pareto-front formed by Economic Objective and Water Consumption Objective - Group 2. Source: the author.

Differently from Figure 4.22, Figure 4.23 shows that, in terms of water consumption, the Pareto-front related to the altered additional constraints instance stabilizes for a volume of around 0.2 trillion liters, representing a virtual decrease of 1.2 trillion liters. After this value, the cost increment of each marginal water volume reduction escalates quickly. Consequently, it is possible to affirm that lowering up to 1.2 trillion liters maintains a feasible trade-off between cost increase and the impact mitigation.

The presented Pareto-fronts provide information on how the total expansion cost behaves once other investment schedules are opted in order to mitigate total GHG emissions and water consumption. The decision making process is then able to evaluate and address financial concerns regarding the willingness and possibility of increasing overall costs in exchange for environmental benefits, depending on resource allocation, adopted policy and intended goals.

However, the inserted graphs are bidimensional and only compare two of the problem objectives at a time out of the existing three. Since the adopted objectives are independent, it is important to analyze them together considering that the intention is to decide for an investment schedule that contemplates all in an integrative approach. Then, the next section presents graphs connecting all three objectives.

4.4.2 Pareto-front: Economic Costs x GHG Emissions x Water Consumption

The adopted Weighted Sum Method approach unified the three existing objectives in a mono-objective formulation by considering external costs for the environmental impacts and a parameter that controlled the weight of the environmental objectives within the whole function. As previously discussed, there is loss of information when applying this process since (i) the problem seeks to minimize the overall cost, not the actual impacts, and (ii) the weighting parameter controls both environmental objectives together.

In view of this, applying the $\boldsymbol{\epsilon}$-Constraint Method was indeed an opportunity of minimizing each impact individually, not by corresponding internalized external costs, but by their relation to the operation and expansion of power sources. Since the environmental objectives conflict with the economic objective and both GHG emissions and water consumption are interconnected due to the available sources, the formed Pareto-front reveals how they affect each other, which assists the decision maker in the planning process.

Figure 4.24 and Figure 4.25 present the three-dimensional representation of the Pareto-front for the instance with all the original additional constraints from PDE ([37]). The vertical axis stands for the Economic Objective while each horizontal axis stands for one of the Environmental Objectives. The vertical bar indicates the solution's corresponding total cost according to the assigned color.

Similarly, Figure 4.26 and Figure 4.27 present the three-dimensional representation of the Pareto-front for the instance with all the modified additional constraints. As discussed below, the possibility of observing the front in three-dimensional graphs enriches the perception of how all the defined objectives relate and behave. In this regard, two distinct views are displayed in each figure, to better capture the nuances of the graphics.

