SOCIOECONOMIC IMPACTS OF LONG-TERM RENEWABLE ELECTRICITY GENERATION: A MULTI-REGIONAL ANALYSIS FOR BRAZIL

Lilia Caiado Coelho Beltrão Couto

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DECLARATION

I, Lilia Caiado Coelho Beltrão Couto, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

London, June 2023

Lilia Caiado Coelho Beltrão Couto

ABSTRACT

This thesis contributes to long-term renewable energy policymaking in developing economies by quantifying the net multi-regional macroeconomic, sectoral, and distributional impacts of renewable electricity investment in the case of Brazil from 2020 to 2050. Brazil has an outstanding potential for renewable electricity generation concentrated in its least developed region, the Northeast. New wind and solar power plants are currently channelling unprecedented investments to the Northeast, which should continue in the long run to maintain the low-carbon profile of electricity generation, potentially creating positive socioeconomic impacts and reducing regional inequalities. This thesis developed a recursive-dynamic Computable General Equilibrium (CGE) model called TERM-BR E15, which has representations of Brazil's five official geoeconomic regions, nine electricity generation sources, ten household income bands and ten wage levels. The CGE model simulations consist of soft links with three energy-system models which provided two long-term renewable electricity policy scenarios and a baseline. Additionally, two industrial strategy options were simulated. Modelling results were tested against the policymaking process through an expert elicitation in which 13 senior-level institutions' representatives of the sector in Brazil provided their insights. Results indicate that the more solar and wind power installed capacity in 2050, the more socioeconomic benefits to Brazil's Northeast region, suggesting that a long-term renewable pathway is not only technically feasible, but also economically and socially beneficial. Regional GDP gains in the Northeast would be between 1.91% and 4.98% relative to the baseline in policy scenarios. All socioeconomic variables analysed indicate gains to the Northeast and reduced regional inequalities. Regional industrial policy in the Northeast yields more positive national results than incentives to specific components nationally, while developing the Northeast economy even further through new manufacturing segments. Socioeconomic development, however, entails structural change in various aspects beyond the scope of modelling that require multi-objective policies across government levels and departments.

Impact Statement

Academic Impact and engagement: Novelty in content and process. This thesis is the first known research to perform multi-regional long-term quantification of the socioeconomic impacts of the renewable electricity transition in emerging markets and developing economies (EMDEs) apart from China. It established a novel research method to overcome the barriers of energy economic data constraints, particularly in EMDEs, through data triangulation, creating the database to calibrate a recursive-dynamic Computable General Equilibrium (CGE) model multi-regional within a country and perform a soft-link with three energy-system models. Additionally, the long-term analysis of socioeconomic impacts in this thesis included a national and a regional industrial strategies' analysis, unlike any previously known work.

This combination of CGE and energy system modelling for long-term analysis, implemented at a multi-regional level and simulating implications of national or regional industrial policy interventions, makes the thesis not only methodologically original but also grounds it in highly policy-relevant questions.

To test the modelling analysis against real-world conditions and to enhance engagement with this thesis, I combined the CGE modelling with an expert elicitation with 13 experts from Brazil's electricity sector companies, government agencies, development banks, think tanks and academia. Officials from relevant institutions in Brazil have been directly informed by the results of this thesis such as the National System Operator (ONS), the national electricity utility Eletrobras and the National Bank for Economic and Social Development (BNDES). The expert elicitation also fed back into the modelling simulations, since the idea to simulate industrial strategies was raised by most participants. This method combination provided insights on how modelling results can inform policymaking, which enlighten the modelling community on the limitations of models in fulfilling policymaking information needs.

The outputs of the different parts and stages of this research to date have included four published papers (Caiado Couto et al., 2021; Cronin et al., 2021; Milani et al., 2020;

Vasconcellos and Caiado Couto, 2021) (see Appendix D), three presentations[1], including at the UK Presidency Pavilion of COP26, a policy brief for COP26 under the Climate Compatible Growth programme (Diniz and Caiado Couto, 2021) and a chapter of a special report for the UN Economic Commission for Latin America and the Caribbean[2].

Wider and future impact. The policy relevance of this thesis falls in the realm of long-term multi-objective policy design, including long-term electricity provision, greenhouse gas emission reduction and regional socioeconomic development in a developing economy. Modelling results indicate the macroeconomic benefits of increasing solar and wind power installed capacity to Brazil's poorest region, the Northeast. They also suggest that income distribution between Brazilian regions would improve more the larger the share of non-hydro renewable sources.

Recognising the policy relevance of these findings, I intend to write up the three results chapters (Chapters 6, 7 and 8) as articles and submit to academic journals after defence. I will promote these impacts by using my networks in Brazil, and at the Royal Institute of International Affairs (Chatham House) where I am a Research Fellow and as such play a role as a convenor of annual conferences on the policy implications of climate economic research. I will use this as a platform to bring in EMDEs into discussions of global decarbonisation and renewable energy policy.

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[1] Caiado Couto (2019). *Socioeconomic Implications and Resource Management for Long-Term Renewable Electricity Generation in Brazil.* 3rd CIRED International Summer School in Economic modelling of Environment, Energy and Climate, 2019.

Caiado Couto (2021). *How many green jobs are there in electricity generation? A replicable quantification method for developing countries under data constraints*. Oral contribution, Energy. IOP Publishing Environmental Research Conference, 2021.

Caiado Couto (2021). *Onshore wind and public development finance in Brazil*. Oral presentation at the event *Economics of Energy Innovation and System Transition* (*EEIST) at COP26: Transformative Energy Innovation Dialogues on 4 November* 2021 UK COP26 Presidency Pavilion.

[2] Chapter III *The social and economic impacts of major renewable energy deployment: multiple opportunities in LAC* of the report *Reducing emissions from the energy sector for a more resilient and low-carbon post-pandemic recovery in Latin America and the Caribbean*.

DEDICATION

To my brother Chico, *in memoriam*.

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ABBREVIATIONS

AC Academia

ANEEL National Electricity Regulatory Agency

ANP National Petroleum, Gas and Biofuels Agency

BAU Business as Usual

BNB Bank of the Northeast

CAPEX Capital Expenditure

CCEE Chamber of Electricity Trade

CGE Computable General Equilibrium

CHESF São Francisco Hydropower Company

CNI National Industrial Confederation

CW Centre-West region

DFI Development Finance Institution

ELS Electricity Sector

EMDEs Emerging Markets and Developing Economies

EPE Energy Research Company

ESOM Energy-System Optimization Models

FNE Northeast Financing Constitutional Fund

FTE Full-Time Employment

GDP Gross Domestic Product

GHG Greenhouse Gas

GPV Gross Production Value

GOV Government agency

IBGE Brazilian Institute of Geography and Statistics

ICMS Tax on the Circulation of Goods and Services

IEA International Energy Agency

IFPRI International Food Policy Institute

IPCC Intergovernmental Panel on Climate Change

IPI Industrialized Product Tax

IRR Internal Rate of Return

LPG Liquified Petroleum Gas

MME Ministry of Mines and Energy

NDC Nationally Determined Contribution

NE Northeast region

NEB National Energy Balance

NG Natural Gas

ONS National System Operator

PDE Decennial Expansion Plan

PNAD National Household Sample Survey

PNE National Expansion Plan

POF Household Budget Survey

PPA Power-Purchase Agreement

ProGD Programme for the Development of Distributed Electricity Generation

PROINFA Incentive Programme for Alternative Sources of Electricity

PV Photovoltaic

RAIS Annual Social Information Report

SE Southeast region

SENAI National Service for Industrial Learning

SIN National Interconnected System

TERM The Enormous Regional Model

T&D Transmission and Distribution

TJLP Long-term Interest Rate

1. INTRODUCTION

Brazil has outstanding potential for renewable electricity generation, and its power system relies heavily on hydropower. However, rainfall regime changes have increased the system's hydrological risks and caused an increase in the use of thermal power in the last ten years. At the same time, wind and solar photovoltaic (PV) electricity prices have become lower than fossil-fuelled electricity prices (EPE, 2020a) and their installed capacity is rapidly increasing. Brazil's least developed region, the Northeast, has a semiarid climate and an extensive coast, where solar irradiation, wind speed, and predictability are comparable to the best sites in the world. Hence, the Northeast region concentrates the national potential for solar and wind electricity generation (as will be detailed in Chapter 2). Thus, renewable energy investment could potentially promote socioeconomic development in the region (Caiado Couto et al., 2021; Milani et al., 2020; Soria et al., 2015; Vasconcellos and Caiado Couto, 2021).

Brazil is divided into 27 states, officially grouped into five regions: North, Northeast (NE), Centre-West (CW), Southeast (SE), and South, as can be seen in Figure 1.1.

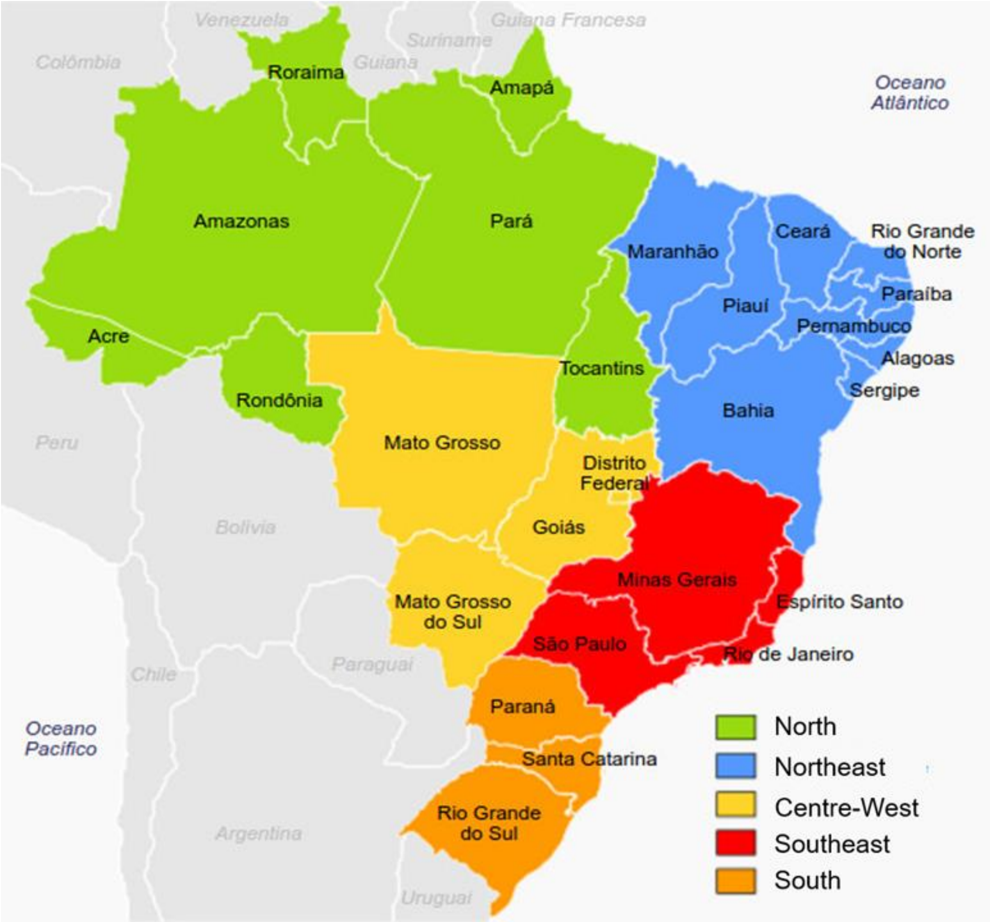

Figure 1.1 Brazil's geoeconomic regional divisions and states

Source: Adapted from Brasil Escola (2018)

Potential socioeconomic impacts of the energy transition are a significant pressure point for long-term energy policymaking, and concerns of negative impacts hinder political support to climate policy (Grubb et al., 2022; Hondo and Moriizumi, 2017). Quantifying these implications allows policymakers and the research community to understand how energy policies will impact welfare, income distribution and identify potential winners and losers of this process. This quantification requires models incorporating interactions among the several sectors affecting economic performance, environmental quality, and social conditions (Böhringer et al., 2013).

To date, studies that address long-term socioeconomic impacts of energy policy are still scarce, particularly in Brazil. Existing literature assesses mainly short-term impacts through Input-Output multipliers for job creation, income, and output generation of specific renewable energy projects. However, it is critical for long-term low-carbon development strategies to assess the net economy-wide impacts for the whole country and its regions of long-term renewable electricity capacity expansion as opposed to allowing the electricity mix to become more fossil-fuel based in the long term.

The long-term socioeconomic impacts of renewable energy policy span several aspects that include, but are not limited to, GDP growth variation, economy-wide effects on job creation, wage levels, household income, economy-wide investment level variations and countries' balances of trade. However, the meaning of long-term development is even wider as it requires sustained increase in the wellbeing and living standards of populations. This is normally achieved by increasing not only physical capital stock and technological improvement, as is the case of renewable energy, but also the development of high value-added economic activities, education, capacity building for skilled labour supply and natural resource management, all of which require multi-objective policy coordination.

Besides, the concept of just transitions entails that the energy transition must not destroy net jobs and should be inclusive to workers and entire economies which currently rely upon fossil fuel exploration. In this regard, assessing whether renewable energy creates more positive socioeconomic impacts than fossil fuels is crucial, and additionally, the income distribution effects of the different long-term energy investment scenarios. This assessment is especially relevant to Emerging Markets and Developing Economies (EMDEs), where populations' basic living standards usually are not guaranteed. However, data constraints significantly hinder efforts toward providing quantitative evidence for such discussions.

This PhD research aims to estimate the impacts on Brazilian regional economies of long-term electricity generation policy scenarios, focusing on wind and solar power in the Northeast region. A multi-region Computable General Equilibrium (CGE) model was calibrated to quantify the interactions across all sectors and final demand.

The CGE model has the 27 Brazilian states as separate regions, grouped into five official geopolitical regions as separate regions of the model for the scenario simulations, nine disaggregated electricity technologies plus transmission and distribution and household and labour disaggregation into ten income groups through the use of a national household survey. Having households and labour disaggregated into income bands allows this thesis to assess distributional impacts of long-term electricity scenarios. This analysis makes this thesis go beyond most modelling results for the economic impacts of energy policy, given that most CGE models only have one representative household.

This thesis models the socioeconomic impacts of alternative electricity investment scenarios relative to a baseline from 2020 to 2050 to evaluate their impacts on the five regions of the Brazilian economy, as well as two options for industrial strategies. This means that a soft link between three energy system models and the CGE model, which is multi-regional within a country. The combination of CGE and energy system modelling for long-term analysis, implemented at a multi-regional level and simulating implications of national or regional industrial policy interventions, makes the thesis methodologically original. It also grounds the thesis in highly policy-relevant questions.

Additionally, to test the modelling analysis against real-world conditions and to enhance engagement with this thesis, I combined the CGE modelling with an expert elicitation with 13 experts from Brazil's electricity sector companies, government agencies, development banks, think tanks and academia. This also fed back into the modelling simulations, since the idea to simulate industrial strategies was raised by the majority of the participants. This method combination has provided insights on how modelling results can inform policymaking, which enlighten the modelling community on the limitations of models in fulfilling policymaking information needs.

Brazil is well known for biofuel production and large hydropower generation. However, since 2013, severe droughts have revealed the country's vulnerability to its dependency on the latter (Mercure et al., 2019; Siegmund-Schultze et al., 2018). Moreover, most of Brazil's remaining hydropower potential lies in the Amazon Basin and is unlikely to be fully utilised due to environmental concerns (Arias et al., 2020; de Faria et al., 2017; de Faria and Jaramillo, 2017; EPE, 2020a; Fraundorfer and Rabitz, 2020; Moretto et al., 2012; Tolmasquim, 2016).

The government considered the 2030 Brazilian Nationally Determined Contribution (NDC) emission reduction target feasible based chiefly on previous levels of hydropower generation and pre-2012 successful deforestation reduction policies. However, lax governance since has increased deforestation back to previous annual levels, and several studies have linked deforestation with hydrological alterations, precipitation changes with impacts on water availability and, therefore hydro electricity generation (Fonseca et al., 2019; Hunt et al., 2022; Rochedo et al., 2018). This shows clear interlinkages between water and energy in Brazil, as treated in the Resource Nexus approach (Caiado Couto et al., 2021). Thus, alternative renewable electricity generation technologies are needed to maintain the renewable profile of the country's generation mix to meet the 2030 climate targets and the growing electricity demand.

Therefore, the Brazilian electricity generation mix's renewable profile is changing due to demand growth and climate change impacting hydropower. As a result, hydropower generation has seen its share fall from almost 85% (67% of installed capacity) in 2012 to nearly 53% in 2021 (55% of installed capacity) (EPE, 2022, 2013a, 2013b). Consequently , dependence on conventional thermal plants has increased, and so have the national system's marginal operating costs and greenhouse gas (GHG) emissions (ONS, 2020). Furthermore, the literature projects hydropower to continue losing its share in Brazil's electricity mix due to irreversible changes in the rainfall regime and environmental impacts associated with dams (Da Silva et al., 2021; de Jong et al., 2018; Lucena et al., 2018; Margulis et al., 2010; Nogueira de Oliveira et al., 2016; Santos et al., 2018; Siegmund-Schultze et al., 2018; World Bank, 2016).

1.1 Research questions

This research aims to assess the economy-wide impacts of future electricity generation capacity expansion scenarios for Brazil and its five official geoeconomic regions. This assessment entails modelling simulations of the economic impacts of a baseline scenario with a higher share of fossil-fuelled electricity installed capacity against two renewable energy policy scenarios which aim, respectively: (i) to achieve net zero emissions in Brazil by 2050; and (ii) to increase as much as possible the share of alternative renewables in Brazil's electricity mix until 2050 respectively.

Therefore, the overarching research question of this thesis is:

What are the differences between the national and regional economy-wide impacts of long-term electricity capacity expansion scenarios considering higher and lower levels of penetration of non-hydro renewable sources?

Further, it simulates two additional industrial incentives to account for the potential socioeconomic co-benefits of incentivising renewable power plants' national and regional supply chains. The main differences between the three long-term electricity capacity expansion scenarios used is in the penetration of wind and solar power. Other non-hydro renewable sources such as biomass do not gain share of total installed capacity substantially. Hence, the industrial strategy simulations focused on wind and solar power.

Industrial policy scenarios simulated consist of: (i) a 1% federal tax reduction to specific domestic industrial segments supplying wind and solar PV power plants; and (ii) a 1% federal tax reduction to selected industrial segments in the NE region. The research focuses on the socioeconomic benefits and losses at the sectoral and regional level and distributional impacts.

Constraints to hydropower will change Brazil’s electricity mix future composition with implications for the country’s regional economies. Brazil has a high potential for non-hydro (alternative) renewable energy generation and is already investing in them. Such sources can make an essential contribution to the country’s socioeconomic development. As the NE concentrates most of Brazil’s wind and solar energy physical potential, the country’s poorest region, it has the potential to contribute to this region’s development.

This thesis performs a multi-region CGE analysis to quantify the economy-wide implications of different Brazilian electricity capacity expansion pathways. CGE models have different scales depending on the research questions. Most of them are global, with the world's different regions represented, or a single region for a country. In the latter, trade only happens with the rest of the world, regardless of origin or destination. In rare cases, CGE models are multi-region within a country. This thesis applies the latter approach, representing a novel contribution to the literature. It takes the following steps:

First, it simulates the implications for all economic sectors, ten groups of households and ten labour grades. It considers different wind and solar power investment levels in each Brazilian region in two policy scenarios compared to a more fossil-fuel and hydropower-based baseline. Then, an expert elicitation was conducted, which consulted 13 experts to inform the discussion and implications of the modelling scenarios and results.

The underlying research questions of this PhD thesis are:

(i) *What are the national and regional macroeconomic impacts of scenarios with higher shares of non-hydro renewable electricity sources in comparison to a baseline scenario in Brazil up to 2050?*

Intense debates discuss whether EMDEs must utilise high-emission technologies to develop, mostly centred on conventional thermal power plants. This research compares the economic implications of a baseline scenario, where additional fossil-fired thermal power plant installation increasingly meets electricity demand, with scenarios in which non-hydro (alternative) renewables increase their share of the generation mix. This research answers this question by simulation of the economic effects of the different electricity capacity expansion scenarios listed above through the multi-regional CGE model with the electricity sector disaggregated into sources.

(ii) *What are the sectoral impacts of industrial strategy options in Brazil and in the Northeast region to retain a larger share of the socioeconomic benefits of renewable energy deployment?*

Although industrial plant components manufacturers have recently installed factories in the NE region, the NE does not have enough local capabilities to produce most of them and provide the skilled labour required. Thus, socioeconomic development in the region might be less than expected by decision-makers, being instead concentrated in more developed regions, particularly the South and the Southeast. This analysis has been done by adding industrial policy simulation on top of the electricity capacity expansion scenarios and reporting results to specific industrial segments which are, to different degrees, relevant to power plants' supply chains. Finally, a review of policies has been combined with an expert elicitation to propose solutions to build the necessary capabilities for poor regions where investment occurs to retain the socioeconomic co-benefits.

(iii) *What are the distributional impacts of the different profiles of electricity generation capacity expansion in the long term in Brazil and its regions, and what are the impacts on the workforce by wage level and on households by income group?*

In addition to macroeconomic aggregates and sectors, analysing the impacts of long-term infrastructure investment on households and the labour force is crucial to determine the actual impacts on national and regional development levels. Employment impacts on different wage levels affect income distribution, affecting household consumption in the different income bands. Therefore, it is crucial to analyse whether household consumption increases the most in the highest or lowest income bands to indicate better or worse effects on income distribution. This research, therefore, analyses the impacts of the scenarios mentioned in research questions (i) and (ii) on ten groups of workers per wage band and ten groups of households per household income band.

1.2 Thesis structure and outline

The thesis outline is structured to answer the overall research question and the three underlying research questions as follows:

- Chapter 2 provides the background information for the electricity sector in the geographical focus of this study: Brazil and its regions. Chapter 2 analyses the data and discusses electricity generation in Brazil, current sources used, the present and the long-term challenges, trade-offs, and potentials for Brazil and its five official geoeconomic regions.

- Chapter 3 provides a literature review on the economic motive of this thesis. It analyses the relationship between long-term electricity capacity investment and regional socioeconomic development, the direct, indirect, induced and economy-wide net economic impacts of electricity capacity expansion. It also contextualises this phenomenon in the Brazilian economy and regional economies within the country. Chapter 3 then explores the methodological options for the economic assessment performed in the thesis and justifies its choice for CGE modelling.

- Chapter 4 presents the methodology applied to answer the research questions of this thesis. First, it explores the choice for the specific modelling approach adopted and details the multi-regional CGE model applied to electricity capacity expansion investment. Then, it explains the soft link with the energy-system optimization models and the complementary expert elicitation performed to ground the modelling findings in the policymaking process.

- Chapter 5 describes the scenarios from the three energy-system optimization models in which socioeconomic impacts have been estimated and the two additional industrial strategy simulations performed.

- Chapter 6 is the first of three result chapters, each of which answers the three underlying research questions outlined in Section 1.1. First, Chapter 6 answers the underlying research question (i) and explores the impacts of each electricity capacity expansion scenario on macroeconomic aggregates. It then presents the results of the policy insights from the expert elicitation on macroeconomic impacts.

- Chapter 7 answers the underlying research question (ii). It explores the sectoral impacts of electricity capacity expansion scenarios combined with industrial strategies and the policy insights from the expert elicitation on industrial strategies.

- Chapter 8 answers the underlying research question (iii) by exploring the modelling and expert elicitation results for the distributional impacts of long-term electricity capacity expansion investment by analysing impacts over ten household income and ten labour wage groups.

- Chapter 9 concludes by revisiting the research problem, summarising the main findings, the policy recommendations, and the contributions to existing knowledge and outlining the limitations of the research and future work emerging from this thesis.

The thesis' structure is divided into three main parts: part 1 comprises Chapters 1, 2 and 3. It contextualises and justifies the research problem and reviews the literature. Part 2 presents the methodology and the electricity capacity expansion scenarios in Chapters 4 and 5. Finally, part 3 consists of the results from modelling simulations and the expert elicitation answering the three underlying research questions of the thesis (Section 1.1), the discussion, the main findings and policy recommendations. Therefore, part 3 comprises Chapters 6, 7, 8, and 9.

Figure 1.2 illustrates the three parts explained above and the flow of the thesis' chapters:

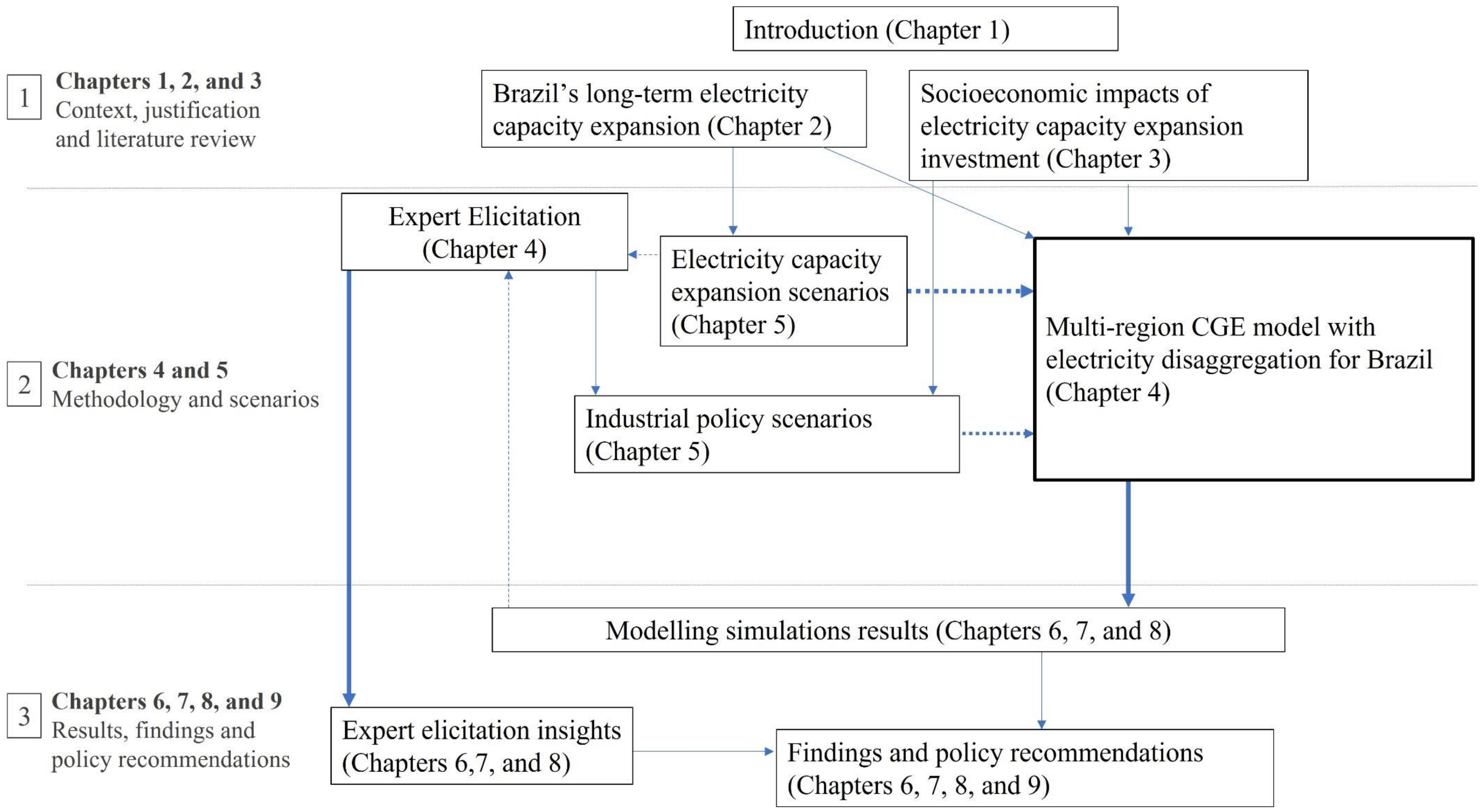

Figure 1.2 Thesis flow

Both the characteristics of the Brazilian electricity system (Chapter 2) and the need to estimate the socioeconomic impacts of electricity capacity expansion investment (Chapter 3) led to the application of the multi-regional CGE model for Brazil (described in Chapter 4). The context of long-term electricity capacity expansion in Brazil (Chapter 2) allows the reader to understand the scenarios for electricity capacity expansion in Brazil until 2050, which will be detailed in Chapter 5. The socioeconomic structures of Brazilian regions and the argument for industrialization (Chapter 3), together with the themes identified in the expert elicitation (Chapter 4), justify the simulation of industrial policy scenarios (described in Chapter 5).

The socioeconomic impacts of the scenarios for electricity capacity expansion in Brazil until 2050 and the industrial policy scenarios presented in Chapter 5 are simulated in the multi-regional CGE model described in Chapter 4. Modelling results for the initial simulations of the socioeconomic impacts of the scenarios for electricity capacity expansion in Brazil until 2050 were presented to the participants of the expert elicitation in the interviews (described in Chapter 4). Participants then reinforced the need to simulate the socioeconomic impacts of additional industrial policy options.

Then, chapters 6, 7, and 8 present the results from multi-region CGE modelling simulations and the expert elicitation for the three underlying research questions from Section 1.1. Each chapter analyses modelling results and expert elicitation insights and discusses them, indicating policy recommendations. Finally, Chapter 9 summarises findings and policy recommendations and concludes.

2. LONG-TERM RENEWABLE ELECTRICITY GENERATION IN BRAZIL

This thesis aims to assess the national and regional macroeconomic, industrial, sectoral, and distributional impacts of long-term scenarios for electricity capacity expansion in Brazil, reaching different electricity mixes in 2050. Hence, it is necessary to address the resources available for electricity generation in Brazil, their regional distribution, the challenges, trade-offs, and constraints embedded in them and the opportunities to maintain the renewable profile of the mix in order to meet the long-term climate targets.

This chapter provides the background information needed about the Brazilian electricity system and its current challenges (Section 2.1), the long-term challenges (Section 2.2), and the opportunities to maintain the renewable profile of the electricity mix in the long term (Section 2.3). Then, Section 2.4 provides a detailed analysis of the regional aspects of non-hydro renewable electricity generation in Brazil, focusing on the NE region. Next, it addresses the substantial potential for the region's solar and wind power generation and the impacts of climate change on its energy resources and economy. Finally, section 2.5 summarizes the main messages of this chapter.

In sum, Chapter 2 provides the background for the long-term electricity capacity expansion scenarios used in the CGE modelling analysis of this thesis, which will be detailed in Chapter 5.

2.1 Brazil’s electricity generation challenge

Brazil is currently at a crossroads in terms of its energy mix. The Brazilian electricity sector is known for being mostly renewable due to the predominance of hydropower generation since the 1940s, but mainly since the 1980s, when dam building accelerated as a response to the 1970s oil crises (La Rovere and Mendes, 2000). This low-emission profile of the electricity mix has been primarily used as an argument for the Brazilian electricity sector not to consider decarbonisation policies or strategies. Instead, climate policies in Brazil have focused mostly on curbing deforestation (Hochstetler and Viola, 2012; Viola and Basso, 2015).

However, severe droughts in 2001 and an ongoing drought which started in 2013 have revealed an intense exposure to hydrological risks of the Brazilian electricity system, in which operation costs have increased as a consequence of resorting to thermal power. Therefore, since 2001, the need to diversify the electricity mix has been clear. Nevertheless, since 2015, after the effects of the droughts from 2013, and when Brazil submitted its first NDC with targets for non-hydro renewable electricity, it became critical.

Climate change impacts on hydropower generation are not exclusive to Brazil and are increasingly becoming a global challenge (Wasti et al., 2022). European countries and China also face energy security challenges related to drought in hydropower dams. In August 2022, droughts caused hydropower shortages in the Chinese province of Sichuan (S&P Global, 2022), and the Yangtze river is known to be sensitive to climate change (Zhao et al., 2022). In the same period, a dry summer reduced Norway's hydropower generation. This source is responsible for 90% of Norway's total electricity generation, including exports to neighbouring countries (The New York Times, 2022).

Thus, diversifying the electricity mix is increasingly essential, even between different renewable sources, given that climate change also impacts renewable energy generation. The following sections, therefore, explore future alternatives for electricity generation in Brazil.

2.2 The future of electricity generation in Brazil

While Brazil's electricity demand is continuously rising, future projections show a challenge in maintaining the renewable profile of Brazil's electricity generation mix. In recent years, while hydropower has lost its share of the total electricity generated, wind power has been essential to maintaining the low-emission profile of the electricity mix.

The federal government's Energy Research Company (EPE) (2020b) has projected that, between 2019 and 2030, Brazil's total electricity demand will increase by 2.6% per year; this includes revised projections which consider the impacts of the COVID-19 pandemic on the economy. Electricity per capita consumption has risen steadily since 1975, at higher rates than in other EMDEs. For example, Brazil's per capita demand increased by 45% from 2000 to 2017 (World Bank, 2018).

Future scenarios project that the share of hydropower in Brazilian electricity generation will decrease, meaning that future demand will have to be met by alternative sources, namely wind and solar (EPE, 2020b; Lucena et al., 2014; Margulis et al., 2010; Nogueira de Oliveira et al., 2016; Santos et al., 2017; Sobrosa Neto et al., 2018). Hydropower will probably continue to lose its share of Brazil's electricity mix due to irreversible changes in the rainfall regime and environmental impacts primarily associated with dams. Recent projections for the electricity sector in Brazil have concluded that by 2030, hydropower installed capacity will have stopped expanding and therefore, its share will have decreased or been stagnant, depending on the scenario (Instituto Escolhas, 2017; Margulis et al., 2010; MRE, 2019).

The EPE, which has a conservative position regarding hydropower replacement (EPE, 2020b), also projects that in 2030, hydropower will represent less than 50% of the electricity mix, primarily due to more stringent environmental licensing processes. Thus, it is necessary to plan to meet this growing demand while maintaining a sustainable, low-emissions electricity generation mix. Therefore, diversification of renewable sources has proven necessary (Paim et al., 2019), and the EPE projects the low emission profile of the electricity mix to be sustained by increased wind and solar power (EPE, 2020b).

The reference expansion from the official Decennial Expansion Plan (PDE 2030) (EPE, 2020b) shows that wind power and thermal power plants with different fossil fuels will dominate capacity expansion until 2030. For hydropower expansion, it only considers modernising existing hydropower plants. Figure 2.1 shows the planned electricity capacity expansion considered by the EPE from 2026 to 2030, where thermal and wind power sources dominate expansion in the whole period.

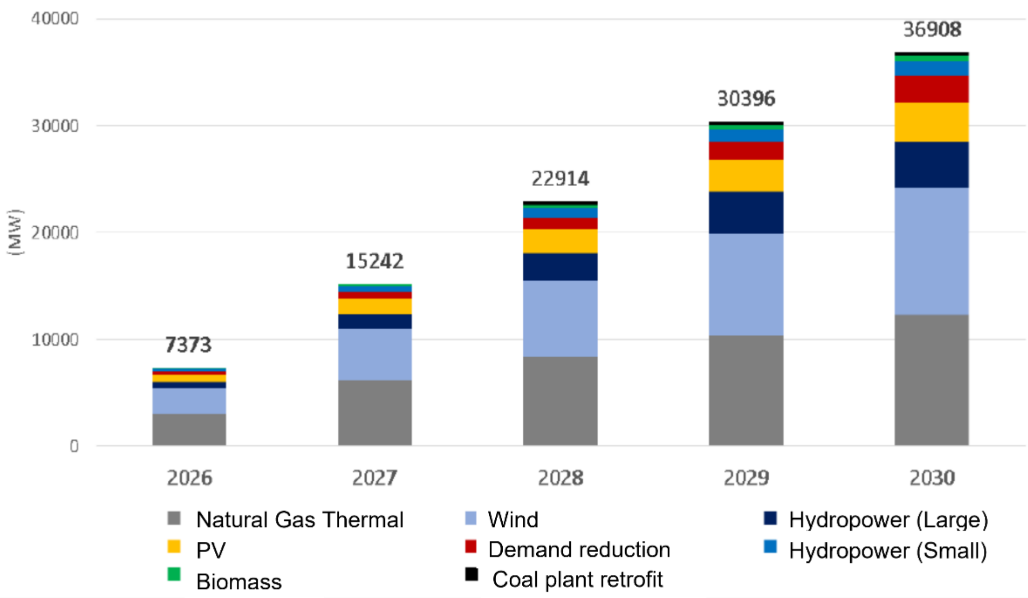

Figure 2.1 Decennial Expansion Plan electricity capacity expansion per source 2026 to 2030

Source: EPE (2020b)

Brazil's electricity generation, transmission and distribution operate through the National Interconnected System (SIN), managed by the National System Operator (ONS). Thus, the power system optimises generation from plants in a given part of the country, meeting demand in different subsystems across the territory with the minimum cost. Such arrangements are beneficial for energy security since hydropower dam reservoir levels have become less and less predictable, and each region can no longer rely solely on their hydropower plants. The only areas currently not connected to the SIN are in the North region, comprising parts of the states of Amazonas, Acre, Amapá, Pará and Roraima.

Changes in precipitation levels have become critical since 2013, lowering reservoir levels and increasing the SIN's marginal operation cost. Also, rainfall regime changes should be the worst consequence of climate change in Brazil. Therefore, a decrease in precipitation levels is expected, especially in the NE region (Magrin et al., 2014; MMA, 2019).

Indeed, Brazil has observed a significant vulnerability related to hydropower dependency from 2013 to date. The period from September 2020 to February 2021 registered the lowest reservoir inflow of a 91-year time series (ONS, 2021a). The latter led to a historical record of coal-fired thermal generation (ONS, 2021b). As a result, conventional thermal plants are increasing their share of the electricity mix, contradicting climate action in the rest of the world, impacting the system's marginal operations costs and consequently increasing electricity prices (EPE, 2020b). Table 2.1 shows the difference between the electricity generation mix in 2012 and 2021.

	2012	Share of total	2021	Share of total	Variation 2012-2021
Total	552498.34		656108.24		19%
Hydropower	415342.17	75%	362818.45	55%	-13%
Natural gas	46679.48	8%	86861.35	13%	86%
Petroleum products	16292.96	3%	18243.69	3%	12%
Coal	8422.07	2%	17585.08	3%	109%
Nuclear	16038.40	3%	14704.59	2%	-8%
Biomass	34705.90	6%	51710.52	8%	49%
Wind	5050.05	1%	72285.97	11%	1331%
Solar	1.62	0%	16752.28	3%	1033991%
Others	9965.70	2%	15146.31	2%	52%

Table 2.1 Brazil's electricity generation by source 2012 and 2021

Source: Author's calculations with data from EPE (2022)

In 2015, after two years of droughts, the Brazilian National Agency for Electric Energy (ANEEL) adopted a new charging system to compensate for the costs of activating more expensive thermal plants. Consumers pay an extra charge that in 2022 was of up to US$1.9 per 100 kWh, depending on how much the system resorts to thermal plants (ANEEL, 2022a).

In 2021, the low reservoir levels led the Electricity Sector Monitoring Committee to implement a surcharge of R$14.20/100 MWh (around USD2.5/100MWh) to cover the additional cost of turning on thermal power plants, which are more expensive than renewable generation.