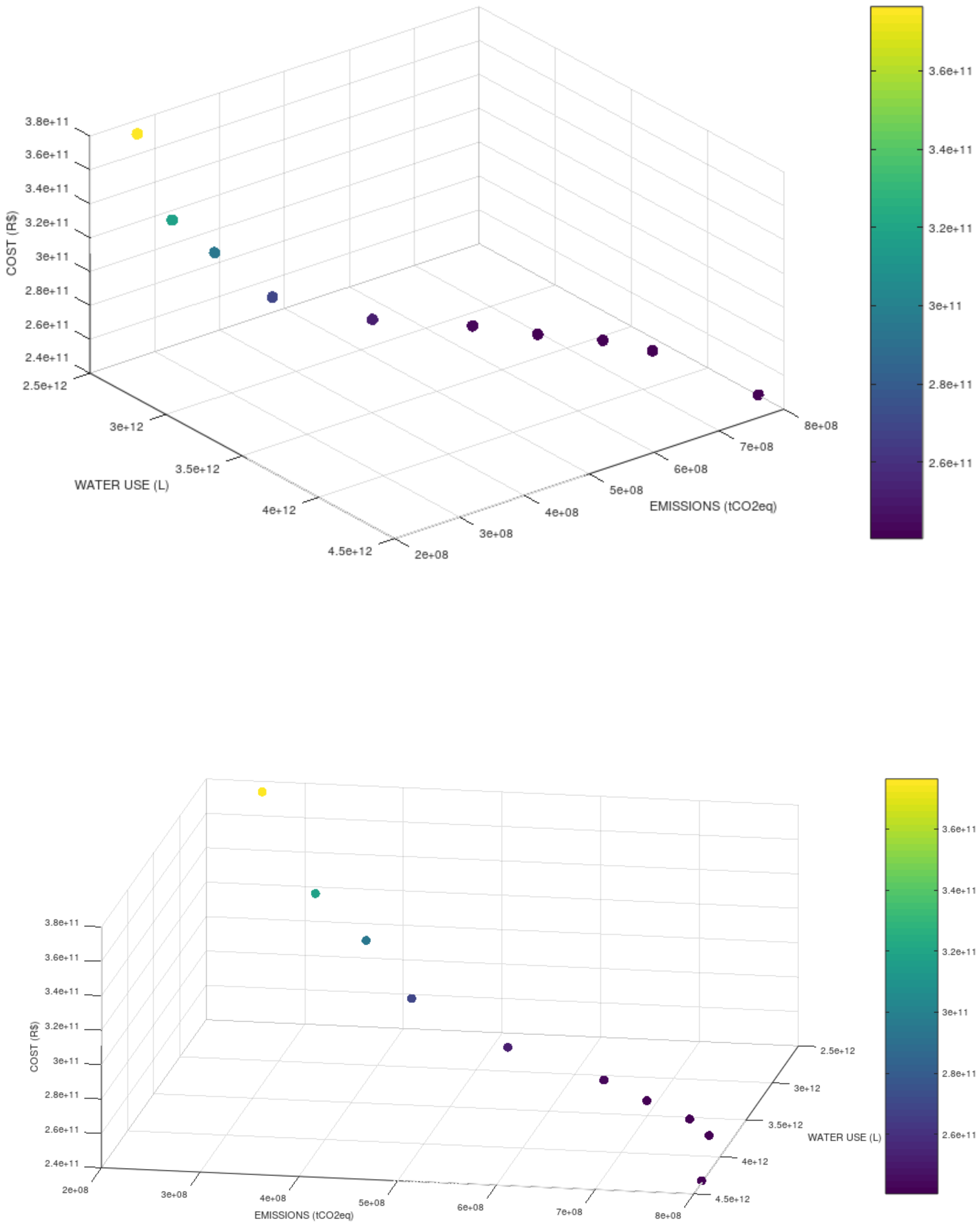

Figure 4.24: Pareto-front formed by All Existing Objectives 1 - Group 1. Source: the author.

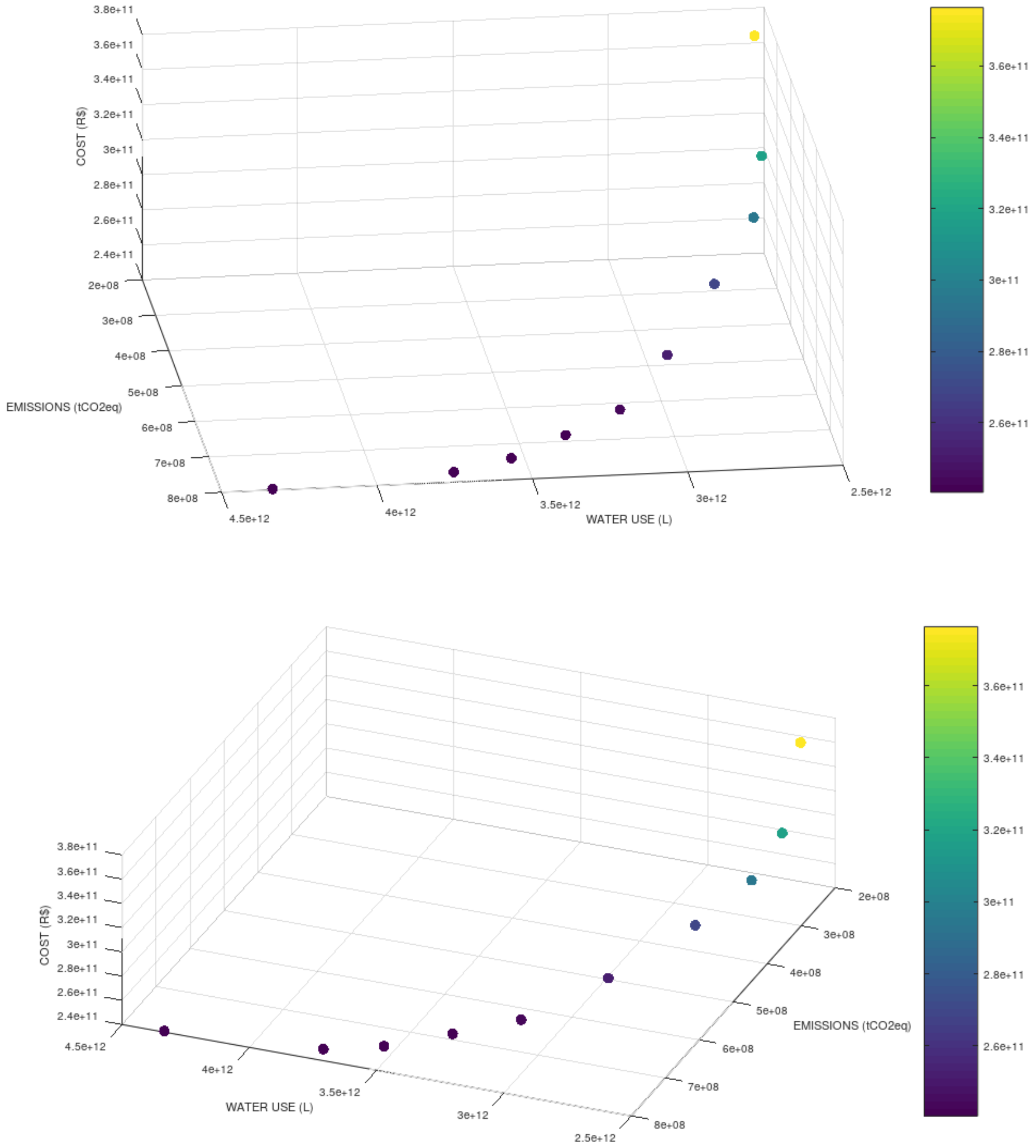

Figure 4.25: Pareto-front formed by All Existing Objectives 2 - Group 1. Source: the author.