The share of fossil-fuelled electricity installed capacity doubled in the last decade, from 12% in 2012 to over 24% of the total in 2022 (ANEEL, 2022b; EPE, 2013b). Noticeably, from 2020 to 2021, fossil-fuelled generation increased by 77% due to another long drought (IEMA, 2022). By the end of March 2021, the SE/CW subsystem, which accounts for 70% of total national storage (EPE, 2021), ended the yearly rainy season, usually the point with the highest reservoir level of the year, below 40% total storage capacity (ONS, 2021c). Since 2015, when levels fell below 30% capacity, this was the first time that the Brazilian Ministry of Mines and Energy considered electricity consumption rationing (Valor Econômico, 2021). Before this, the last time the Brazilian government resorted to rationing in response to a power supply shock was in 2001, when the government obliged consumers to curtail electricity by 20% (Scaramucci et al., 2006).

Cavaliero and Silva (2005) and Scaramucci et al. (2006) argue that, particularly in the aftermath of the 2001 supply crisis, it became clear that the Brazilian electricity mix should pursue diversification through expanding alternative renewables. Arguably, diversification will avoid power shortages and the rise of GHG emissions caused by increasing the use of fossil-fuelled thermal power.

Since the 1990s, the Brazilian government has avoided new hydropower dams due to the socioenvironmental impacts on flooded areas. Flooding indigenous reserves, *quilombola*[3] communities and biodiversity loss have been considered the most critical threats. Since then, it has prioritised run-of-the-river projects, even if reducing the system's firm power[4] capacity (EPE, 2018a; Margulis et al., 2010). For this reason, the main project significantly changed was the Belo Monte dam. The first proposal dates back to 1975. In 1994, Eletronorte altered the 11 GW project to operate run-of-the-river instead of building a dam, reducing environmental risks and firm power by 40% of the initially planned capacity (Tancredi and Abbud, 2013).

The Brazilian NDC, submitted to the United Nations Convention on Climate Change (UNFCCC) in the context of the 21st session of the Conference of the Parties (COP21), contains an economy-wide absolute target of reducing GHG emissions by 37% by 2025 and 43% by 2030, having 2005 as a base year. In addition, the NDC has a specific target for energy generation and aims to reach 23% renewables in the country's electricity mix, and 33% in its energy mix, excluding hydropower, by 2030. This

[3] Afro-Brazilian traditional communities established by escaped slaves, whose rights over inhabited land were ensured by the decree 4,887 from 20th November 2003.

[4] Firm power means power-producing capacity which is intended to be available at all times during the period covered by a guaranteed commitment to deliver, even under adverse conditions (EIA, 2022).

particular target was ambitious, given that, in 2015, the share of non-hydro renewables in the electricity mix was 11.6% (EPE, 2018b).

The updated NDC Brazil submitted ahead of the 26th session of the Conference of the Parties (COP26) kept the original NDC targets and set an indicative net zero emissions target by 2060, conditional on finance. In April 2021, as part of the 2021 Leaders' Climate Summit, then President Jair Bolsonaro announced a target to achieve net-zero emissions by 2050. However, it is not anchored in legislation and has no interim target consistent with this long-term goal.

Using 2005 as a base year for the NDC was controversial, as 2005 was the beginning of deforestation policy implementation, with the second historical highest deforestation level in a year (19,014 km^2) associated with the third highest level of annual emissions in Brazil (2.62 $GtCO_2e$) (INPE, 2021a; SEEG, 2021). In 2015, when the NDC was submitted, emissions were at 1.99 $GtCO_2$, already 24% below the base year (SEEG, 2021). This fact raised criticism in the country that the NDC target was not ambitious enough.

The NDC economy-wide emission reduction target relied primarily on successful deforestation control policies, which from 2005 to 2012, managed to reduce 54% of emissions by a 78% reduction in deforestation, reaching a low of 4,571 km^2 in 2012 (INPE, 2021a; Rochedo et al., 2018). However, from 2012 to date, weakened governance has allowed deforestation in the Amazon to rise to its highest rate in over a decade: 11,088 km^2 in 2020 (Fonseca et al., 2019; INPE, 2021a; Rochedo et al., 2018).

Weakened deforestation control represents an ongoing environmental crisis with both global and local implications, according to recent literature about deforestation processes in Brazil (Aguiar et al., 2020; Arias et al., 2020; Azevedo et al., 2017; Hochstetler, 2021; Lovejoy and Nobre, 2018; Nobre et al., 2016; Rajão et al., 2020; Strand et al., 2018). Furthermore, increased GHG emissions from deforestation and forest fires could cancel the European Union (EU) climate change mitigation efforts (Rajão et al., 2020). Moreover, increased deforestation significantly impacts rainfall regimes and hydropower generation (Arias et al., 2020; Caiado Couto et al., 2021; Nobre et al., 2016).

Farmers broadly use forest fires for deforestation and invade standing forests to clear agriculture and pastureland areas (Barlow et al., 2020). Aguiar et al. (2020) essentially link forest fires to large-scale land appropriation and deforestation. Furthermore, uncontrolled fires become more likely due to climate change impacts, making forests hotter and dryer (Barlow et al., 2020; Brando et al., 2019).

According to INPE (2021b) data, both 2019 and 2020 had decade-high numbers of fire hotspots. In 2020, there were 222,798 hotpots, 150,783 of which were in the *Legal Amazon*[5] and 63,819 in the *Cerrado* biome. They have translated into a 312,140 km^2 burnt area, 139,644 km^2 in the *Cerrado* biome and 77,396 km^2 in the Amazon (INPE, 2021c).

Increased deforestation and decreased hydropower generation led to emissions in 2019 above those of 2005: 2.18 $GtCO_2e$ in 2019 against 2.1 $GtCO_2e$ in 2005 (SEEG, 2021). As a result, the NDC absolute target would mean net emissions of 1.65 $GtCO_2e$ in 2025 and 1.49 $GtCO_2e$ in 2030. Brazil would therefore need to reduce its emissions by 0.69 $GtCO_2e$ from 2019 to 2030, a 31.5% reduction in 11 years, to remain within the original target (own calculations using data from SEEG (2021)).

Thus, as highlighted by Rochedo et al. (2018), additional efforts will be required across sectors to compensate for increased deforestation emissions if Brazil aims to comply with the Paris Agreement's long-term temperature targets. Therefore, it pressures the electricity sector for renewable diversification to meet future demand with clean alternatives to hydropower.

If Brazil aims to maintain the renewable profile of its electricity mix and meet its climate targets, it must explore the non-hydro renewable resources of its territories, securing alternative renewable electricity to meet its growing demand in the long-term. The current administration has shown a strong sign that this is the case, by creating the Energy Transition Secretary under the Ministry of Mines and Energy on the 2nd of January 2023, one day after president Lula da Silva's inauguration (MME, 2023). The next sections explore the alternative renewable resources of the Brazilian territory, the

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[5] Legal Amazon (Amazônia Legal, in Portuguese) is an area of over 6 million km^2, 60% of Brazil's total area, established in 1953 for the economic development planning and deforestation control of the Amazon (IPEA, 2008).

renewable electricity policy background and the options to exploit them in the long run.

2.3 Alternative renewable electricity generation policies and their outcomes

Brazil pioneered the adoption of alternative renewable energy support instruments in EMDEs by legally establishing the *Incentive Programme for Alternative Sources of Electricity* (PROINFA), in 2002[6]. In addition, following a significant electricity supply crisis in 2001, the Brazilian government designed PROINFA to diversify Brazil's electricity mix by deploying wind, biomass, and small hydropower plants (SHP), initially using feed-in tariffs as its primary driver (Kissel and Krauter, 2006).

PROINFA's official aims were to: (i) enhance energy security, (ii) explore regional potentialities, leading to employment creation and capacity-building and (iii) ensure a low-greenhouse gas emission development of the electricity sector (Eletrobras, 2021). Brazil's electricity mix was already heavily based on large hydropower (81%) by 2002, combined with thermal (13%) and nuclear (4%) back-ups and small hydropower plants (2%) (ECEN, 2002). Hence, PROINFA aimed at diversifying the mix by introducing renewable sources alternative to large hydropower plants (Dutra and Szklo, 2008).

Feed-in tariffs were initially the basis of PROINFA combined with a long-term Power-Purchase Agreement (PPA) instrument, widely used in countries like Germany and Spain, but Brazil was the first EMDE to introduce it (Kissel and Krauter, 2006). The first phase consisted of a 20-year guaranteed PPA through Eletrobras, the national electricity utility, which differentiated its tariffs per source as a proportion of average retail tariff in the last 12 months: 50% for SHP, 70% for biomass and 90% for wind power (GWEC, 2011).

Indeed, Willcox and Araujo (2018) argue that the foundations of the wind energy success in Brazil were: (i) demand induction mechanisms through feed-in tariffs, guaranteed procurement through Power Purchase Agreements (hereafter PPA) and dedicated regulated auctions; (ii) public finance mechanisms and (iii) exploring the national geographic potential including industrial development through local content

[6] Law 10,438 2002

requirements. As a result, successful programs and policies excelled in putting Brazil first among EMDEs in the share of primary energy from wind in 2019 (Figure 2.2) and third in the world, behind Germany and the United Kingdom only (Our World in Data, 2021).

Wind power installed capacity increased from 927MW in 2011 to 22GW in 2022, with prices per MWh already more competitive than traditional sources in recent auctions and lower capital expenditure (CAPEX) requirements than hydropower plants (ANEEL, 2022b; CCEE, 2020; EPE, 2020b). Wind electricity generation reached over 10% of the total in 2021 (EPE, 2022), following a nearly exponential growth since 2011, highly attributable to the PROINFA programme. Figure 2.2 shows the growth of wind electricity as a share of the total for the BRICS countries, where Brazil surpassed China and India in 2014 and has widened the gap since.

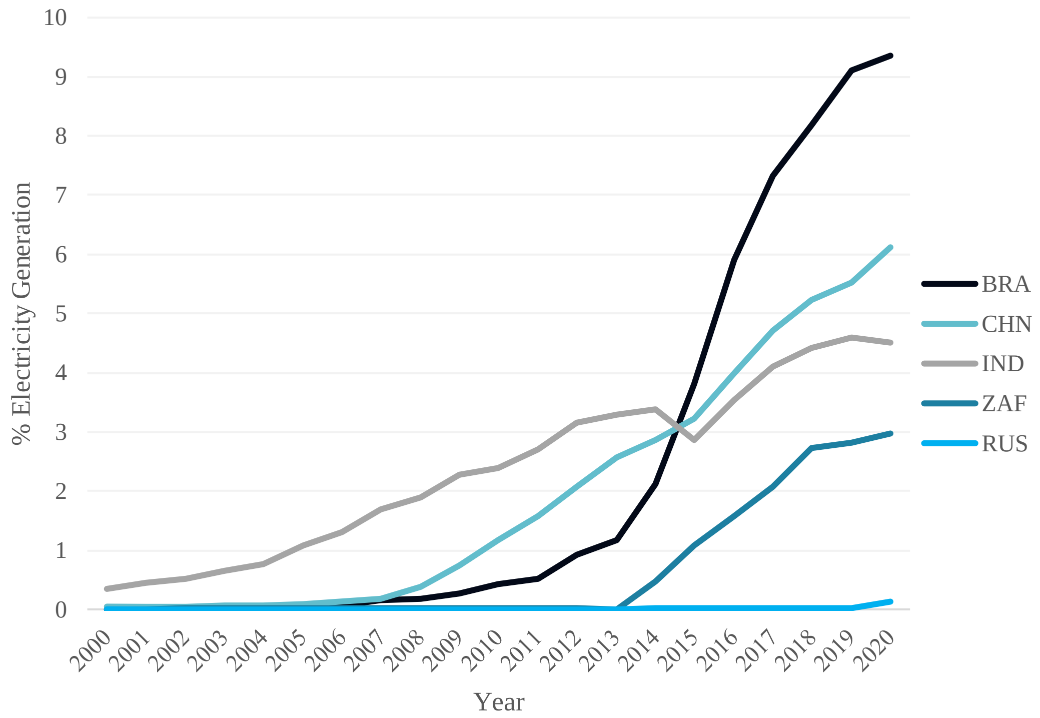

Figure 2.2 Wind share of electricity generation per country per year 2000-2020, BRICS[7]

Source: Author’s calculations with data from Our World in Data (2021)

An electricity market reform in 2004 put procurement auctions at the core of Brazil’s regulatory framework (Azuela et al., 2014), so much so that they became a key mechanism for integrating alternative renewable sources into the system (Willcox and Araújo, 2018). Wind projects started bidding in 2007, and the first auction dedicated explicitly to wind power procurement took place in 2009. Until 2019, wind power projects participated in 28 auctions, with a total procurement of nearly 19 GW (ANEEL, 2022b). In order to create the conditions for wind power to become competitive, the dedicated agency designed contracts to accommodate unmanageable risks that are particular to the Brazilian context, such as inflation (Kissel and Krauter, 2006) and the variability of power generation, and to attract investors (Azuela et al., 2014).

[7] Brazil, Russia, India, China, and South Africa.

It is vital to note that PROINFA did not include solar energy, which delayed the process of solar PV deployment in Brazil. Until 2017, solar PV installed capacity in Brazil had a negligible share of the total, with under 2 GW installed. Nevertheless, solar PV capacity installation has entered a nearly exponential growth curve and reached 20.3 GW in October 2022. Until 2019, solar PV installed capacity was centralised, large utilities. Utility-scale centralised projects were 84% of total solar PV installed capacity in 2017, 76% in 2018 and 54% in 2019. Since 2020, distributed generation has increased exponentially, and in October 2022, it accounted for 68% of solar PV installed capacity at 13.72 GW (ABSOLAR, 2022).

In 2012, the ANEEL launched two programmes to boost solar PV in Brazil. First, it increased the discount on the Tariff for the use of Electrical Transmission Systems and the Tariff for the use of Electrical Distribution Systems from 50% to 80% for projects which inject at least 30 MW into the grid to foster PV generation (WWF, 2012). Then, the ANEEL launched bill nº482/2012 with a new regulatory framework to allow the trading of self-generated power to use their connection to the system's distribution network. Therefore, it allowed for compensation for consumers who are also micro or mini-distributed generators.

Nevertheless, it was not until December 2015 that the Brazilian Ministry of Mines and Energy (MME) launched the Programme for the Development of Distributed Electricity Generation (ProGD), which aimed to mobilise over R$100 billion (around US$25 billion) in PV generation investment, to reach 23.5 GW of installed capacity comprising households, stores, industrial plants, and the agricultural sector.

The initial boost in solar PV deployment in 2017 was mainly attributable to the decrease in auction prices offered by this technology. The solar PV auction price per MWh decreased by 43.4% between the last auction in 2015 and 2017. It decreased by 55% between the former and the auction of 2018. Between 2015 and 2019, solar PV auction prices decreased by 77.5%. Hence, initially, the solar PV increase was led by utilities, which increased from zero in 2016 to 968 MW in 2017, 1.83 GW in 2018, and 2.48 GW in 2019 (ABSOLAR, 2022).

Centralised utility-scale generation is 23% in the SE state of Minas Gerais, which is also the first state in distributed generation at 15.5%. As a result, the SE region has 35.1% of total solar PV distributed generation. On the other hand, the nine states of the NE region concentrate 67% of the centralised solar PV installed capacity but only 20.6% of distributed generation (ABSOLAR, 2022).

2.4 The case for renewable electricity in Northeast Brazil

Brazil is a country of continental dimensions with five different climatic zones. One of these is a semiarid area located in the country's least developed region, the NE, and the lack of water, energy and food security are among the causes of underdevelopment (Marengo et al., 2022). It is also the most densely populated semiarid area in the world, predominantly rural, with strong constraints on the use of natural resources due to water scarcity and a lack of alternatives to reduce such dependency historically (Krol et al., 2006).

Future climate change projections show that the Brazilian semiarid is one of the world's regions at the highest risk and presents one of the highest levels of vulnerability to climate change impacts (Jenkins and Warren, 2015; Magrin et al., 2014; Marengo et al., 2011a; Margulis et al., 2010). Figure 2.3 below indicates the Brazilian semiarid zone demarcation (in yellow), the NE states, and their capitals.

Figure 2.3 The Brazilian Semiarid Demarcation

Source: IBGE (2021a)

2.4.1 Alternative renewable electricity generation and its untapped potential

The NE region is vital for Brazil to increase its share of non-hydro renewable electricity, as it concentrates most of its physical potential for solar and wind power generation. The NE region has an estimated wind power capacity potential of 95.5 GW (78% of national potential) for 80-metre towers, 172 GW for 100-metre towers (55% of national potential) and 352 GW (59% of national potential) for 150-metre towers (EPE, 2020c). Figure 2.4 shows the geographical distribution of onshore wind average wind speed, where it is visible that onshore rates above ten m/s are only in the

NE region. Noticeably, onshore wind speeds above 12 m/s occur only in the NE states of Bahia, Piauí, and Ceará.

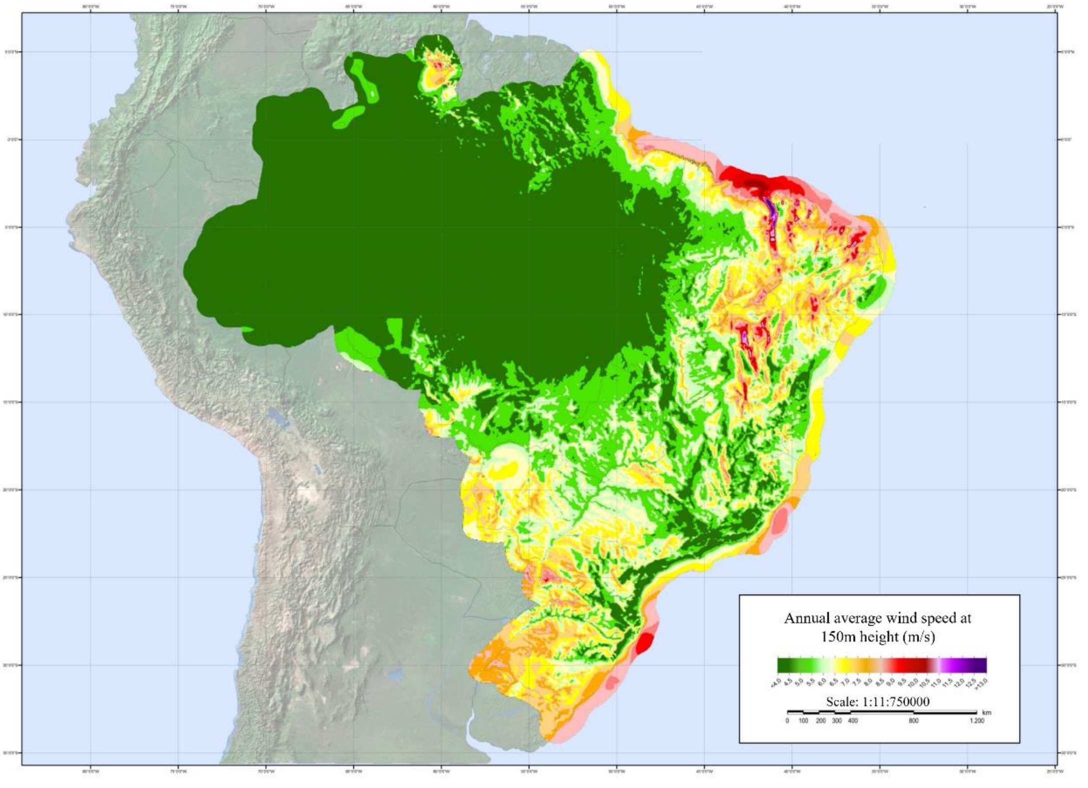

Figure 2.4 Brazil's wind speed 150m above sea level

Source: Adapted from CEPEL (2017)

The NE semiarid region is also the most appropriate for PV generation, showing comparable irradiation to the best spots on earth, such as Dongola in Sudan and the Mojave Desert in California (ANEEL, 2008). The Brazilian Solar Power Association estimated that Brazil's total solar PV potential for installed capacity is near 28 TW, which is comparable to the US estimate (ABSOLAR, 2016). Brazil's maximum irradiance (6500 Wh/m^2/day) lies in the central area of the state of Bahia, in the NE Semiarid area (Pereira et al., 2017) (Figure 2.5).

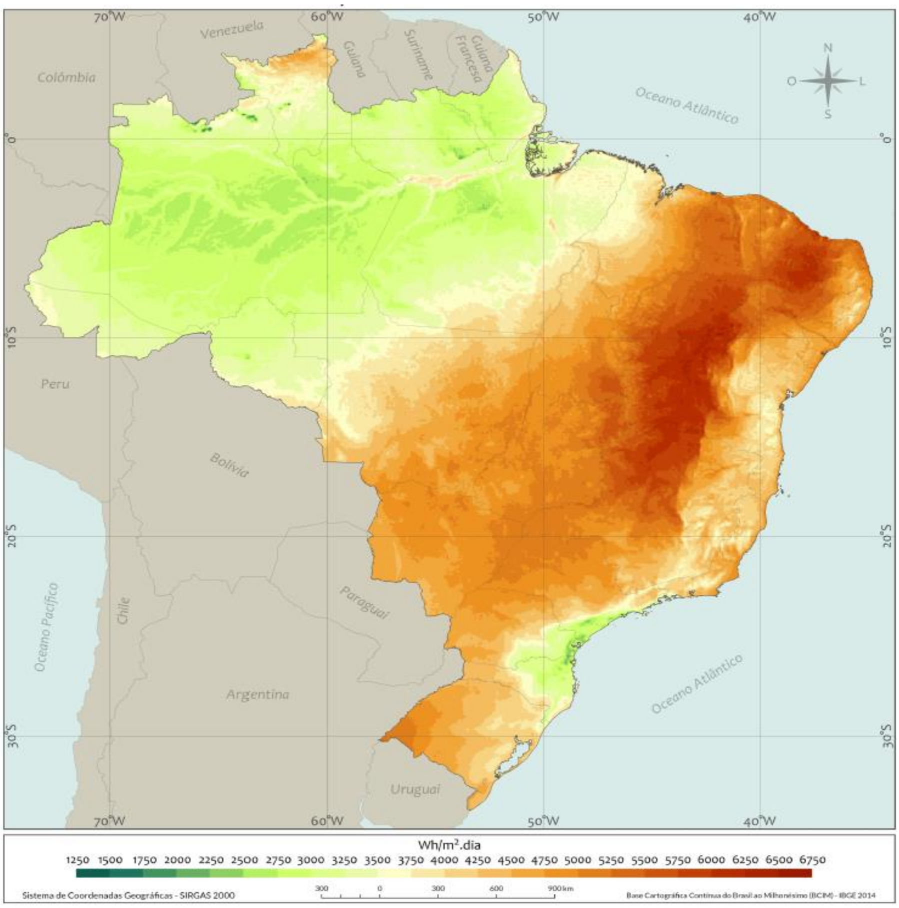

Figure 2.5 Brazil direct normal irradiation daily total (yearly average)

Source: Pereira et. al (2017)

Although the North region, where the Amazon is, concentrates the remaining hydropower potential of Brazil, it does not present a similar potential for wind and solar power. It is the second least developed region of the country, with some development indicators worse than the NE (IBGE, 2020). However, the potential for solar generation is less than 1,400 kWh/year, contrasting with an average of 1,800 kWh/year in the NE (Pereira et al., 2017). For wind power, speed is under 4.5 m/s in all its territory, whilst in the NE, speed reaches a maximum of 13 m/s. Table 2.2 compares each region's physical potential for solar PV and wind generation.

	Solar (average kWh/m^2/day)	Wind (TWh/year)	Maximum wind speed (m/s)
North	4.7	24.6	4.5
Northeast	5.5	144.3	13
South	4.5	22.8	8.5
Southeast	5	54.9	8.5
Centre-West	5	5.4	7

Table 2.2 Solar and Wind potential in Brazilian regions

Source: Author's calculations with data from ANEEL (2008) and Pereira et al. (2017)

The NE potential for solar and wind generation is clear. 65% of projects procured in electricity auctions starting to supply from 2017 to 2024 are in the NE. Solar PV energy accounted for 142 projects, 27% of the total, 73% of which are in the NE. Wind energy accounted for 229 projects, 45% of the total and 99% of which are in the NE.

Despite the concentration of solar and wind power plants in the NE, it is still a significant research gap in whether the investment canalised to the region has propelled socioeconomic development. One study has conducted an ex-post assessment of such effects: Gonçalves et al. (2020) analysed job and real wage increases in Brazilian municipalities which have hosted at least one wind farm through an econometric difference in difference model. Their results suggest that wind farms increase employment in the transformation industry, agriculture and construction, and wages in all economic sectors. Furthermore, they concluded that indirect effects are relevant, and most impacts occur over low-skill labour.

The potential for wind power generation in Brazil was assessed initially by ANEEL in 2001(ANEEL, 2018), considering lower tower heights and blade diameters, which averaged 51 metres and 40 metres, respectively. From 2001 to 2022, technical development has allowed tower heights to increase to 200 metres and blade diameter to 170 metres (Época Negócios, 2019). The mean diameter of wind blades in Brazil doubled in ten years: from 60 metres in 2008 to 120 metres in 2018 (Pereira et al., 2019).

This process follows an international trend through which wind blade diameter increased from 90%, smaller than 80 metres in 2007, to above 110 metres in 2018 (Pereira et al., 2019). Wind international levelized costs of energy (LCOE) consequently dropped 70% from USD 135/MWh in 2009 to USD 41/MWh in 2019 (Our World in Data, 2022). Thus, technical progress combined with the predictability and speed of local wind brought, in 2018, Brazil's wind capacity factor to the world's highest at 56% (Bloomberg, 2018; Pereira et al., 2019), having increased by 28% from 38% in 2010 (Pereira et al., 2019).

The availability of low-interest rate finance was an essential enabler for achieving renewable energy targets, although it is unclear if the financing was the main explanatory force for wind power success in Brazil. The BNDES was a critical player, initially financing up to 70% of each wind power project within PROINFA, which increased to 80% in 2005 through dedicated credit. The amortisation period was initially 12 years, increased to 16 years by BNDES in 2007. The incentive interest rate was the so-called long-term interest rate (TJLP), which was 50%-60% the official bank rate from 2002 to January 2018, when it ceased (BNDES, 2022).

BNDES had yet another relevant role in which it held shares not only of wind farms but also companies along their supply chain through its subsidiary BNDESPAR. In such a case, BNDES became a shareholder. Project finance funded most wind farms, and the guarantees to BNDES were its own assets and PPAs (Diniz, 2018). For instance, the component manufacturer Tecsis and the electricity generator *Renova Energia* were both in the BNDESPAR portfolio for a few years (BNDESPAR, 2018).

Brazil's renewable policies and programmes aimed to develop national wind plant component industrial segments and its supply chain through nationalization indexes (GWEC, 2011). The first phase of the PROINFA, until the country reached a 3,300 MW installed capacity of the targeted sources, established the 60% above mentioned nationalisation index for equipment and services (GWEC, 2011; Rennkamp et al., 2020). Parallelly, BNDES included the wind power supply chain within the so-called Progressive Nationalisation Plans (PNPs), which prioritise higher added-value stages of the supply chain as a condition for higher shares of BNDES financing (Willcox and Araújo, 2018).

The majority of available literature, however, does not account for the role of the regional development bank: the Bank of the Northeast (BNB), which is also relevant in supporting regional potentialities. The BNB manages the Northeast Financing Constitutional Fund (FNE), created by the 1988 Brazilian constitution, intending to reduce socioeconomic disparities in regional inequality between the Northeast and other Brazilian regions (BNB, 2021). The BNB concedes FNE resources to wind power projects at even lower investment costs than BNDES, although on a smaller scale: up to a 20-year amortisation period with an eight-year grace period and lower interest rates, particularly after the incentivised interest rate TJLP ceased in 2018 (BNB, 2021).

BNDES, as well as BNB, provides essential support to propel wind power in Brazil. However, one should note that it would not be adequate to attribute such success exclusively or majorly to finance availability without a careful analysis of the PROINFA programme and the role of the auction system as well as the reduction of the prices of wind power components and the technological progress experimented worldwide.

BNDES has provided abundant cheap finance to other technologies in the past, which did not grow as much or as fast as wind power generation. The geographical wind generation potential of the NE region and technology availability were among the synergies encountered by the government's combination of policies and programmes to deploy wind power in Brazil.

Although the NE climate provides a high physical potential for renewable energy generation, it has historically hindered the region’s socioeconomic development. The NE region's economy is notably vulnerable to its climate, with long and severe drought periods. Most NE region population lives in rural areas, with livelihoods dependent on low technology and subsistence-oriented agriculture. In 2015, the NE rural population was over 15 million people, which amounted to 48.7% of the total rural population of Brazil (IBGE, 2018a). Irregular rainfall regimes and water scarcity have harmed the development of local agricultural activities, and the region is marked by the consequences of its droughts: rural unemployment, poverty, famine and migration (Marengo et al., 2011b). In 2016, 25.4% of the Brazilian population lived under the poverty threshold (USD 5.5 *per capita* per calendar month), while in the NE, this rate was 43.5% (IBGE, 2017), showing that the NE region has much poorer socioeconomic conditions than the country's average.

2.4.2 Climate impacts

Long-term energy system planning must consider the mitigation of GHG emissions and the impacts of a changing climate on electricity generation resources (Pye et al., 2017). According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) projections, the Brazilian NE Semiarid is one of the world's regions where climate change impact trends are the most alarming (Castellanos et al., 2022). The IPCC has assessed that NE Brazil is among the world's most sensitive regions in terms of climatic-related migrations and displacements (Castellanos et al., 2022). They state that rainfall will vary geographically in South America, but most notably showing a reduction of 22% in NE Brazil.

The previous IPCC report, the Fifth Assessment (AR5) from 2014, stated that "in California, NE of Brazil and parts of the Andean region, increases in temperature and decreases in precipitation could decrease the productivity in the short term (by 2030), threatening the food security of the poorest population (medium confidence)" (Magrin et al., 2014, p. 1503)[8]. The IPCC indicates impacts over highly consumed agricultural products in the NE, such as cassava and maize (up to -10%) and rice and beans (up to -30%) (Magrin et al., 2014). Additionally, de Jong et al. (2018) compared several modelling results and concluded that the average annual rainfall of the NE region could decrease by 25–50% in different climate scenarios.

Three studies based on the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, 2022) scenario framework have indicated that NE Brazil is one of the most vulnerable regions in the world regarding climate change impacts (Byers et al., 2018; Stenzel et al., 2021; Thompson et al., 2021). Stenzel et al. (2021) simulated three scenarios for the impact of bioenergy with carbon capture and storage (BECCS) on water stress from 2007 to 2100, which differ in terms of the degree of climate change, BECCS deployment, and land use change trajectories. NE Brazil experiences high water stress levels in all three scenarios, comparable to most Sub-Saharan Africa and India.

[8] This information has not been updated in the AR6, hence the reference to AR5.

Byers et al. (2018) analysed global multi-sector climate change in which they calculated 14 impact indicators at different levels of global mean temperature (GMT) change and socioeconomic development comprising water, energy and land sectors. They concluded that SE Brazil is an area of particular concern for water stress primarily due to agricultural water exploitation that would violate environmental flow requirements related to sugar-cane biomass plantations. However, they indicated NE Brazil as one of the hotspots with high multi-sector risk.

Finally, Thompson et al. (2021) analysed climate-related risks of ecological change in 321 major river basins globally for four temperature increase scenarios (relative to pre-industrial conditions): 1.0, 1.5, 2.0 and 3.0°C. Their results indicate that the Southern Subtropical (SST) hydro belts, which include NE and SE Brazil, have higher risk scores for the four warming scenarios than the corresponding medians for the 321 basins. For example, basins in NE Brazil reached 60-70 per cent risk scores in the 2^{o}C scenario and 70-80% in the 3^{o}C scenario.

In the first half of the twenty-first century, the NE of Brazil was particularly at risk and vulnerable to worsening drought conditions caused by climate change, representing an increased risk to hydrological systems and water resources. The drought that started in 2013 and triggered an electricity system crisis has been the worst in the region in the last 50 years (Jenkins and Warren, 2015). A 12-month Standardised Precipitation Index used to assess long-term changes in annual precipitation patterns indicated that droughts are likely to become particularly severe. Duration was projected to increase by 30 months and some events to last over seven years (Jenkins and Warren, 2015).

Severe losses in terms of water availability are projected for the NE region, with relevant impacts on electricity generation, crops, and livestock as impacts of climate change (Margulis et al., 2010). Therefore, governing institutions in the NE should coordinate water resources management with energy planning. These institutions must identify the most severe cases, prioritise water uses, and anticipate adaptation measures for the most vulnerable, poor people and economic activities. In the next 10-20 years, intensified droughts might impact migration, increasing pressure on the NE region's urban areas and worsening its fragile socioeconomic conditions (Margulis et al., 2010). Therefore, this work explores how the main strength of the NE region, electricity generation potential, intrinsically linked to its climate, can be a vector of regional development.

Until 2100, rainfall may decrease by 2-2.5 mm/day in the region, with agriculture losses across all NE states (Margulis et al., 2010). Except for sugar cane, all crops would be affected. According to the authors, corn, a widely consumed commodity in the region, may face a 15% production reduction, even higher than that indicated by the IPCC (2014). Hence, the impacts of climate change on the current economic structure of the NE are clear.

The highest productivity loss would be subsistence crops in the NE. In addition, the hydrological debt would lead to a 25% reduction in cattle productivity, leading to lower yield husbandry. Also, a rainfall decrease can cause a reduction in the NE basin river flow, affecting electricity generation. For example, in the *Atlântico Leste* and the Parnaiba River basins, climate change can reduce flows by up to 90% between 2070 and 2100. As a result, firm electricity generation loss in Brazilian hydropower plants could be between 29.3% and 31.5%, with the highest levels projected to happen in the NE (Margulis et al., 2010).

Frequent droughts, particularly in a semiarid area relying on hydropower dams, will affect the electricity supply severely. São Francisco river basin hydroelectric dams historically generated most of the NE electricity (typically over 70%). The subsidiary of the national utility (Eletrobras) called São Francisco Hydropower Company (CHESF) holds the two main hydropower dams in the NE: Sobradinho (28,669 Hm^3 useful dam volume and 4,214 km^2 surface area) and Luiz Gonzaga/Itaparica (3,549 Hm^3 useful dam volume and 828 km^2 surface area) (CHESF, 2018). However, due to rainfall regime changes from 2013 to 2017, hydropower plants only supplied 18% to 42% of the NE's total electricity demand each year, well below previous levels. From 2005 to 2007, for example, hydropower was over 87% of the supply (de Jong et al., 2018).

Climate change can, therefore, systematically reduce hydropower predictability and firm energy, particularly in the Sao Francisco River basin. Since 2013, dam water volume levels have reached historic lows. For example, the Sobradinho dam reached 1,11% of total capacity in stored energy in January 2016, and the Tres Marias dam reached a minimum of 2.91% in October 2014 (ONS, 2018). According to de Jong et al. (2018), due to the impact of reduced rainfall on the streamflow and increased irrigation in this basin, the decrease in the NE's hydroelectricity generation could be twice the predicted rainfall reduction. Thus, they conclude that wind and solar must be significantly exploited for the NE to bridge the hydropower generation gap sustainably.

2.5 Chapter 2 conclusions

Brazil is at a crossroads in terms of its long-term electricity mix. Although non-hydro renewable sources are not the only option, if the country aims to take a low-carbon path, efforts must be made to maintain the renewable profile of its energy mix while hydropower becomes less reliable. Moreover, due to socioenvironmental regulation, most remaining hydropower resources cannot be explored.

For Brazil to maintain the renewable profile of its electricity mix in the long run, exploiting the resources of its least developed region, the NE, is critical. The estimated potential of the NE region for wind power installed capacity is 95.5 GW (78% of national potential) for 80-metre towers, 172 GW for 100-metre towers (55% of national potential) and 352 GW (59% of national potential) for 150-metre towers (EPE, 2020c). The NE semiarid region is also the most appropriate for PV generation, showing comparable irradiation to the best spots on earth. The estimated solar PV installed capacity potential is near 28 TW, comparable to the US estimate (ABSOLAR, 2016). Brazil's maximum irradiance (6500 Wh/m^2/day) lies in the central area of the state of Bahia, in the NE Semiarid area (Pereira et al., 2017) (Figure 2.5).

Answering the research questions of this thesis (Section 1.1) help demonstrate the economic and social value of low-carbon pathways for Brazil's electricity mix by bringing co-benefits to the NE region. Chapter 3 will therefore explore the socioeconomic structures of Brazilian regions and the extent to which their development is intertwined with energy generation.

3. REGIONAL SOCIOECONOMIC DEVELOPMENT AND ENERGY GENERATION

This thesis addresses the interlinkage between energy policy and socioeconomic development, focusing on long-term electricity capacity expansion in Brazilian regions. First, Chapter 3 assesses the context of the relationship between energy policy and development objectives in Section 3.1. Then, Section 3.2 presents the main characteristics of Brazil's five geoeconomic regions' economies, socioeconomic and industrial development stages, income distribution issues, and the relationship between these economic aspects and electricity generation. Section 3.3 follows with a review of the literature and a discussion of the evidence raised on the socioeconomic impacts that renewable energy policies have had. Moreover, subsection 3.4 explores the relevance of quantifying the socioeconomic effects created by energy policy in the long term and the methodological options applied in the literature. Finally, having assessed all of the previous aspects, Chapter 3 clearly states the research gap this thesis fills.

This chapter, therefore, contextualises the interpretation of the results for the regional socioeconomic impacts of electricity capacity expansion scenarios explored in Chapters 6, 7 and 8. The three results chapters, in turn, respond to each of the three underlying research questions posed in Section 1.1: the impacts of the long-term electricity capacity expansion scenarios on macroeconomic aggregates, industrial sectors, jobs, wages and income distribution. Besides, by presenting a review of the existing literature on the socioeconomic impacts of energy policy and addressing the analytical tools applied, Chapter 3 justifies this thesis's method choice, leading to Chapter 4 – Methodology.

3.1 Energy policy and socioeconomic development

Renewable energy policy is usually multi-objective, aiming at simultaneously tackling issues such as energy security, GHG emission reduction, and industrial and socioeconomic development. Notably, Hochstetler (2020) assessed the political economy of energy transitions in Brazil and South Africa and suggested four main dimensions influencing the objectives of policies to increase the share of renewables, namely: climate change, industrial development, distributive impacts and local community benefits.

Arguably, market forces do not seem to have been the main drivers of renewable energy policy across successful policy cases. Experiences from Brazil, China, Germany and South Africa have shown that thriving in the deployment of both wind and solar power is attributable to both demand and industrial supply-side policies, which were not enacted based on traditional appraisals of cost-benefit analysis (Grubb et al., 2021a; Hochstetler, 2020). According to Grubb et al. (2021a), the steep reduction in wind and solar technologies costs has increased their market share. In addition, the internationalisation of the industry has included production and markets in major emerging economies. To achieve this, governments have implemented combinations of multi-objective mutual transformative policies.

Renewable policy design is path-dependent on existing policy and institutional contexts (Aklin and Urpelainen, 2013). For example, different power structures within emerging economies may hinder the extent to which researchers can compare the renewable policies and development strategies from China's most studied power market case to other emerging economies such as Brazil (Hochstetler, 2020).

One relevant aspect of renewable energy policy design in EMDEs is an overall decision regarding the roles of the public and private sectors (Hochstetler, 2020). A strong state presence frequently characterizes energy utilities in EMDEs, and noticeably in cases such as Brazil and South Africa, Independent Power Producers (IPPs) were introduced to the market through wind and solar programmes (Hochstetler, 2020).