For instance, in the case of the instance with all the original additional constraints (Group 1), Figure 4.24 and Figure 4.25 reveal that initially the model finds opportunities to reduce water consumption while maintains the GHG emissions, which is due to the fact that the first iterations occur setting the maximum upper bound value for emissions. In addition, this is also the initial trend of the instance as the Weighted Sum results presented the same pattern, as shown in Figure 4.12.

Through Figures 4.24 and 4.25 it is also possible to observe that in the first model executions, when GHG emissions and water consumption volumes are close to their respective upper bounds, significant impact reductions are achieved with relatively small cost increment when taking into account the total's order of magnitude. In fact, a representative share of the front's length corresponds to a cost range between R$ 240 and 280 billion. The results corroborate with the increase in the expansion cost previously illustrated in the other method, which presents a reasonable variation for the initial values of the $\boldsymbol{\alpha}$ parameter (Figure 4.2).

Moreover, the curvature expresses how both impacts are concomitantly decreasing while the cost rises. Apart from the initial executions which basically opted for prioritizing reductions in water consumption, GHG emission levels begin to drop as well along the front, as it is visible due to the the diagonal pattern. This means that the curves introduced in Section 4.4.1 reflect cost variations in a joint action of both environmental impacts. In other words, those expressed cost values in the graphs result from GHG emissions decreasing in consonance with water consumption reduction and vice versa, not from each objective operating individually.

Correspondingly, Figure 4.26 and Figure 4.27 exhibit the graphs for the instance with modified additional constraints, also demonstrating how the cost values grow due to the simultaneous decrease in the adopted environmental objectives.

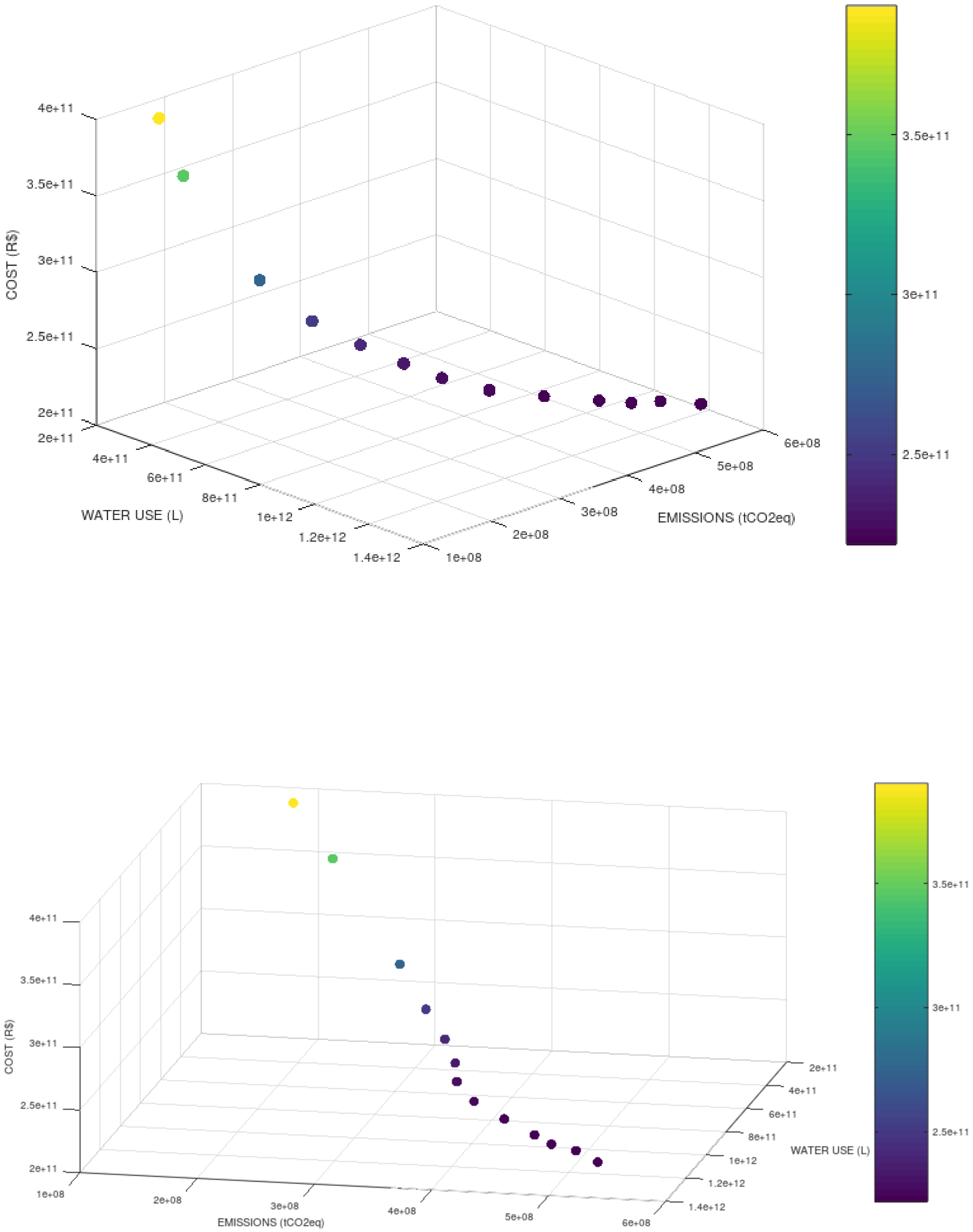

Figure 4.26: Pareto-front formed by All Existing Objectives 2 - Group 2. Source: the author.