Previous industrialization policies and strategies shape the approach through which each developing economy structures its renewable power market (Hughes and Urpelainen, 2015). Existing industrial segments provide building blocks and help renewable power plants' supply chains increase activity in national manufacturing (Hochstetler, 2020; Hughes and Urpelainen, 2015; Milani et al., 2020). Existing industrial innovation systems also determine whether countries are subject to technology transfer or become exporters of renewable energy technology. Thus, industrial development co-benefits of renewable power plants components and the whole of their supply chain are usually intrinsic to renewable energy policy design, reflecting ultimately on employment and growth effects (Hochstetler, 2020; Hughes and Urpelainen, 2015).

3.2 Regional socioeconomic structures, income distribution and industrial development in Brazil

Renewable energy programmes in Brazil naturally identified and explored the synergy between geographical potentialities and development goals. For example, after conceiving PROINFA, policymakers identified synergies with the programme's initial focus. Hence, they targeted the NE region for wind power expansion. However, regional industrial and labour capability disparities determine the development of energy projects and the resulting impacts on Brazilian regions' economies.

As stated by Walz *et al.* (2017), sustainable, inclusive economic development requires countries of the Global South, including Brazil, to develop their capabilities for green technologies. Furthermore, the authors emphasise that technology co-evolves with socioeconomic development. Therefore, countries that manage to create and maintain an industrial innovation system experience better socioeconomic conditions (Matsuo and Schmidt, 2019; Walz et al., 2017).

In Brazil, income distribution dimensions are complex. Although the South and SE regions do not show a comparable physical potential for renewable energy generation to the NE, the wind power plant supply chain was initially concentrated in these regions due to its industrial and labour force capabilities. Due to their greater manufacturing capacity and higher human resources, the SE and South regions are still likely to benefit from investment in renewable energy through their supply chains. By contrast, while the NE has the most significant physical potential, its lower industrial and human capacity means that regional benefits are uncertain, which is a crucial question this research aims to enlighten.

The relevant sectors for most power plant components manufacturing supply chains are in the South and SE regions. The construction industry represents 37% of the NE industrial GDP, and the regional industry could supply the demand for these services. However, metallurgy, for example, is a sector that provides materials for all kinds of power plants, representing 6.6% of industrial GDP in the SE and only 3.9% in the NE. Machinery and equipment is another relevant industrial segment for power plants, representing 3.2% of the SE industry. It is almost inexistent in the NE, with 0.3% (CNI, 2018). Noticeably, the NE has not been prioritised for industrialisation or agricultural development, partly due to its semiarid climate, with prolonged and severe droughts annually.

At the beginning of the wind power deployment process in Brazil from 2012, most industrial plants were in the SE state of São Paulo. It was a natural choice for manufacturing industries, given its proximity to the industrial hub of the South and Southeast regions. However, it has proven to be logistically prohibitive to maintain such industrial plants far from the wind farms, which are over 90% located in the NE region. Thus, especially since 2017, industrial plants have been increasingly relocating industries manufacturing wind power plant components (Bezerra and Santos, 2017). Currently, manufacturers supplying industrial components to wind farms are primarily in the NE, except for motors and aerogenerators, which remained in the state of Santa Catarina in the South region, where the leading company, WEG Motors, has always been located (Table 3.1).

Manufacturer	*Region*	*Components*	*Annual capacity (units)*
Gamesa	NE	Nacele	300
Acciona Windpower	NE	Wind cube	150
Vestas	NE	Concrete towers	200
Wobben/Enercon	NE	Turbines	250
Wobben/Enercon	SE	Blades	1000
WEG	South	Towers	144
GE	SE	Blades and turbines	384
TEN	NE	Turbines	200
Tecsis	NE	Blades	2500
LM Wind Power	NE	Blades	1000
Torrebras	NE	Towers	200
Aeris	NE	Blades	2000
IRAETA	NE	Towers and flanges	N/A
Harald	South	Towers	N/A

Table 3.1 Wind power plant component manufacturers' location and annual capacity in 2017

Source: ABDI (2017) and Bezerra and Santos (2017)

However, manufacturers of such components are highly concentrated in the South and SE, mainly producing steel products. ABDI (2017) mapped 23 industrial plants supplying steel goods to wind farms, of which 18 are in the SE, 4 in the South and only one in the NE.

Although 27% of the Brazilian population lives in the NE region, it produces just 14.2% of the country's GDP. It has thus the lowest per capita GDP and the lowest GDP share/population share ratio, as seen in Table 3.2. On the other hand, SE is the most developed and industrialised region, concentrating 42% of Brazil's population and 54% of its GDP (Table 3.2).

	2021 Population (10^6)	Population Share	GDP 2019 (10^6 USD)	GDP Share	GDP per capita (2019 USD)	Ratio Share GDP/Share population
Brazil	213.32	100%	1,844,383	100%	8,646	1.00
North	18.91	8.86%	102,611	5.40%	5,427	0.61
Northeast	57.67	27.03%	240,938	14.20%	4,178	0.53
Southeast	89.63	42.02%	993,000	54.00%	11,079	1.29
South	30.40	14.25%	322,452	16.80%	10,606	1.18
Centre-West	16.71	7.83%	185,382	9.70%	11,096	1.24

Table 3.2 Brazil's regions population, GDP, GDP per capita and corresponding shares

Source: Author's elaboration with data from IBGE (2022a, 2022b) and Ipeadata (2022)

Moreover, SE is responsible for 55% of Brazil's industrial GDP, while the NE share of industrial GDP is 12.9% of the total. Whilst SE represents 49.5% of the industrial labour force in Brazil, the corresponding figure in the NE is 15.2% (CNI, 2018).

From Table 3.2, it is noticeable that the SE, the South and the CW regions have higher GDP levels relative to their population share, while the NE and North regions produce much less GDP relative to their population share. This happens because although the whole Brazilian economy comprises 74% of services, SE concentrates most of the country's industry and, therefore, much of the value added. At the same time, the CW has a significant agriculture and livestock-based economy, and the South presents a mix of the two kinds of activities.

The NE is a large region in terms of its population and area. Although it has a world-leading potential for energy generation in terms of physical advantages, it shows alarming social and environmental contrasts. The NE encompasses an area of over 1.5 million km^2 separated into nine states: Alagoas, Bahia, Ceará, Maranhão, Paraíba, Pernambuco, Piauí, Rio Grande do Norte and Sergipe, divided into 1,793 municipalities.

The 2022 Census published new data showing that the NE region's population was above 55 million in 2022 (IBGE, 2023a). Located inside the NE, the semiarid region (Figure 2.3) officially comprises 1,262 municipalities, covering an area of over 1.03 million km^2, 12% of the total area of Brazil). The semiarid population was above 27 million in 2017, accounting for 42% of the NE population and 13% of the Brazilian population (ASA, 2021). It is the world's most densely populated dry area, with over 25 people per km^2 (Marengo et al., 2016).

While investment in renewable power plants in the NE should aim to deliver socioeconomic co-benefits to the region, it poses a challenge, for example, regarding the availability of skilled labour. According to the 2015 National Household Sample Survey (PNAD)[9], 16.1% of economically active people in the NE earned up to half the minimum wage and 71.8% up to two minimum wages (lowest income class) in the reference week (IBGE, 2019).

The average in Brazil, in contrast, is only 7.1% of economically active people in the reference week earning up to half the minimum wage and 58.6% up to two minimum wages (lowest income class). In the SE, this index is even lower, with 3.5% of economically active people in the reference week earning up to half the minimum wage and 52.8% up to two minimum wages (lowest income class).

The average real income of labour in the NE region compared to Brazil and other regions reflects the regional economy's skilled labour deficiency, showing, since 2012, steadily the lowest level. Moreover, according to an analysis from the Brazilian Central Bank, labour productivity in the NE is the lowest among Brazilian regions in all sectors: industry, services, agriculture and livestock (BCB, 2018). The share of uneducated people in the NE region reinforces this view. It has been the highest in Brazil since the start of the time series; more than 15% of the population has no formal education (IBGE, 2019).

The NE has been, throughout Brazilian history, disadvantaged in terms of its socioeconomic development. Across the centuries, economic activities in the region have used production relationships and organizations, which represented a delay

[9] Updates to the graphs and tables using PNAD data have not been possible due to discontinuities in the data series during the Bolsonaro administration (2018-2022).

compared to other regions, particularly the Southeast (SE), high concentration of labour force and extremely low productivity (IIAC, 2013). During the nineteenth century, when most of Brazil's workforce was enslaved, the NE specialized in less technology-intensive crops such as cotton and sugar, while the SE produced coffee, more technology-intensive and focused on exports.

Even after the end of slavery in 1888, economists like Wilson Cano (2010, 1997) have claimed that the NE region never constituted capitalist production relationships with an enormous concentration of land property and income. Thus, until the end of the twentieth century, the NE had not properly shaped labour, consumption, a credit market, or a proper entrepreneurship environment (IIAC, 2013). The 1988 Brazilian Constitution established a priority for the NE in tax revenue distribution and access to production activities finance (Article 159) (BRASIL, 1988) and a Constitutional Fund specifically created to foster economic activities in the NE.

The IBGE (2019) data show that the NE region's unemployment rate is systematically higher than that of other regions and Brazil, as seen in Figure 3.1 below. Furthermore, Figure 3.1 shows that since 2012, unemployment in the NE region systematically pulls the Brazilian average upwards.

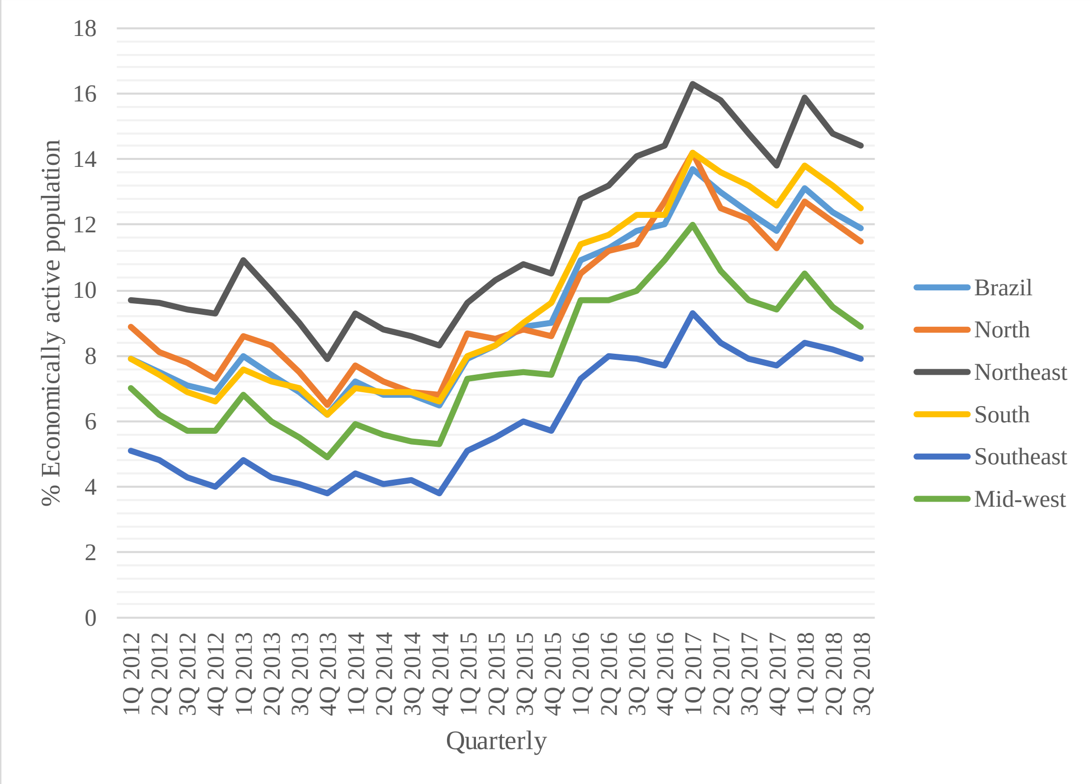

Figure 3.1 Percentage of unemployed people in economically active age per Brazilian Region 2012-2018 quarterly

Source: Author’s elaboration with data from IBGE (2019)

Figure 3.1 shows the detachment of the NE unemployment curve from the rest of the country. Levels in all regions varied slightly between 2012 and 2015. In 2014, the North and the SE experienced increases, but the NE had a steep increase that detached it even further, going from 1.11 million discouraged people in the first quarter of 2012 to 2.9 million people in the third quarter of 2018.

Inequalities in education between the regions reflect the wage gap. The NE has consistently been the region where average years of education are the lowest in Brazil and where there is the most significant percentage of uneducated people. In 2015, 28% of the NE population who were ten-year-old or older had up to three years of education. In Brazil, this index was 19% and 14% in the SE. 14% of the NE population of economically active age was uneducated, while in the SE, only 6% were uneducated. Data shows that this pattern has not changed in time, and at least since 2012, the percentage of uneducated economically active people in the NE has been around double the percentage in the SE.

Income concentration inside the NE also calls attention. It has historically had the highest income concentration among Brazilian regions, with the NE's highest Gini[10] coefficient. In 2001, the NE’s Gini index was 0.60, while the SE’s index was 0.568 and the Southern 0.547 (IPEADATA, 2018). In 2014, after a fall across all regions, the NE Gini index was 0.516, contrasting with SE’s 0.501 and Southern 0.456 (IPEADATA, 2018). However, from 2014 to 2017, this index increased again in some regions of Brazil. The most significant variation was in the NE, which rose 10%, reaching 0.567 in 2017 (IBGE, 2018a). According to the Household Budget Survey (POF) data (IBGE, 2018b), in 2008, considering the ten most consumed food and beverage items in Brazil, on average, per capita intake in the NE region is 20% lower than the Brazilian total, and 22% lower than the SE region.

[10] Gini Index is a measure of household per capita income distribution among individuals. Its value varies theoretically between zero, when there is no inequality (all individuals income has the same value) and one, when inequality is maximum (one individual holds all the income of the society and the rest have their income equal to zero).

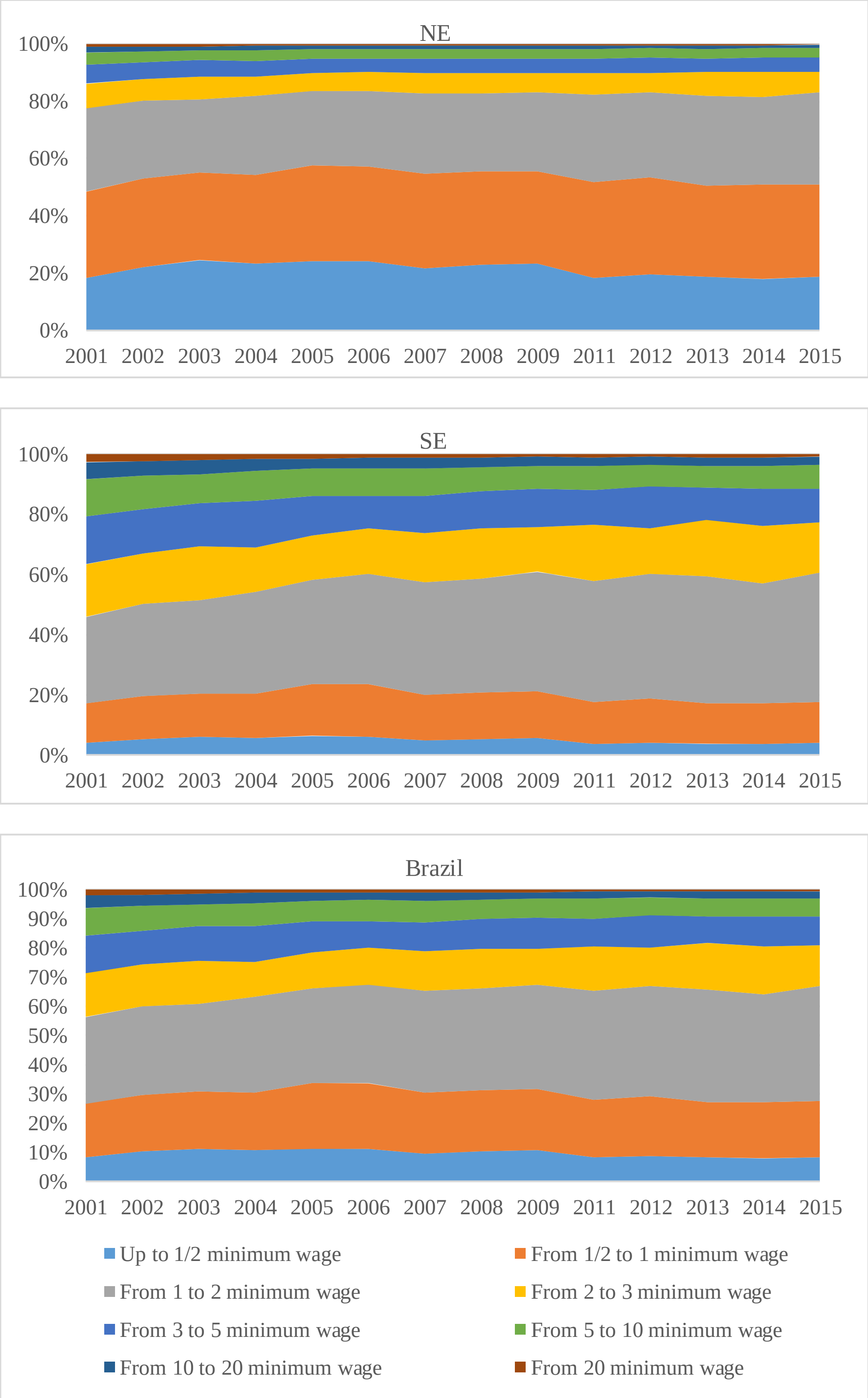

Figure 3.2 Average monthly income of economically active population (% of total per Brazilian region

Source: Author's elaboration with data from IBGE (2019)

According to PNAD data (IBGE, 2018c), 165,000 households lacked access to electricity in Brazil, around 51% of which reside in the NE region. The NE *per capita* electricity consumption reflects this; in 2017, the NE rate was only 62% of the Brazilian average, with 1,389 kWh/inhabitant, whilst the Brazilian average was 2,241/kWh/inhabitant, pulled by the SE rate of 2,665 kWh/inhabitant (EPE, 2018c). In 2017, according to PNAD data, 84,000 households in the region did not have access to electricity, 82% of which were in rural areas. Table 3.3 compares the percentages of households lacking access to basic services in the NE, the SE and Brazil as a whole.

2015 (% households without the service)		**Region**					
		NE		**SE**		**Brazil**	
		Urban	Rural	Urban	Rural	Urban	Rural
Basic service	Electricity	0.11%	1.44%	0.01%	0.61%	0.05%	1.75%
	Water Network	2.95%	34.85%	0.63%	6.14%	1.37%	22.29%
	Sewage (any kind)	1.32%	16.98%	0.16%	2.30%	0.55%	10.20%
	Sewage collecting system	49.92%	95.36%	4.18%	53.46%	12.37%	61.29%

Table 3.3 Household access gap to electricity, water network and sewage

Source: Author's calculations with data from (IBGE, 2019)

From Table 3.3, it is clear that household access to electricity is no longer a significant issue in Brazil, primarily due to the success of the *Luz para Todos* (*Light for all*) programme. So far, the main focus of this programme has been the NE region, where it made 1.69 million new connections between 2003 and December 2017 (EPE, 2018c). However, connecting households and small businesses to electricity alone does not necessarily guarantee equal access to energy services. As mentioned before, with the increase in electricity prices, mainly due to droughts and consequent hydropower shortages, people who now have access to electricity are not necessarily able to afford to use it. According to EPE (2018a), the average household electricity price increased by 59% from 2013 to 2017 and 66% in rural areas.

Water scarcity is one of the main characteristics of the region that governments have never successfully addressed. Silva *et al.* (2016) calculated the Water Scarcity Index

(WSI) and net virtual water exports (or imports) for all Brazilian regions and the whole country from 1997 to 2012. The NE presented a WSI of 76.7%, an alarming disparity with the country total of 5%, being the SE the second worst region with a WSI of 46.3%. Furthermore, all NE states apart from Piauí showed net international virtual water imports for their crops between 1,032 and zero m^3/year imported (Silva et al., 2016). Table 3.3 also shows that access to the water network and sewage systems in the NE is considerably worse than in the rest of Brazil, with particularly alarming indicators in the rural area.

The direct relation between resource availability and socioeconomic development in Brazilian regions is evident. The following section will explore the interlinkages between socioeconomic development and long-term energy and climate policy.

3.3 Socioeconomic impacts of energy and climate policy

When analysing the socioeconomic impacts of renewable energy deployment, it is vital to explore objectively whether the low-carbon transition is inherently or naturally more economically beneficial or equitable than fossil-based, business-as-usual development. The impacts of climate change deepen inequalities and justify the investment in renewable electricity (Cappelli et al., 2021; Paglialunga et al., 2022; Taconet et al., 2020). However, arguably, infrastructure investment of any kind tends to create positive regional economic impacts (Batini et al., 2022; Garrett-Peltier, 2017; Vagliasindi and Gorgulu, 2021). The question to be answered is whether investing in renewable electricity infrastructure can have net positive socioeconomic impacts compared to fossil-based infrastructure, particularly in the least favoured regions concentrating wind and solar power generation potential.

Falling costs of renewables and the ‘risk amplifier’ of locking into fossil fuel infrastructure oppose the assumption that decarbonisation is an economic burden (Grubb, 2014; Grubb et al., 2015). Lower electricity costs benefit lower-income household groups (Chapman et al., 2018). However, renewable technologies do not necessarily have higher employment factors than fossil-based ones (Cameron and Van Der Zwaan, 2015; Cartelle Barros et al., 2017). Variables such as plant capacity factors, labour productivity of different countries or regions, industrial development and other regional development indicators seem to be more determinant than the technology itself.

Renewable energy systems exploit flows as opposed to stocks of resources and therefore are less concentrated in a small number of countries. The latter lowers economic and geoeconomic incentives for states to secure control over them (Månsson, 2015). However, the minerals required as inputs to renewable energy and related storage and transport technologies will experience increased demand (Sovacool et al., 2020), and there will be a strong incentive for states to seek control over these mineral resources, some of which are of high geoeconomic strategic interest (IEA, 2021a).

Decentralised renewable energy technologies are often portrayed as being universally accepted in EMDEs. However, community acceptance should not be taken for granted, particularly as involving local organisations in projects can reduce resistance to these projects (Thornley et al., 2008). Therefore, it is crucial to communicate the widespread effects of the technology to the communities, whether positive or negative, which can improve acceptance and increase scale-up (Sathaye et al., 2011).

It is often argued that renewable energy and low carbon infrastructure create more jobs and propel more socioeconomic development than traditional, ‘brown’ infrastructure, making the case for the just transition argument (Cronin et al., 2021). The concept of just transition entails the idea of the low-carbon energy transition as a means for poverty eradication and social inclusion (Vasconcellos and Caiado Couto, 2021). Policymakers also often see renewable energy sources as means to provide increased electricity access in rural and remote areas (Monyei et al., 2018; Mulugetta et al., 2019), so much so that electricity access is usually among the main aims of renewable policy design.

The discussion around just transitions and the extent to which renewable energy creates more positive socioeconomic effects than fossil fuels increasingly attract policymakers' and researchers’ attention. However, data constraints in EMDEs expose a critical gap in providing quantitative evidence for such discussions. The inexistence of a dataset providing socioeconomic information for different energy technologies increases the challenges of model calibration.

The gap is especially relevant in EMDEs with outstanding potential for renewable deployments, which is the case of Brazil. Quantifying the socioeconomic impacts of different energy investment scenarios in these countries can strengthen the case for renewable energy investment. For this purpose, datasets such as the number of jobs per electricity source must be estimated using creative data triangulation methods. Then, socioeconomic effects of different electricity capacity expansion scenarios, with different levels of renewable versus non-renewable energy shares, should be quantified and compared.

The next sections explore the methods generally used to conduct this type of analysis and the research gap this PhD fulfils. Chapter 4 then explores how this is done, the specific method developed in this research.

3.4 Estimating the socioeconomic impacts of energy and climate policy

Assessing the economic and social impacts of energy policy is an essential stage in policy design (Hondo and Moriizumi, 2017). Furthermore, quantifying trade-offs for policy decision-making requires models that encompass interacting forces among sectors affecting economic performance, environmental quality and social conditions (Böhringer et al., 2013).

Socioeconomic impacts of electricity capacity expansion occur over several relevant economic variables and take place during different periods. Impacts can be observed at direct, within the project, indirect, across the supply chains, and induced levels, through the income-effect when new income creates new demand. Effects therefore occur over entire chains and price feedbacks between different sectors. They may be measured at local, regional, or national levels.

Different methods assess the different aspects of socioeconomic impacts. The selection of a method depends fundamentally on which questions one intends to answer, for example, whether the research aims at estimating past or future impacts, gross or net impacts across the economy, to focus on a specific technology, a set of projects, or scenarios for the whole of the electricity mix (Calzadilla and Parrado, 2017a; ILO, 2017).

It has been widely argued in the literature that infrastructure investment can cause economic stimulus, creating jobs and generating income in areas hosting such projects and therefore receiving at least part of the investment. In cases where discretionary fiscal policy translates into government expenditure in infrastructure, Keynesian economics argues that public stimulus creates the so-called fiscal multipliers (Vagliasindi and Gorgulu, 2021).

According to the Keynesian approach, one dollar of government expenditure translates into a given number of jobs, and an amount of income arguably higher than one, propelling the economy and therefore justifying such expenditure. This ultimately means that either the investment in fossil-fuel infrastructure or renewable energy infrastructure would yield positive economic effects. The matter would therefore be which technology would create the largest multipliers.

The General Equilibrium approach, however, follows the Neoclassical economic assumptions of equilibrium, specifically Walrasian assumptions of market-clearing price-adjustment mechanisms in product and factor markets, therefore assuming full employment (Robinson, 2006). The equilibrium assumption means that when building a CGE model, one assumes that in the base year to which the model is calibrated, the economy operated in equilibrium, with full employment. This normally means that shocks will make the model optimise its equations in order to reach a new equilibrium in the subsequent period.

While in the CGE approach total employment does not change substantially, following economically active population growth in the long-run, one can still identify winners and losers in terms of sectors, regions, income, and wage bands. It also allows for the comparison of net impacts of different scenarios, in which the energy mix has larger or lower shares of fossil fuels and renewable energy.

3.4.1 Applied methodologies

Multiplier analysis is usually used for ex-ante analysis, normally focusing specifically on one technology and a set of projects at a time, as is the case of Simas and Pacca, (2014) Milani et al. (2020), Vasconcellos and Caiado Couto (2021). Some studies focus on a specific aspect of socioeconomic impacts, normally job creation in the context of green jobs and just transition (Garrett-Peltier, 2017). This type of analysis is clearly relevant and allows for a closer look at the supply chains of certain projects, and across the duration of the implementation and operation phases.

Studies on socioeconomic impacts of renewable energy in EMDEs, apart from China[11], normally apply static multipliers from Input-Output analysis, with rare exemptions using CGE models (Chatri et al., 2018; Chunark et al., 2017; Effendi and Resosudarmo, 2021; Kat et al., 2018; Nong, 2020) and econometric analysis (Gonçalves et al., 2020; Koengkan and Fuinhas, 2020). For Brazil, Input-Output multipliers have been used to assess the socioeconomic impacts of renewable energy investment (Milani et al., 2020; Simas and Pacca, 2014; Vasconcellos and Caiado Couto, 2021). Although CGE applications to renewable energy are fairly recent, starting from 2008 according to Web of Science search results analysis[12] (Web of Science, 2022), the literature has been increasingly recognising its relevance.

The International Labour Organisation (ILO, 2017) reviewed methodologies to assess green jobs creation analysing what are the assessment tools and methods available to measure these impacts, and what are their strengths and limitations. They analysed through a comparison of inventories, surveys, application of employment factors, Input-Output models, Social Accounting Matrices (SAMs), CGE models, Econometrics and System Dynamics.

Inventories and surveys are useful ex-post tools to quantify existing jobs, especially in the absence of detailed official statistics. However, they are constrained to direct effects, and refer almost exclusively to job creation, potentially assessing income generation if wages of such job creation are also surveyed.

Input-Output analysis manage to estimate job creation by disaggregating value chains and imputing shocks on final demand that, through multipliers, allow to calculate direct, indirect and even induced impacts if households are endogenized. Input-Output

[11] China clearly differs from the wider group of EMDEs in terms of research funds, data production and therefore diversity of methods and methodological advancement. Although it is classified as a developing country by the World Bank (2021) income per capita threshold, China had the most academic publications in 2018 (Tollefson, 2018). China has the world’s second largest research funding, and in 2020, it spent a record of 2.5% of GDP (USD322 billion) in R&D investment (Normile, 2020).

[12] A search for the words “CGE AND Renewable AND Energy” resulted in 218 results, 91% of which published from 2013, which was the first year when over ten documents were published.

models use social accountancy data to provide a picture of an economy in a particular year, with flows of goods and services between all sectors.

Technical coefficients from the Leontief model describe the embedded demand for goods and services across sectors and allow tracking direct, indirect and induced demands throughout the economy. However, the major drawbacks of Input-Output models are that they assume prices are constant, what does not allow them to estimate effects caused by price feedback. They do not provide expenditure patterns of economic actors (households, firms, and government) either, hindering distributional analysis.

SAMs, in turn, are the extension of input-Output tables, including information on income and spending (ILO, 2017). SAMs are still static, with fixed coefficients, referring to a single period and lack information on behaviour. Macroeconomic models then provide a more complex modelling framework that addresses these limitations. They allow calculating effects of specific policies and investments in predefined scenarios, as the present research proposes to do.

Optimization models can be sectoral, partial equilibrium optimization, considered bottom-up models, or macroeconomic, multisectoral, CGE models, which normally assume a top-down approach to production technologies. Partial equilibrium sectoral models, as Energy-System Optimization Models (ESOMs) can optimize energy supply, according to demand, minimizing costs.

The main examples of such models are the MARKAL model that evolved to TIMES and the TIAM models. These models are bottom-up, technology detailed cost optimization models for the energy sector that analyse mostly impacts of decarbonization policies and pathways over the sector’s costs and prices (UCL, 2018). These models, as partial equilibrium approaches, can estimate socioeconomic impacts through the use of multipliers, considering the rest of the prices fixed (ILO, 2017). Hence, their limitations in terms of quantifying socioeconomic impacts are similar to other partial equilibrium approaches such as Input-Output analysis.

Some of these models, however, have developed hard links with a CGE module. The CGE module is normally highly simplified, in some cases optimising the production function of a single sector which yields macroeconomic results such as the impact of climate policy over GDP by changes in prices of fuels, which are represented as production factors. This is the case, for example, of the REMIND-MAgPIE model (IAMC, 2022). Notably, economic analyses of climate and energy policy long-term scenarios tend to adopt the equilibrium approach in economics given its optimization nature, and hence its compatibility with energy-system modelling (Anderson and Jewell, 2019).

CGE models take a step further than partial equilibrium models by simulating responses in the full economy to exogenous changes. CGE models bring more complexity to the Input-Output framework by providing a microeconomic base theoretical structure to describe interactions among different representative economic agents. Although they are based on similar databases, all agents and sectors supply and demand are described in a consistent way and interconnected by price feedback mechanisms (Calzadilla and Parrado, 2017b). A series of economic equations are designed to comprehensively capture complexities, accounting for changes in multiple variables in multiple sectors. They can explore in detail relationships between sectors, consumers and government, modelling the dynamic effects of policies over several macroeconomic variables. They are used to analyse impacts over welfare and distributional impacts (ILO, 2017).

Econometric models rely basically on observed, empirical data to validate interactions between markets, testing hypothesis to verify theoretical propositions (Calzadilla and Parrado, 2017b). They use historical data to estimate relationships among key drivers, with a set of equations that describe the structure of the system analysed. Most econometric analysis will be limited to a particular set of energy projects, especially in EMDEs, given data constraints.

Physical relationships as well as behaviour are modelled estimating the causality among variables using historical data to determine elasticities. Forecasts are possible through the simulation of changes in exogenous variables. The main example is the Cambridge Econometrics Energy-Environment-Economy model (E3ME) (Cambridge Econometrics, 2022) that consists of 22 sets of equations (each disaggregated by sector and by country) covering the components of GDP, prices, the labour market and energy demand (ILO, 2017).

System dynamics create descriptive models providing information of policy effects in specific contexts. They provide stocks and flows that allow the identification of causal relationships within the system analysed. It allows for the full incorporation of biophysical and monetary variables and can integrate different methodologies in different sectors. Their main weakness is, though, that they tend to be limited to a high-level approach, with quite little detail of sectors. At last, Integrated Assessments combine two or more models, inputting one model results into other models (Calzadilla and Parrado, 2017b).

While partial equilibrium models provide interesting insights about potential socioeconomic impacts, they do not account for the intersectoral interactions and feedbacks, and so their results are gross results accounting for what happens in sectors regardless of how other sectors may be impacted negatively or positively. Similar limitations apply in general to ex-post analyses. They are quite valuable given that they analyse existing phenomena, for example, what have been the actual socioeconomic impacts of certain projects. However, they are hardly generalisable, and differences in geographies, size of projects for example may be relevant enough for past experiences not to be similar the forthcoming ones which socioeconomic impacts we may need to estimate.

CGE models, in contrast, have feedback mechanisms among all sectors, through changes in relative prices, which provides the estimation of net impacts over relevant variables such as GDP and employment creation. This means, for example, that if some sectors yield GDP growth resulting from a given policy, while other sectors experience degrowth, economy-wide net results will account for all such effects (Diniz and Caiado Couto, 2021).

		Criteria		
		Application	**Main strenght**	**Main Weakness**
Method	**Inventories and Surveys**	Ex-post analysis that quantify existing job creation, income generation in specific groups of agents i.e. Households	Allows for actual observations of existing projects and give a good qualitative basis for further assessments.	The method itself simulations and pr
	Econometrics	Analyse trends, need observed, empyrical data to perform both ex-post analysis and ex-ante simulations based on previous observations.	Using statistic tools, they are very accurate for short-term projections based on recent trends.	Observed data fro are needed in large not suitable for lo significant change economy.
	Partial Equilibrium	Sector-specific optimisation, explicitly stablish supply and demand to reach sectoral equilibrium. This is the case of energy system models used to build future energy scenarios.	Bottom-up approach, quite detailed about the sector analysed. For energy systems, they provide a wide range of energy technologies delivering future energy service at the least cost.	Doesn't analyse in sectors and change
	Input-Output	Providing a picture of the whole economy, with flowa of goods and sectors across all the economy, with the possibility of including households, allows for ex-ante analysis. Multipliers calculate direct, indirect and induced impacts across all sectors.	Analysis interactions among all sectors of the economy and is simple to build.	Doesn't encompas mechanisms and te fixed.
	SAM	Extension of Input-Output framework improving the level of information on income and spending.	Analysis interactions among all sectors of the economy and it is more detailed that Input-Output models.	Tends to add more model building tha when compared to
	System Dynamics	High-level approach linking several sectors and dimensions.	Allows for the integration of socioeconomic and environmental indicators	Being quite high-l many sectors and c in each of them.
	CGE	Bring more complexity to the Input-Output framework by providing a microeconomic based theoretical structure to describe interactions among different representative economic agents. All agents and sectors supply and demand are described in a consistent way and are interconnected by price feedback mechanisms.	They can explore in detail the relationships between sectors, consumers and government, modelling the dynamic effects of policies over several macroeconomic variables. They are used to analyse impacts over welfare and distributional impacts in both short and long term.	They are quite labo several different da assume economy i as in the base peric

Table **3.4** below summarises and compares suitable methods, their strengths, and weaknesses in terms of their fit to the objectives of this PhD research.

		Criteria			
		Application	**Main strenght**	**Main Weakness**	**Fit to the objective**
Method	**Inventories and Surveys**	Ex-post analysis that quantify existing job creation, income generation in specific groups of agents i.e. Households	Allows for actual observations of existing projects and give a good qualitative basis for further assessments.	The method itself cannot be used for simulations and projections.	No, because this is an ex-ante, long-term analysis with a macroeconomic approach, not focused on specific projects.
	Econometrics	Analyse trends, need observed, empyrical data to perform both ex-post analysis and ex-ante simulations based on previous observations.	Using statistic tools, they are very accurate for short-term projections based on recent trends.	Observed data from previous observations are needed in large quantity and they are not suitable for long-term analysis with significant changes in the structure of the economy.	No, because of the lack of data existence and the long-term nature of the analysis.
	Partial Equilibrium	Sector-specific optimisation, explicitly stablish supply and demand to reach sectoral equilibrium. This is the case of energy system models used to build future energy scenarios.	Bottom-up approach, quite detailed about the sector analysed. For energy systems, they provide a wide range of energy technologies delivering future energy service at the least cost.	Doesn't analyse interactions between all sectors and changes in relative prices.	No, because interconnections of all sectors are needed to estimate changes in the whole economy.
	Input-Output	Providing a picture of the whole economy, with flowa of goods and sectors across all the economy, with the possibility of including households, allows for ex-ante analysis. Multipliers calculate direct, indirect and induced impacts across all sectors.	Analysis interactions among all sectors of the economy and is simple to build.	Doesn't encompass price-feedback mechanisms and technical coefficients are fixed.	Fits the objective but with limitations to the quality of the analysis.
	SAM	Extension of Input-Output framework improving the level of information on income and spending.	Analysis interactions among all sectors of the economy and it is more detailed that Input-Output models.	Tends to add more labour-intensivity to model building than complexity to results when compared to Input-Output.	Fits the objective, however, still shows important limitations for long-term analysis.
	System Dynamics	High-level approach linking several sectors and dimensions.	Allows for the integration of socioeconomic and environmental indicators	Being quite high-level and integrating many sectors and dymensions, lacks detail in each of them.	Would not be a desirable fit since it lacks the elevel of detail in terms of the structure of the economy found in Input-Output, SAM and CGE.
	CGE	Bring more complexity to the Input-Output framework by providing a microeconomic based theoretical structure to describe interactions among different representative economic agents. All agents and sectors supply and demand are described in a consistent way and are interconnected by price feedback mechanisms.	They can explore in detail the relationships between sectors, consumers and government, modelling the dynamic effects of policies over several macroeconomic variables. They are used to analyse impacts over welfare and distributional impacts in both short and long term.	They are quite labour-intensive, require several different databases and they assume economy is always in equilibrium as in the base period of the analysis.	CGE is the best fit for this analysis because it is models full economic responses to exogenous shocks as policies across sectors and different household groups.

Table 3.4 Modelling method choice

3.4.2 Methodological fit to the research questions

The aim of this research is to assess medium and long-term regional and sectoral impacts of energy policy with future changes in the electricity mix in Brazil. Macroeconomic multisectoral analysis is the most suitable for this purpose, since impacts occur across different regions and economic sectors, while partial equilibrium models do not address any of these aspects.

Some studies have shown that CGE models are suitable to simulate infrastructure investment impacts at the regional level (Ferreira Filho and Horridge, 2014; Horridge et al., 2005, 2003). Multiregional CGE models are able to do so because they take into account the structural and interregional characteristics of the economy in an integrated and consistent way, thus evaluating both the sectoral and geographical levels (Ribeiro et al., 2018). The choice of a CGE model for this research therefore derives from the fact that CGE modelling has been widely used to assess exogenously determined policies and their impacts over the whole economy and therefore society, as set out in the research questions.