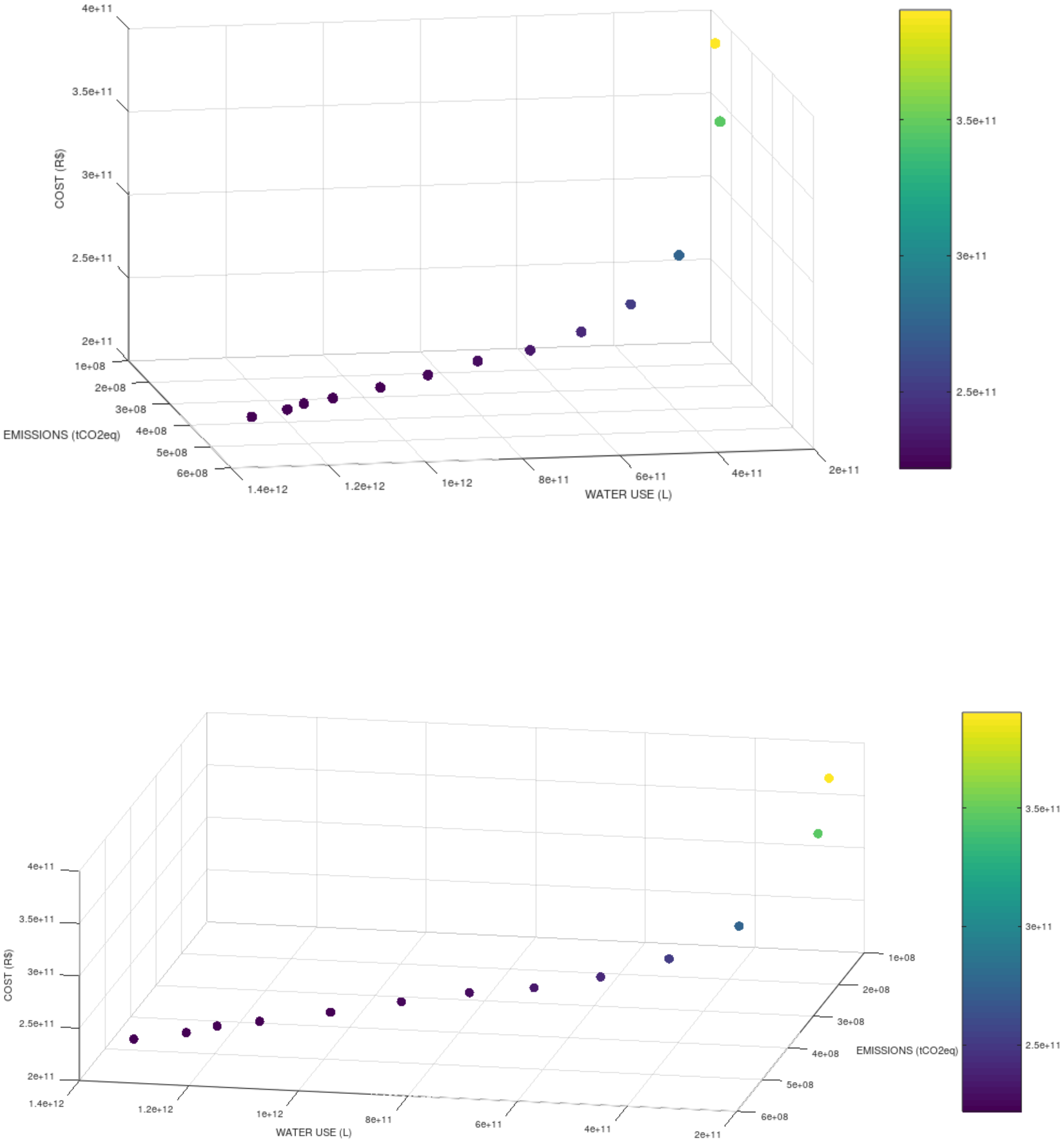

Figure 4.27: Pareto-front formed by All Existing Objectives - Group 2. Source: the author.

In this case, unlike the previous instance, Figure 4.26 and Figure 4.27 indicate that both environmental impacts begin to decrease since the first method iterations. In Section 4.3.2, Figure 4.13 revealed that the formulated application of the Weighted Sum Method caused the water consumption to increase up to a determined level while the environmental objective's weight in the overall function was also incrementing.

This behaviour happened due to the fact that both environmental impacts were incorporated in the objective function modulated by the same parameter. In order to reach a minimum cost, considering that emissions were more expensive than water consumption, the model chose to focus in reducing GHG emissions. For the $\boldsymbol{\epsilon}$-Constraint method application, the water consumption objective diminishes for all model executions because it is detached from the GHG emissions objective.