According to Harrison et. al (2015), when implemented, CGE models are used to carry simulations mainly to answer the "*what if*" type of questions, for example: If the government were to increase tariffs by 10 percent, how different would the economy be in five years' time from what it would otherwise have been?

Studies show that CGE models are suitable to simulate infrastructure investment impacts on certain regions. This is because they take into account the structural and interregional characteristics of the economy in an integrated and consistent way, evaluating impacts sectoral and geographically (Ribeiro et al., 2018).

According to Boccanfuso et al. (2011)

> *"The relevance [of CGE models] is even stronger when the objective of analyses is impacts on welfare, since these models enable the identification of winners and losers and can therefore help establish compensatory policies to attenuate losses."*

The choice of a CGE model for this research therefore derives from the fact that CGE modelling has been widely used to assess exogenously determined policies and their impacts over the whole economy and therefore the society, as proposed in the research questions of Section 1.1.

CGE modelling has been widely used to assess exogenously determined policies and their impacts over the whole economy, and therefore society, as proposed in the research questions. CGE models have been popular since the 1970s and their application to environmental policy emerged in the 1980s, becoming wider since the 1990s (Boccanfuso et al., 2011).

CGE models aim to reproduce, in the most realistic possible manner, the structure of a country or region's economy. They are completely specified models, including all production activities, factors and institutions, such as firms, households and the government. CGE models are used to analyse the social and economic impacts of a wide range of policies and other changes in the economic and social structure of the country such as technological changes, assets redistribution and human capital formation (Gray and Irwin, 2003).

According to Hazilla and Kopp (1990), CGE models are more appropriate than cost-benefit analysis, for instance in what relates to social welfare measures. According to these authors, this derives from the fact that measuring the social costs of such environmental policies requires a modelling structure with particular features, being the most important of them using household willingness to pay. This, for instance, can be done by constructing appropriate demand and supply curves for goods whose prices may be affected by the policy or programme, or characterizing household preferences with an indirect utility or expenditure function within the CGE model framework (Hazilla and Kopp, 1990).

The main sectors to be modelled in this research are the main electricity generation alternatives, such as hydropower and thermal power plants as well as wind farms and photovoltaic panels value chain. The CGE model will also be used to analyse in detail the income levels of the population so that the distributional impacts can be assessed for different socioeconomic groups. Thus, through an interregional national CGE model, the effects of national policies to foster wind and solar energy generation can be measured.

Through the modelling of the whole economy, it will be possible to measure how much the supposed changes in energy generation, industry development to produce solar power plants components and in natural resources demand will affect variables such as employment, income, value added and government revenue. Impacts on jobs and income will then represent impacts on households which will change the region's scale and pattern of consumption, as well as its natural resources consumption patterns. The CGE model will also quantify forward-chaining effects, in sectors that should experience economic vitalization through a broader access to energy.

Through careful analysis of methodological options, it was possible to choose CGE modelling as the best available methodology to answer the research questions. Thus, the following section will review approaches adopted in the literature for similar research questions.

3.4.3 Existing CGE analysis of the socioeconomic impacts of renewable energy policy

Previous literature reviews show a gap in building and applying CGE models to climate policy in general in EMDEs apart from China. Babatunde et al. (2017) undertook a systematic review of CGE applications to climate mitigation policies and found 154 peer-reviewed papers within their choice criteria in Web of Science and Scopus. This demonstrates that little to no attention has been paid to Latin America (Babatunde, Begum and Said, 2017). Figure 3.3 illustrates the incidence of papers found by the authors systematic review for each country of the world.

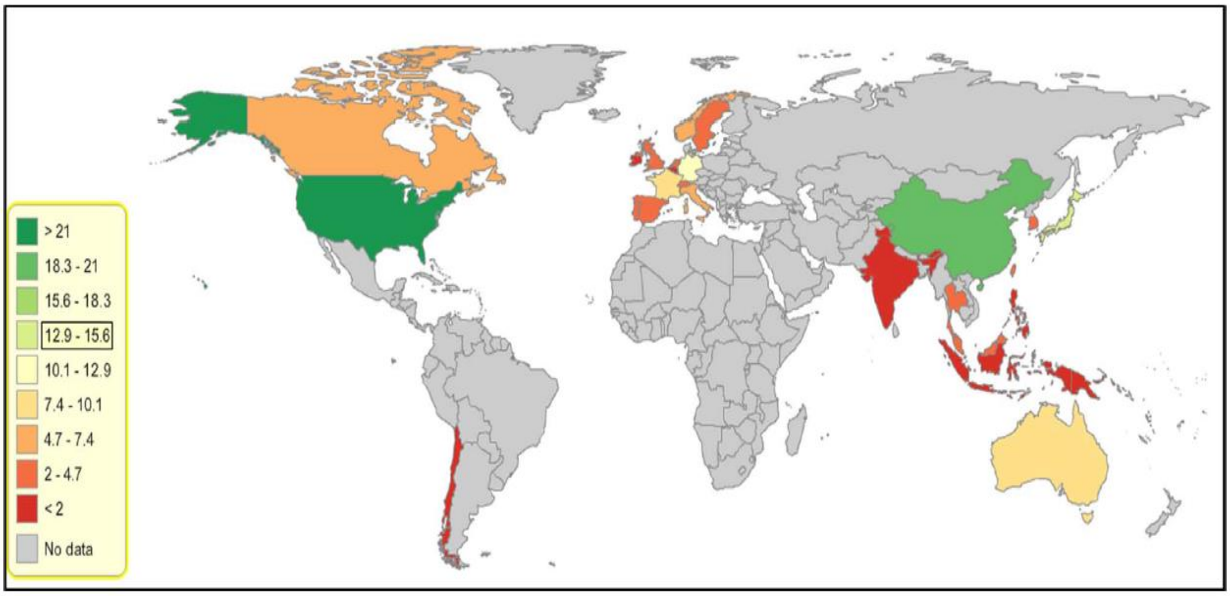

Figure 3.3 Global distribution of papers applying CGE models to climate policy

Source: Babatunde et al. (2017)

Clearly, CGE assessments of economic impacts of climate change mitigation policies were concentrated in the US and China, with no research for most EMDEs in Africa, Latin America and parts of Asia. Only 23% of all papers published analyse EMDEs. Most analyses apply CGE models to simulate comparative static outcomes of a change in national mitigation policies, also showing that less complex models tend to be used when analysing climate policy.

There is a clear gap in studies that quantify socioeconomic impacts of renewable energy generation in the world. Macroeconomic models as such with a representation of different electricity generation technologies apart from the cases of China (Dai et al., 2016; Mu et al., 2018a, 2018b) and the USA (Caron et al., 2018) were absent from the literature reviewed.

. Existing analyses of the economic effects of more general renewable energy policy in EMDEs apart from China are restricted to Malaysia (Chatri et al., 2018) and Turkey (Kat et al., 2018) (Table 3.5).

Dai et al. (2016) use a single-region recursive dynamic CGE model to conduct an ex-ante assessment of the economic impacts of large-scale development of renewable energy in China until 2050.They model two scenarios for the share of renewables in electricity capacity expansion and conclude that the scenario which maximises renewable energy penetration would cause a decrease of 0.27% in GDP in 2050. Similarly, Dai et. al (2018) apply this CGE model for China to estimate the impacts of China's first Nationally Determined Contribution (NDC), up to 2030, through emissions trading scheme (ETS) and renewable energy policy. The authors have reached the conclusion that higher levels of renewable energy development would reduce GDP loss.

On a similar fashion, Mu et al. (2018b) analyse the economic impacts of China’s first NDC through the China Hybrid Energy and Economic Research (CHEER) model, a dynamic CGE model with highly disaggregated technologies in the electricity sector, including a nest separating baseload, with perfect substitution, and separately wind and solar power respectively. This study indicates that the implementation of a national carbon market reduces the costs of achieving the NDC targets, with renewable power deployment as a means to create further employment and reduce permit prices in the carbon market.

Table 3.5 summarises the literature found with similar research questions and applications of CGE models.

Author	Year	Published	Title	Location	Case study Shock	Model	Objective
Cansino, J.M., Cardene, M.A., Gonzalez-Limon, Roman, R.	2014	Energy (Journal)	The economic influence of photovoltaic technology on electricity generation: A CGE (computable general equilibrium) approach for the Andalusian case	Andalusia	Increase installed capacity of solar PV	Single region CGE	To provide an estimation of the socio-economic impacts of increasing the production capacity of installed solar parks in Andalusia (southern Spain).
J. M. Cansino · M. A. Cardenete · J. M. Gonzalez · M. del P. Pablo-Romero	2013	The Annals of Regional Science	Economic impacts of solar thermal electricity technology deployment on Andalusian productive activities: a CGE approach	Andalusia	Increase installed capacity of solar CSP in 2 scenarios: i) based in two types of solar thermal electricity plants currently in operation and ii) based on an increase from 11MW in 2007 to 800MW installed capacity by 2013 to comply with the ‘Plan Andaluz de Sostenibilidad Energética (PASENER)	Single region CGE	Using CGE approach, estimates of the changes in the economic sectors’ activity under two different scenarios are obtained.
Heming Wang, Hancheng Dai, Liang Dong, Yang Xie, Yong Geng, Qiang Yue, Fengmei Ma, Jian Wang, Tao Du	2018	Journal of Cleaner Production	Co-benefit of carbon mitigation on resource use in China	China	3 scenarios: business as usual (BaU), nationally determined contributions (NDC), and the scenario of achieving the 2-degree target (2deg).	Combined CGE and the economy-wide material flow accounts or analysis (EW-MFA) method	Analyse resource use, CO2 emissions and economic co-benefits of three emisisons scenarios.
Hancheng Daia, Yang Xieb, Jingyu Liub, Toshihiko Masuib	2018	Renewable and Sustainable Energy Reviews	Aligning renewable energy targets with carbon emissions trading to achieve China's INDCs: A general equilibrium assessment	China	(INDCs) through emissions trading scheme (ETS) and renewable energy policy	Dynamic China CGE	To evaluate the economic impact of achieving China's Intended Nationally Determined Contributions (INDCs) through emissions trading scheme (ETS) and renewable energy policy, using a Computable General Equilibrium (CGE) model.
Yaqian Mu, Wenjia Caia, Samuel Evansd, Can Wanga, David Roland-Holst	2018	Applied Energy	Employment impacts of renewable energy policies in China: A decomposition analysis based on a CGE modeling framework	China	1 TW h expansion of solar PV and wind power	China Hybrid Energy and Economic Research (CHEER) model	Quantify the full scope og jobs changes (direct, indirect and induced) brought by solar and wind energy development in China.

Hancheng Dai, Xuxuan Xie, Yang Xie, Jian Liu, Toshihiko Masui	2016	Applied Energy	Green growth: The economic impacts of large-scale renewable energy development in China	China	Two scenarios are constructed: a reference scenario assuming conventional development of RE and an REmax scenario assuming large-scale RE development by tapping China's RE potential.	China dynamic computable general equilibrium (CGE) model with distinguished improvements in the power sector	Assesses the economic impacts and environmental co-benefits of large-scale development of renewable energy (RE) in China toward 2050
Puttipong Chunark a, Bundit Limmeechokchai, Shinichiro Fujimori, Toshihiko Masui	2017	Renewable Energy	Renewable energy achievements in CO2 mitigation in Thailand's NDCs	Thailand	Four mitigation scenarios are assessed at given GHG emission levels and renewable power generation targets	Asia-Pacific Integrated Model/Computable General Equilibrium (AIM/CGE).	Assess the potential of greenhouse gas (GHG) emission reduction by the use of renewable energy in Thailand's INDCs and the economic impacts from GHG emission reduction.
Bora Kata, Sergey Paltseva, Mei Yuana	2018	Energy Policy	Turkish energy sector development and the Paris Agreement goals: A CGE model assessment	Turkey	4 scenarios were modelled: BAU, no nuclear and each of them with an ETS in place	TR-EDGE Model with GTAP power data dividing Turkey and RoW. Recursive dynamic.	Impacts of Turkey's NDC pledge over GDP.
Fatemeh Chatria, Masoud Yahoob, Jamal Othmana	2018	Renewable and Sustainable Energy Reviews	The economic effects of renewable energy expansion in the electricity sector: A CGE analysis for Malaysia	Malaysia	4 scenarios concerning phasing out natural gas subsidies and use of revenues.	ORANI-G (Generic version of ORANI) with Malaysian 2010 I-O table data	Assess impacts of gas subsidies removals to remunerate feed-in tariffs in Malaysia.
Grant Allan , Peter Mcgregor & Kim Swales	2010	Regional Studies	The Importance of Revenue Sharing for the Local Economic Impacts of a Renewable Energy Project: A Social Accounting Matrix Approach	Scotland	Two different scenarios for community ownership of the wind farm.	SAM	Evaluate the potential local economic and employment impacts of a large proposed onshore wind energy project in Shetland Islands.
Caron, J., Chen, S. M., Brown, M. and Reilly, J M	2018	Climate Change Economics	Exploring the Impacts of a National U.S. CO2 Tax and Revenue Recycling Options with a Coupled Electricity-Economy Model	USA	Various carbon tax trajectories and options for using the revenue collected by the tax	USREP Multi-regional CGE	Estimate impacts of economy-wide carbon taxes in the U.S. simulated using a detailed electric sector model.

Table 3.5 **Literature review on socioeconomic impact assessments for energy and climate policy in EMDEs**

Mu et. al (2018a) use the same CHEER model to assess employment impacts of renewable energy policies in China. The authors conclude that each TWh of solar PV and wind power would create up to 45.1 thousand and 15.8 thousand direct and indirect jobs respectively in China. They highlight, nevertheless, that the scale of induced job changes is significant and may lead to net job losses in the remaining sectors.

Chatri et al. (2018) assessed the economic impacts of renewable electricity expansion in Malaysia through two different methods to fund the development of renewable energy production: (i) reallocating revenues from gas subsidy removal, and (ii) remunerating the Feed-in Tariff mechanism. They apply a single-region static CGE model, based on the ORANI-G modelling framework. Results have shown that phasing down natural gas subsidies and not recycling its revenues causes a decrease in electricity demand and emissions but causes only minimal negative effects on macroeconomic variables.

Finally, Kat et. al (2018) apply a single-region recursive-dynamic model for Turkey built on the GTAP-Power database, to assess the economic effects of scenarios for an ETS to achieve Turkey's NDC pledges up to 2030: the baseline includes the planned nuclear development and a renewable subsidy scheme, and the alternative scenario without any nuclear generation. They conclude that achieving the NDC would cause a decrease in GDP of a 0.8–1% range by 2030.

When it comes to multi-regional CGE models applied to renewable energy policy, the literature is considerably limited. Once more, most publications conduct applications to the case of China, yet solely two have been found, namely: Fan et al. (2017) and Zhang et al. (2020).

Fan et. al (2017) use a static multi-regional CGE model for China, with a representation of the 30 Chinese provinces as separate regions. The model was used to analyse the economy-wide impacts of a renewable energy standard policy combined with the implementation of an ETS. Their baseline considered the absence of either policy, and two alternative scenarios were modelled: the first case considering an ETS with a cap to reduce national CO_2 emissions in 10% and the second case consisted of adding a renewable energy standard with the same emission reduction target. Their model has the electricity sector disaggregated into eight sources, among which hydropower, wind and solar photovoltaic. They concluded that the implementation of a renewable energy standard further decreases GDP and welfare associated with the ETS.

Zhang et. al (2020), similarly, apply a multi-regional CGE model representative of the 30 Chinese provinces to assess the economy-wide impacts of CO_2 emission reductions in China. Their model, in contrast, is a recursive dynamic CGE model. The authors applied such model to compare the effectiveness of national versus subnational emission reduction policies. They analysed the impacts of policies to achieve China's 2030 national CO_2 abatement target either as a national target as opposed achieving the same absolute target but only through the provinces of eastern China (EP), the Jiangsu-Shanghai-Zhejiang area (JSZP), and the Beijing-Tianjin-Hebei area (BTHP). The authors concluded that the regional approach causes carbon leakage to untargeted regions and therefore extending the spatial coverage or increasing policy stringency should avoid leakage.

3.5 Research gap: socioeconomic impacts of long-term renewable electricity generation policies in Brazil

The main aim of the present research is to assess medium and long-term regional and sectoral impacts of infrastructure investment considering changes in the electricity mix profile in Brazil. Macroeconomic multisector analysis is suitable for this purpose once impacts occur across different regions and, mainly, across economic sectors, while partial equilibrium models do not address this aspect.

The first aspect that makes this research novel is the scarcity of assessments of socioeconomic co-benefits of renewable energy generation, not only in Brazil, but worldwide. There have been efforts from the International Renewable Energy Agency (IRENA, 2023) to address these potential co-benefits, particularly in terms of jobs creation. Further, the US National Renewable Energy Laboratory (NREL) created a model called Jobs and Economic Development Impacts (JEDI), with a set of Input-Output tools to estimate impacts over jobs, income and output for several energy sources projects for US states. This model has been used in several papers, which can be found on JEDI's platform (NREL, 2023). It has also been adapted to be used for the Brazilian economy by Milani et al. (2020) and Vasconcellos and Caiado Couto (2021) which are the only assessments for the country so far. Table 3.6 summarizes all papers and thesis, published in English and Portuguese, about socioeconomic impacts of energy or environmental policy in Brazil.

Author	Year	Published	Title	Method	Objective	Difference from this research
			Electricity sector			
Simas, M. e Pacca, S.	2013	Estudos Avançados USP	Energia eólica, geração de empregos e desenvolvimento sustentável	I-O	Wind energy job creation	Methdology is simple, only focuses on wind jobs.
Simas, Moana	2012	USP - PhD Thesis	Energia Eólica e Desenvolvimento Sustentável no Brasil: Estimativa da geração de empregos por meio de uma matriz insumo-produto ampliada	I-O	Wind energy job creation	Methdology is simple, only focuses on wind jobs.
Santos, Gervásio Ferreira dos	2010	FEA/USP - PhD Thesis	Política energética e desigualdades regionais na economia brasileira	ENERGY-BR CGE Inter-regional	Distributional impacts of electricity charging systems	Does not consider alternative renewables, does not analyse electricity capacity expansion.
Escolhas/Wills, W.	2018	Escolhas	Qual o Impacto de zerar as emissões no setor elétrico no Brasil?	IMACLIM-BR CGE National	Zero emissions electricity impacts in 2050	Does not analyse scenarios for the electricity system, applies a zero emission constraint which may be unfeasible to the system. The model does not have disaggregated renewable technologies. Scenarios are only macroeconomic, not energy policy scenarios.
Perobelli, F. S., Costa, L. R., Domingues, E. P	2009	PhD thesis PPGE UFJF	Variações na Produtividade e Impactos Sobre o Setor de Energia: Uma Análise de Equilíbrio Geral	EFES-ENERGY	Economic impacts of productivity shocks in the energy sector.	Electricity as one agreggated sector, no relation to climate policy.
Vasconcellos, H. A. S. and Caiado Couto, L.	2021	Renewable and Sustainable Energy Reviews	Estimation of socioeconomic impacts of wind power projects in Brazil's Northeast region using Interregional Input-Output Analysis	I-O	Regional socioeconomic impacts of wind power projects procured in auctions to start operation until 2024 for two regions: Northeast and rest of Brazil.	Methodology is simple and does not consider scenarios or different tecnologies rather than wind.
Diniz, T. B.	2019	PhD Thesis Esalq USP	Impactos econômicos e regionais dos investimentos em geração de energia elétrica no Brasil	TERM-BR 10 Multi-regional	Regional socioeconomic impacts of three ten-year official planning scenarios from 2017 to 2026.	Previous version of the model applied to shorter term planning scenarios not considering climate-related objectives.
Noronha, M. O., Zanini, R. R., Souza, A. M.	2019	Environmental Science and Pollution Research	The impact of electric generation capacity by renewable and non-renewable energy in Brazilian economic growth	Econometrics	Ex-post analysis of the relation between electric generation capacity by renewable and non-renewable energies and Brazilian socioeconomic variables between 2009 and 2017.	Does not assess future scenarios or interactions between different sectors.
Milani, R., Caiado Couto, L.	2020	Journal of Cleaner Production	Promoting social development in developing countries through solar thermal power plants	Multi-regional I-O	Assessment of Brazil's local industry through the industrial capabilities for developing CSP plants in the semi-arid region and estimation of socioeconomic co-benefits using a regionalized Input-Output Model.	Simpler methodology applied to the short-term and for CSP projects only.
Gonçalves, S, . Rodrigues, T.P, Chagas, A.L.S.	2020	Renewable and Sustainable Energy Reviews	Estimation of socioeconomic impacts of wind power projects in Brazil's Northeast region using Interregional Input-Output Analysis	Econometrics	Impact of wind farms on employment in Brazilian municipalities hosting or not wind farms from 2004 to 2016.	Does not assess future scenarios or interactions between different sectors.