An observed pattern for this instance is the balance between both environmental aspects. The diagonal front appears to be located closer to the center of the plane when compared to the instance with all the original additional constraints. It indicates a clearer existing equilibrium between GHG emissions and water consumption for less restrained expansion of power sources. In this sense, relaxing the additional constraints, i.e. increasing maximum renewable capacity available for expansion, is not only capable of generating less environmental impacting investment schedules without even considering emissions or water consumption, but it is also capable to more equally avoid or mitigate both impacts with the same solution.

Despite the aforementioned singularity and some other differences, both instances present a similar pattern. In this sense, the Pareto-fronts demonstrate that, whether maintaining the existing additional constraints or flexibilizing them, there is opportunity to significantly decrease GHG emissions and water consumption in the power generation expansion process. In fact, both reveal that almost half of the possible reduction in the environmental impacts is able to be achieved by increasing the total expansion cost in less than R$ 40 billion.

PDE 2029 ([91]) states that the indicative reference generation expansion requires estimated investments in the order of R$ 239 billion by 2029. Considering this cost, R$ 40 billion represents approximately 17% of the total share. In other words, half of the virtual GHG emissions and water consumption volume of the actual power expansion investment schedule may be avoided by increasing the solution cost in 17%.

Still, depending on the financial feasibility, these Pareto-fronts are able to indicate the related decrease in emissions and water consumption for a defined cost, being capable of assisting the decision maker in the planning process. The complete results obtained from the $\boldsymbol{\epsilon}$-Constraint method application are also presented in Appendix A.

Chapter 5

Conclusions and Future Studies

This work tackled the Generation Expansion Problem - GEP - considering the Climate-Water-Energy nexus in order to find the optimal investment schedule of electricity generation sources not only in an economic perspective, but also through a more sustainable outlook. Given the current world situation concerning Climate Change and other sorts of ecological collapses, planning future energy generation without including the different impacts this activity imposes to natural environment goes against humanity goals and, thus, new methodologies are being required.

Therefore, this dissertation proposed a reformulation of the original mathematical model that is applied for official power generation expansion planning in Brazil. The implemented approaches were based on multi-objective optimization and sought to include environmental considerations referring to related GHG emissions and water consumption of each available project for investment.

The obtained results demonstrated that the model in its current state indicates an investment schedule with higher GHG emission levels and water consumption volume. They also reveal that these mentioned environmental impacts are able to be fairly reduced over an increase in total expansion cost as a trade-off, mostly due to the necessity of investing in larger quantities of renewable energy generation. The group with more constrained instances opted for expanding solar photovoltaics, battery and offshore wind power capacities, while decreasing open cycle natural gas power plants.

Yet, the second group, with more flexible constrains, chose to maximize onshore wind power capacity and also invest in thermoelectric plants running on wood chip and biogas. Both, however, indicated the expansion of batteries and high power quantity of offshore wind, mainly for the instances with low or absent financial costs. In relation to official planning, these options are often not invested precisely due to their exorbitant involved costs.

In terms of the existing relations between all three adopted objectives, the analysis of Pareto-fronts formed by Pareto-optimal solutions become a possibility to assist in the decision-making process. They reveal the amount of avoided emissions and water volume that is able to be achieved according to the expansion total cost.

In view of these results, this work brings a good contribution to the Brazilian power sector, which seeks to adapt towards a more sustainable activity. Brazil has committed to reduce overall emissions under the Paris Agreement and this dissertation brought light on how to achieve this target in a feasible way, balancing both economic and environmental aspects. It also discussed a methodology to calculate emissions and water consumption impacts for the system's available projects, as well as how to incorporate environmental aspects into the mathematical formulation.

Furthermore, the obtained data brought information over GHG emissions and water consumption of different power generation sources, which is relevant to the planning process. For instance, hydropower generation is usually considered as a sustainable source, but the provided data showed that extensive hydropower units are also related to large GHG emissions when considering the project's life-cycle. In this sense, this work also accomplishes the objective of demonstrating that all sources need to be properly addressed in order to reach environmental outcomes in generation expansion planning.

However, the adopted methodology still has limitations. The valuation process of assigning monetary values for environmental impacts prevents the model from actually saving defined quantities of natural resources. It is a disadvantage because the results stand for monetary savings that may not reflect impact reduction in the same proportion. It is recommended that new studies test other monetary values for externalities, observing how the investment schedule behaves when applying higher costs.

Besides, emissions and water consumption factors may vary within a wide range of values depending on the context, indicating that more work needs to be conducted on carbon an water accounting in the life cycle of power sources in Brazil. In fact, more comprehensive water stress indicators would better represent the associated environmental impacts rather than just water consumption. In addition, as water resources management in Brazil is a crucial topic, these should address the problem of how to calculate proper water stress indicators in the Brazilian context, taking into account particularities of the regions and basins.

Understanding the complexity of all the distinct environmental impacts related to power generation and expansion, new analyses concerning other impacts rather than GHG emissions and water consumption are encouraged - biodiversity, land use, waste generation and others - as well as the possibility of introducing a climate risk. Moreover, in terms of sustainability, it is also important to assess other possible technological options such as Carbon Capture and Storage and to consider the existing social impacts related to the problem.

In terms of computational efforts, it was not possible to investigate strategies to improve the model performance or reinforce the formulation. In this sense, research on that matter may be capable of efficiently reduce total execution time. Solving the problem through other methods, e.g. metaheuristic approaches, is also an interesting opportunity to investigate other possible investment schedules.

In any case, we expect that the results provided in this dissertation can contribute in guiding the nation's future energy planning on the importance of considering environmental aspects.

Acknowledgements

In this section, I would like to Acknowledge CAPES - *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* - for sponsoring this work with the Graduate Studies Grant, which allowed the necessary research and study for the purpose of this dissertation's execution.

Appendix A

Tables of Results

This appendix presents the solver results for all created instances of the Weighted Sum method application, separated by their respective groups, and for the non-dominated solutions of the $\boldsymbol{\epsilon}$-Constraint method application.

The first table - Table A.1 - refers to the set which maintained the original additional constraints from PDE 2029 ([37, 91]), while the second - Table A.2 - refers to the set with modified additional constraints. The graph charts in Section 4.3 originated from this data.

Similarly, the third - Table A.3 - and fourth - Table A.4 - tables show the results when altering $\boldsymbol{\epsilon_{\xi_{em}}}$ and $\boldsymbol{\epsilon_{\xi_{wu}}}$ in the created environmental constraints of the $\boldsymbol{\epsilon}$-Constraint method application for both instances with the original and modified additional constraints. The graph charts presented in Section 4.4 originated from this data.

Table A.1: Optimization Results for Instances of Group 1 - Weighted Sum Method. Source: the author.

α	Total OF (R$)	Energy Deficit (R$)	Power Deficit (R$)	Total Other Costs (R$)	Op[1]Cost w/o Other Costs (R$)	Exp[2]Cost w/o Other Costs (R$)	Total OF w/o Other Costs (R$)	Economic Cost Op (R$)	Emissions Op (tCO_{2eq})	Emissions Cost Op (R$)	Water Cons Op (L)	Water Cons Cost Op (R$)	Economic Cost Exp (R$)	Emissions Exp (tCO_{2eq})	Emissions Cost Exp (R$)	Water Cons Exp (L)	Water Cons Cost Exp (R$)	Total Emissions (tCO_{2eq})	Total Emissions Cost (R$)	Total Water Cons (L)	Total Water Cons Cost (R$)	Environmental Cost (R$)
0.00	3.80E+11	2.94E+10	4.11E+09	3.59E+10	1.34E+11	2.11E+11	3.44E+11	1.08E+11	6.05E+08	2.12E+10	1.10E+12	3.84E+09	1.85E+11	2.16E+08	5.79E+09	6.70E+12	1.96E+10	8.21E+08	2.70E+10	7.81E+12	2.34E+10	5.05E+10
0.10	3.71E+11	2.94E+10	3.67E+09	3.56E+10	1.33E+11	2.02E+11	3.36E+11	1.08E+11	5.99E+08	2.10E+10	1.09E+12	3.77E+09	1.86E+11	2.19E+08	5.85E+09	3.32E+12	1.02E+10	8.18E+08	2.69E+10	4.41E+12	1.40E+10	4.08E+10
0.20	3.69E+11	2.94E+10	3.66E+09	3.56E+10	1.33E+11	2.01E+11	3.34E+11	1.08E+11	5.96E+08	2.09E+10	1.08E+12	3.75E+09	1.87E+11	2.19E+08	5.86E+09	2.49E+12	7.90E+09	8.15E+08	2.68E+10	3.58E+12	1.17E+10	3.84E+10
0.30	3.69E+11	2.94E+10	3.66E+09	3.55E+10	1.33E+11	2.01E+11	3.34E+11	1.08E+11	5.93E+08	2.08E+10	1.08E+12	3.74E+09	1.87E+11	2.19E+08	5.86E+09	2.46E+12	7.80E+09	8.12E+08	2.67E+10	3.54E+12	1.15E+10	3.82E+10
0.40	3.69E+11	2.94E+10	2.99E+09	3.44E+10	1.34E+11	2.01E+11	3.35E+11	1.09E+11	5.97E+08	2.09E+10	1.09E+12	3.76E+09	1.88E+11	2.04E+08	5.53E+09	2.41E+12	7.70E+09	8.02E+08	2.64E+10	3.49E+12	1.15E+10	3.79E+10
0.50	3.70E+11	2.94E+10	2.50E+09	3.37E+10	1.33E+11	2.02E+11	3.36E+11	1.09E+11	5.89E+08	2.05E+10	1.08E+12	3.72E+09	1.89E+11	2.06E+08	5.57E+09	2.39E+12	7.66E+09	7.94E+08	2.61E+10	3.46E+12	1.14E+10	3.75E+10
0.60	3.70E+11	2.94E+10	2.44E+09	3.34E+10	1.33E+11	2.04E+11	3.37E+11	1.09E+11	5.73E+08	2.00E+10	1.06E+12	3.64E+09	1.91E+11	2.07E+08	5.60E+09	2.38E+12	7.64E+09	7.80E+08	2.56E+10	3.44E+12	1.13E+10	3.69E+10
0.70	3.71E+11	2.94E+10	2.44E+09	3.32E+10	1.32E+11	2.06E+11	3.38E+11	1.08E+11	5.58E+08	1.95E+10	1.04E+12	3.58E+09	1.93E+11	2.07E+08	5.63E+09	2.38E+12	7.64E+09	7.65E+08	2.52E+10	3.42E+12	1.12E+10	3.64E+10
0.80	3.76E+11	2.94E+10	2.44E+09	3.26E+10	1.29E+11	2.14E+11	3.44E+11	1.07E+11	5.31E+08	1.86E+10	9.98E+11	3.46E+09	2.01E+11	1.95E+08	5.29E+09	2.37E+12	7.35E+09	7.25E+08	2.39E+10	3.37E+12	1.08E+10	3.47E+10
0.90	4.05E+11	2.94E+10	2.44E+09	3.21E+10	1.05E+11	2.68E+11	3.73E+11	8.76E+10	3.74E+08	1.43E+10	7.32E+11	2.72E+09	2.56E+11	1.95E+08	5.31E+09	2.37E+12	7.36E+09	5.69E+08	1.96E+10	3.10E+12	1.01E+10	2.96E+10
1.00	9.60E+11	2.95E+10	2.44E+09	3.21E+10	9.47E+10	8.33E+11	9.28E+11	8.27E+10	2.24E+08	1.01E+10	4.34E+11	1.91E+09	8.21E+11	1.92E+08	5.24E+09	2.28E+12	6.89E+09	4.16E+08	1.53E+10	2.72E+12	8.80E+09	2.41E+10

[1] Op stands for Operation.
[2] Exp stands for Expansion.

Table A.2: Optimization Results for Instances of Group 2 - Weighted Sum Method. Source: the author.

α	Total OF (R$)	Energy Deficit (R$)	Power Deficit (R$)	Total Other Costs (R$)	Op[1]Cost w/o Other Costs (R$)	Exp[2]Cost w/o Other Costs (R$)	Total OF w/o Other Costs (R$)	Economic Cost Op (R$)	Emissions Op (tCO_{2eq})	Emissions Cost Op (R$)	Water Cons Op (L)	Water Cons Cost Op (R$)	Economic Cost Exp (R$)	Emissions Exp (tCO_{2eq})	Emissions Cost Exp (R$)	Water Cons Exp (L)	Water Cons Cost Exp (R$)	Total Emissions (tCO_{2eq})	Total Emissions Cost (R$)	Total Water Cons (L)	Total Water Cons Cost (R$)	Environmental Cost (R$)
0.00	3.46E+11	2.94E+10	3.41E+09	3.80E+10	1.02E+11	2.06E+11	3.08E+11	8.13E+10	4.58E+08	1.72E+10	8.45E+11	3.12E+09	1.93E+11	1.87E+08	5.04E+09	2.58E+12	8.07E+09	6.45E+08	2.22E+10	3.43E+12	1.12E+10	3.34E+10
0.10	3.45E+11	2.94E+10	3.43E+09	3.76E+10	1.02E+11	2.06E+11	3.08E+11	8.18E+10	4.49E+08	1.68E+10	8.42E+11	3.09E+09	1.93E+11	1.87E+08	5.04E+09	2.56E+12	8.02E+09	6.36E+08	2.19E+10	3.41E+12	1.11E+10	3.30E+10
0.20	3.45E+11	2.94E+10	3.46E+09	3.69E+10	1.02E+11	2.06E+11	3.09E+11	8.26E+10	4.43E+08	1.66E+10	8.89E+11	3.18E+09	1.93E+11	1.87E+08	5.05E+09	2.58E+12	8.06E+09	6.30E+08	2.17E+10	3.47E+12	1.12E+10	3.29E+10
0.30	3.46E+11	2.94E+10	3.53E+09	3.56E+10	1.03E+11	2.08E+11	3.10E+11	8.30E+10	4.34E+08	1.63E+10	9.05E+11	3.23E+09	1.94E+11	1.89E+08	5.09E+09	2.72E+12	8.39E+09	6.22E+08	2.14E+10	3.62E+12	1.16E+10	3.30E+10
0.40	3.46E+11	2.94E+10	3.53E+09	3.47E+10	1.03E+11	2.09E+11	3.12E+11	8.39E+10	4.23E+08	1.59E+10	9.45E+11	3.31E+09	1.95E+11	1.89E+08	5.10E+09	2.77E+12	8.51E+09	6.12E+08	2.10E+10	3.71E+12	1.18E+10	3.28E+10
0.50	3.48E+11	2.94E+10	2.44E+09	3.26E+10	1.05E+11	2.11E+11	3.15E+11	8.60E+10	4.05E+08	1.52E+10	1.02E+12	3.49E+09	1.97E+11	1.91E+08	5.18E+09	2.82E+12	8.68E+09	5.96E+08	2.04E+10	3.84E+12	1.22E+10	3.25E+10
0.60	3.49E+11	2.94E+10	2.44E+09	3.21E+10	1.02E+11	2.15E+11	3.17E+11	8.44E+10	3.73E+08	1.41E+10	1.02E+12	3.43E+09	2.01E+11	1.93E+08	5.22E+09	2.82E+12	8.72E+09	5.65E+08	1.93E+10	3.84E+12	1.22E+10	3.14E+10
0.70	3.51E+11	2.94E+10	2.44E+09	3.21E+10	9.41E+10	2.25E+11	3.19E+11	7.84E+10	3.21E+08	1.25E+10	9.32E+11	3.18E+09	2.11E+11	1.93E+08	5.24E+09	2.74E+12	8.48E+09	5.14E+08	1.78E+10	3.67E+12	1.17E+10	2.94E+10
0.80	3.59E+11	2.95E+10	2.44E+09	3.22E+10	8.18E+10	2.45E+11	3.27E+11	6.82E+10	2.71E+08	1.09E+10	7.82E+11	2.72E+09	2.33E+11	1.64E+08	4.47E+09	2.60E+12	7.67E+09	4.35E+08	1.53E+10	3.38E+12	1.04E+10	2.57E+10
0.90	3.76E+11	2.95E+10	2.44E+09	3.21E+10	7.27E+10	2.71E+11	3.44E+11	6.18E+10	2.02E+08	8.51E+09	7.12E+11	2.44E+09	2.59E+11	1.60E+08	4.39E+09	2.42E+12	7.10E+09	3.62E+08	1.29E+10	3.14E+12	9.54E+09	2.24E+10
1.00	8.82E+11	2.95E+10	2.44E+09	3.21E+10	5.20E+10	7.98E+11	8.50E+11	4.54E+10	1.11E+08	5.56E+09	1.99E+11	9.99E+08	7.87E+11	1.88E+08	5.26E+09	2.12E+12	5.93E+09	2.99E+08	1.08E+10	2.32E+12	6.93E+09	1.78E+10

[1] Op stands for Operation.
[2] Exp stands for Expansion.

Table A.3: Optimization Results for Instance with Original Additional Constraints - $\boldsymbol{\epsilon}$-Constraint Method. Source: the author.

$\epsilon_{\xi_{em}}$ (tCO_{2eq})	$\epsilon_{\xi_{wu}}$ (L)	**Total OF** (**R$**)	**Emissions** (tCO_{2eq})	**Water Cons** (**L**)
799,136,892.00	4,335,434,742,536.00	240,510,267,837.81	799,131,884.55	4,335,373,306,738.77
799,136,892.00	3,742,297,058,923.40	240,670,769,987.52	775,321,341.62	3,742,297,049,501.70
745,205,758.50	3,544,584,497,719.20	240,980,526,756.97	745,204,963.99	3,544,584,491,442.74
691,274,625.00	3,346,871,936,515.00	241,779,473,694.70	691,267,480.42	3,346,871,932,481.64
637,343,491.50	3,149,159,375,310.80	243,906,584,080.01	637,336,233.73	3,149,159,369,935.65
529,481,224.50	2,951,446,814,106.60	251,756,725,422.70	529,476,790.21	2,951,446,808,945.31
421,618,957.50	2,753,734,252,902.40	268,937,857,088.79	421,611,494.02	2,753,734,251,799.82
367,687,824.00	2,753,734,252,902.40	294,823,270,555.12	367,680,902.60	2,604,394,511,149.20
313,756,690.50	2,556,021,691,698.20	318,662,956,527.38	313,747,379.81	2,556,021,686,736.14
259,825,557.00	2,556,021,691,698.20	376,402,928,005.35	259,818,207.72	2,556,021,688,961.52

Table A.4: Optimization Results for Instance with Modified Additional Constraints - $\boldsymbol{\epsilon}$-Constraint Method. Source: the author.

$\epsilon_{\xi_{em}}$ (tCO_{2eq})	$\epsilon_{\xi_{wu}}$ (L)	**Total OF** (**R$**)	**Emissions** (tCO_{2eq})	**Water Cons** (**L**)
536,082,584.00	1,359,537,783,648.00	221,912,225,125.68	536,079,480.47	1,330,474,735,798.99
536,082,584.00	1,246,666,903,796.10	222,197,758,653.38	510,229,153.79	1,246,666,900,560.59
500,589,083.50	1,246,666,903,796.10	222,042,087,762.76	485,415,301.67	1,201,852,483,640.70
500,589,083.50	1,133,796,023,944.20	222,115,870,381.59	465,095,583.00	1,133,796,016,014.63
500,589,083.50	1,020,925,144,092.30	222,897,794,235.10	429,602,082.50	1,020,925,137,320.66
500,589,083.50	908,054,264,240.40	224,843,149,413.51	394,108,582.00	908,054,254,318.47
465,095,583.00	682,312,504,536.60	233,003,868,436.65	358,615,081.50	682,312,496,075.80
465,095,583.00	230,828,985,129.00	347,923,521,985.09	215,269,838.99	230,828,975,893.09
429,602,082.50	795,183,384,388.50	229,027,621,180.87	369,715,081.50	795,183,383,035.25
394,108,582.00	569,441,624,684.70	240,609,530,060.61	340,121,581.00	569,441,621,046.21
358,615,081.50	456,570,744,832.80	252,791,344,624.08	314,221,581.00	456,570,742,754.44
287,628,080.50	343,699,864,980.90	277,064,002,330.91	282,300,549.75	343,699,863,146.10
252,134,580.00	230,828,985,129.00	347,808,638,647.19	215,219,786.88	230,828,977,870.16
181,147,579.00	230,828,985,129.00	390,495,098,696.67	181,147,579.00	226,578,127,951.88

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