Author	Year	Published	Title	Method	Objective	Difference from this research
General Climate Policy						
Dubeux, C. B. S. and Margulis, S.	2010	Book	Economia da Mudança do Clima no Brasil: Custos e Oportunidades	EFES CGE National	Estimate the economic impacts of climate change physical impacts until 2030.	Not focused on energy.
Wills, W.	2013	PPE-COPPE/UFRJ	Modelagem dos Efeitos de Longo Prazo de Políticas de Mitigação de Emissão de Gases de Efeito Estufa na Economia do Brasil	IMACLIM-BR CGE National	Socioeconomic impacts of carbon pricing mechanisms in Brazil until 2030.	Not focused on energy.
Oliveira, T. D., Gurgel, A. C., Tonry, S.	2019	Energy Policy	International market mechanisms under the Paris Agreement: A cooperation between Brazil and Europe	EPPA	Estimate economic impacts of emissions trading between Brazil and Europe until 2030.	Use of global model not specific to Brazil and not focused on renewable enrgy policy
Garaffa, R. et al.	2021	Energy Economics	Distributional effects of carbon pricing in Brazil under the Paris Agreement	TEA Global CGE	Assess the distributional effects of a carbon tax on Brazilian households until 2030.	Global, general climate policy, Brazil as a not detailed region of a global model.

Table 3.6 Literature review on energy and climate policy socioeconomic impact assessment for Brazil

The few CGE models that have been developed for Brazil and analysed either energy or climate impacts are mostly based in the Australian tradition of CGE models, and follow the structure of the ORANI Generic Country Model (ORANIG) (Horridge, 2003). The BeGreen model (Magalhães, 2013) and the EFES model applied to climate policy model (Haddad and Giuberti, 2014) also follow this structure. From the ORANI basis, the Enormous Regional Model (TERM) model was created as a bottom-up inter-regional version (Horridge et al., 2005).

The TERM-BR model is the Brazilian version and is the structure most widely used in general multi-regional CGE modelling, although this methodology has not been widely applied in the country (Carvalho et al., 2017; Ferreira Filho and Horridge, 2014; Filho and Horridge, 2006; Gonçalves Da Silva et al., 2014). This is the case of the TERM-BR 10 version built by Diniz (2019), which is the only previous version with electricity source substitution.

Table 3.6 makes it clear that there are few CGE models that have been developed to assess socioeconomic impacts of climate policy on the Brazilian economy. Those that have been developed include the EFES model from the University of São Paulo and the IMACLIM-BR model, developed by *Centre International de Recherche sur l'Environnement et le Développement* (CIRED) and used by researchers at the Federal University of Rio de Janeiro. It is important to note that none of them has the electricity sector disaggregated into sources and their simulations were until 2030 only.

An illustration to the scarcity of analyses is that searching the Web of Science database for several combinations of keywords, it is noticeable that energy socioeconomic impact modelling assessments are scarce and recent, specially referring to the use of CGE models applied to Brazil. Even in broad searches, with the keywords, “CGE + Brazil + Energy” 25 papers are found in total, seven of which actually refer to CGE applications of energy shocks in Brazil, mostly related to sugar cane biomass policies. To the keywords “CGE + Brazil + Electricity”, eight papers were found, from which only two are actually CGE applications to Brazil, both focused on sugar cane. To the keywords “CGE + Brazil + Electricity + Regional” only one paper was found, using a global model, not a country multi-regional model.

In terms of policy value, as discussed, there are a few issues related to the maintenance of the renewable profile of the Brazilian energy generation mix. Hydropower generation costs are low, but there are serious environmental impacts associated with exploiting the remaining potential of this source in the country. Furthermore, the fact that no additional dams are planned to be built already raises concerns on the reliance of the Brazilian electricity mix on hydropower, forcing planners and policy makers to assess alternative scenarios. For these reasons, together with climate issues that are reducing water reservoir levels, conventional thermal power plants are increasingly being used. Wind power has been also growing in share of the energy mix, but this growth is subject to subsidies. Thus, is it crucial to develop a model that takes this energy generation costs into account to better address how can the Brazilian energy generation mix change towards low carbon options and what would be the effects for the country´s economy.

There is also great value generation, in terms of development policies, in the analysis that will be conducted specifically on households. The analysis will be over income generation through the socioeconomic development of the regions where the power generation and components production plants will be installed. This is even more relevant in regions of economic fragility such as the NE of Brazil, but it is also relevant for the rest of the country, along these technologies value chains.

Although the importance of quantifying socioeconomic impacts of policies is known, this kind of assessment for renewable energy policy is not yet a subject with significant published literature, particularly in EMDEs. When searched for in Scopus and Web of Science, so far, only 60 documents have been published globally. EMDEs are represented almost entirely by China, with 20 papers, Malaysia, Thailand and Turkey with one publication each. For the case of Brazil, although it has been recognized by several studies as an important gap in literature, and a next recommended step, very few studies have assessed the socioeconomic aspects of renewable energy deployment.

Margulis et. al (2010), Silva (2010), Magalhaes (2013) and Wills (2013) used different national CGE models to assess climate policy impacts in Brazil, but all focused on the land use and land use change sector, without relevant energy sector substitution components. Diniz et al. (2019) used the global model EPPA to assess impacts of Emissions Trading Systems (ETS) interaction between Brazil and in the European Union, but without a detailed analysis for Brazil. Brazil is one region of the global top-down model, meaning there is not enough detail about the country specifically.

The TERM-BR model is the only model which has been developed for Brazil and applied to renewable energy policy. Applications, however, have a focus exclusively on substitutions of the transport sector and land use, encompassing a large range of crop disaggregation (Diniz, 2019; Ferreira Filho, 2011; Ferreira Filho and Horridge, 2017, 2014, 2011).

Socioeconomic impact assessments for renewable energy in Brazil are limited to Simas (2012) who assessed wind energy job creation through interviews with companies, and to Milani et al. (2020), who performed an Input-Output analysis for a programme of solar power plants in the NE.

We can therefore conclude that there is a research gap in terms of methodology, given that no CGE model has been used to assess relevant electricity substitutions, specially concerning renewable energy integration and climate policy in Brazil. There has been no analysis of industrial policy to incentivise national renewable power plants additional to renewable electricity integration policy in a CGE framework.

The aim of this research is to estimate the socioeconomic impacts of the infrastructure investment of increasing electricity installed capacity in Brazilian regions. Although the CGE model used in this work has the electricity sector disaggregated into sources, the aim of this modelling is not to generate future scenarios neither for electricity generation nor for capacity expansion in the future. Instead, the multi-regional CGE model estimates the regional economic impacts of the electricity capacity expansion obtained by energy system models.

In order to keep rigour and consistency to the operation of the SIN, electricity sources' capacity expansion scenarios must be feasible from the power system's point of view. Scenarios built through energy system modelling which account properly for system operation, the constraints to transmission lines, their expansion, their losses, distribution centrals and the expansion of the SIN as a whole are the most adequate inputs to determine shocks to be modelled in the CGE framework. Therefore, this research applies a soft link between energy system models and the multi-regional CGE model.

One immediately available option in this sense would be using the National Energy Plan (PNE) (EPE, 2020a) official scenarios until 2050. However, two main issues arise against this first option: (i) the EPE, as a government agency, tends to reflect the incumbent government's views, tending to overestimate hydropower expansion; (ii) these scenarios solely reflect system cost optimization. They do not reflect climate policies which can favour low carbon sources, the electrification of the economy as a result of climate policies across sectors or policies that prioritise renewable sources. Hence, a conservative scenario from the EPE was selected as the baseline.

The alternative options, which have been adopted for this research as the policy scenarios, are the scenarios produced by the Centre for Energy and Environmental Economics - Cenergia Lab (2021) at the Federal University of Rio de Janeiro and the electricity-system specialised consulting firm PSR Energy Consulting and Analytics.

Cenergia has specialised in energy and climate modelling since 2002 and is the only scientific centre which publishes national, regional and global climate policy scenarios, obtained through energy-system modelling, in Latin America. PSR Energy Consulting and Analytics is a global provider of technological solutions and consulting services performing electricity and natural gas system modelling since 1987 (PSR, 2022a). PSR has the most sophisticated power system modelling framework in Latin America and has recently modelled scenarios maximising the integration of intermittent renewable sources.

The three scenarios used were obtained through private request to Cenergia Lab and PSR Energy Consulting and Analytics, and through the Brazilian access to information law[13] by filing a formal request to the EPE in order to obtain the regional disaggregation of the scenario published in the National Energy Plan 2050 (EPE, 2020a).

Recursive dynamic CGE models analyse the impacts of alternative, or policy scenarios in comparison to a baseline scenario. Thus, in this research, the first scenario, provided by the EPE, was considered the baseline, and the scenarios obtained from Cenergia and PSR were the so-called *policy scenarios* modelled. The next chapter will present the CGE modelling methodology and the combination with the expert elicitation performed. Then, Chapter 5 will explore the link between the energy-system models with the CGE framework, and therefore the scenarios which will represent shocks to the multi-regional CGE model.

3.6 Chapter 3 conclusions

Renewable energy policy is usually implemented in a multi-objective fashion, aiming to address issues such as energy security, GHG emission reduction, and industrial and socioeconomic development. In Brazil, although previous policies promoting non-hydro renewable energy have targeted the NE region, regional industrial and labour capability disparities will be determinant for the development of energy projects and for retaining socioeconomic co-benefits in each of the regions. Income distribution dimensions are complex, and although the South and SE regions do not show a comparable physical potential for renewable energy generation to the NE, they are naturally the main suppliers of industrialised goods to power plants' supply chains.

The NE region has historically lagged behind in terms of socioeconomic development, and the new investment being channelled to this region to deploy solar and wind power has the potential to mitigate regional inequalities. This thesis analyses the multi-regional macroeconomic, industrial, sectoral and distributional impacts of long-term investment in electricity capacity expansion in Brazilian regions through a multi-regional CGE model with nine electricity sources and transmission and distribution of electricity as sectors.

[13] Federal law nº 12,527 from 18th November 2011 (Brazilian Presidency, 2011) enforced through the *Falabr* platform held by the General Comptroller's office (CGU, 2022).

Given the complexities of the macroeconomic modelling of energy policy, data constraints in EMDEs and the lack of trade data between different regions of the same country, there are very few similar analyses published in the existing literature. Studies for China dominate the latter. Input-Output analysis, SAMs, and econometric analysis are available to assess energy policy's socioeconomic impacts, among others. However, CGE modelling has been chosen as the most appropriate method since it is widely used to assess exogenously determined policies and their impacts on the whole economy and society, as set out in the research questions outlined in Section 1.1. Therefore, Chapter 4 will explain the methodology to respond to the three research questions, detailing the combination of the multi-region CGE modelling with the energy-system models and the Expert Elicitation approaches.

4. METHODOLOGY

In this thesis, multi-regional CGE modelling simulations estimate the socioeconomic impacts of electricity capacity expansion in Brazilian regions. Therefore, the model applied here must be multi-regional within a country and feature a disaggregation of the electricity sector into several sources. That is, the CGE model must allow shocks to specific electricity generation sources as separate sectors, while the vast majority of existing CGE models treat the electricity sector as uniform since all sources produce a uniform good: electricity.

This chapter describes in detail the modelling approach adopted in this research. First, Section 4.1 revises the existing CGE models, which represent multiple regions within a country. Then, it justifies the selection of the TERM modelling framework as the most adequate to be used in this analysis in Section 4.2. Section 4.3 describes the TERM-BR E15 model calibrated as part of this thesis, its main features and equations. Section 4.4 describes the databases used for the model calibration, while Section 4.5 specifically details the disaggregation of the electricity sector into nine sources and a Transmission and Distribution (T&D) sector. Then, Section 4.6 describes the method used within the TERM-BR E15 model to run simulations by applying shocks corresponding to the three electricity capacity expansion scenarios until 2050.

Additionally, this thesis combines the modelling with an expert elicitation, including electricity sector companies, government agencies, development banks, think tanks and academia representatives, to test the analysis against real-world conditions and enhance engagement. This method combination has provided insights into how modelling results can inform policymaking, enlightening the modelling community on the limitations of models in fulfilling policymaking information needs. Section 4.7 describes the Expert Elicitation process. Finally, Section 4.8 concludes this chapter.

4.1 National multi-regional Computable General Equilibrium modelling

Multi-regional national CGE models found to date represent only five countries. China is the only country to which more than one model is found (Horridge and Wittwer, 2008; Li et al., 2009; Wang and Wei, 2019), while the other countries are the UK (Verikios et al., 2020), Canada (Ochuodho et al., 2016), the US (Wittwer, 2017) and Brazil (Ferreira Filho and Horridge, 2014). Apart from Wang and Wei (2019) and Li et al. (2009) (both for China, which has official interregional trade data), all are versions of *The Enormous Regional Model* - TERM model (Horridge et al., 2003). Noticeably, the application of these models to energy policy is virtually inexistent, although the TERM-BR model has been applied to several land-use analyses encompassing bioenergy (Ferreira Filho and Horridge, 2011; Veiga et al., 2018) and one analysis of electricity generation policy (Diniz, 2019).

The availability of interregional trade data for China enables the creation of multi-regional CGE models for the country through traditional modelling frameworks, the main example being the GTAP model (Hertel and Tsigas, 1997). However, the most common case is the absence of interregional trade data, in which multi-regional CGE models must rely on databases created through gravitational methods (Dixon et al., 1982; Horridge et al., 2003). Furthermore, Horridge (2012) points out that estimated inter-regional Input-Output tables normally do not hold the properties needed for a multi-regional CGE model database. This happens because they are normally composed of a small number of highly aggregated sectors, which hinders assumptions such as uniform technologies in different regions (one should not assume that very aggregated sectors use the same technology in all regions). Moreover, they do not provide any information about trade and transport margins, which are essential for CGE models (Horridge, 2012).

National multi-regional CGE models can be top-down or bottom-up in terms of regionalisation. In the top-down regional approach, the model computes national results and breaks them down into regional results. Noticeably, this simplification constraints modelling options significantly, for example, not allowing regional supply shocks depending on regional prices. Bottom-up multi-regional models, in contrast, treat each region as a separate economy through interregional trade flows. National results in this case are the aggregation of regional results. Regional bottom-up models allow simulations with price effects that specific to one or more regions (Horridge et al., 2003).

In order to assess the socioeconomic implications of investment in electricity plants in Brazilian regions, a multi-regional analysis of the national economy is needed. For the purpose of this study, the main sectors to be modelled in the CGE framework are renewable electricity sectors (wind farms, biomass-fired plants and photovoltaic electricity generation), agricultural sectors, as well as the main energy generation alternatives (e.g., hydropower and thermal power plants). The CGE model will be used to analyse in detail the income levels of the population so that the distributional impacts can be assessed for different socioeconomic groups. This is done by the ten representative household groups by income bands.

Thus, through a multi-regional national CGE model, the effects of national future electricity expansion policy scenarios can be measured. By modelling the whole economy, it is possible to measure how much the supposed changes in energy generation, industry development, and in natural resource demand will affect variables such as employment, income and government revenue. The CGE model will also quantify forward-chaining effects in sectors that should experience economic dynamization through broader access to energy.

The next sections explain the model choice, how it is used and the methodology applied for the modelling simulations that respond to the thesis' research questions (Section 1.1).

4.2 Selection of modelling approach

Several challenges emerge when attempting to model a large economy through a national multi-regional framework. Different modelling options were carefully considered in order to select the most suitable model. As seen in the literature review (Section 3.3), EMDEs do not have a tradition of CGE modelling (apart from China), due to, among many reasons, data challenges. A major challenge encountered is the lack of data for inter-state or interregional trade flows. Normally, multi-regional CGE models are global models, using data for international trade, typically the Global Trade Analysis Project (GTAP) (2021) database.

Options considered included primarily the International Food Policy Institute (IFPRI) standard CGE model (Löfgren et al., 2002), the GTAP E-Power model (Burniaux and Truong, 2002) and The Enormous Regional Model - TERM model (Horridge et al., 2003). The IFPRI Standard CGE model is a generic open access single-region static model that is calibrated with data from EMDEs like Mozambique, Zambia and Zimbabwe for example (IFPRI, 2021). This model could possibly be used to analyse the NE region alone, or Brazil as a single region. However, it does not have the features in place to become a multi-regional model, particularly given the lack of data for interregional trade within Brazil. Besides, the IFPRI model does not have any substitution between energy sources, which also adds the effort of creating new sectors and commodities.

The GTAP-E-Power model is a version of the GTAP model that extends it by adding substitutions between electricity sources as well as electricity transmission and distribution. This is a similar approach to what is needed in this research in terms of technological detail. However, there is no application of the GTAP model to multi-regional analysis within a country, and data constraints are prohibitive to create interregional trade flows within the country. A new methodology could potentially be created, but there was a non-negligible risk it would not work given the computational complexity of such models. Furthermore, the GTAP-E database is global, created through a generic methodology with a top-down approach which lacks specific regional or national details, especially relevant for modelling the particularities of the Brazilian electricity sector.

The TERM model framework, on the other hand, was created exactly with the aim of meeting a strong demand from policymakers to answer research questions related to regional development (Horridge et al., 2003). In the TERM-derived models, each of the regions in the model has its own Input-Output database with trade flows between regions which characterise the so-called bottom-up model from a regional point of view (as opposed to the technological point of view).

The TERM model was created at the Centre of Policy Studies (CoPS) to deal with highly disaggregated regional data (Horridge et al., 2005, 2003). It derives from a series of Australian models that started with the ORANI model, which was innovative in distinguishing over 100 sectors. A second-generation of models, derived from ORANI, allowed for multi-regional, dynamic models, and region-specific demand and supply shocks. One particular example of these models with price variables at the regional level was the Monash Multiregional Forecasting model (MMRF) (Horridge et al., 2005), in which economies are independent, connected by trade and population flows and economic policy (Santos, 2013). This is crucial for interregional analysis and this framework was therefore used to create the TERM model framework, which advanced in allowing larger numbers of sectors and regions, maintaining the computational requirements feasible (Horridge, 2012).

The authors of the original TERM model acknowledge data constraints to creating multi-regional single-country models: "*As formidable as the computational demands of regional CGE models, are the data requirements—which usually far exceed what is available*" (Horridge et al., 2003, p. 7). Specifically in terms of interregional trade data; the TERM model was originally built for the Australian economy, which did not produce such dataset (Horridge et al., 2003). The authors therefore created a methodology to obtain an estimated trade matrix, which is crucial to enable this kind of analysis and to date is the only known methodology to estimate interregional trade in order to build multi-regional national CGE models.

The TERM model does not originally include any substitution between electricity sources, but rather follows a traditional CGE approach where electricity is aggregated in one sector and one commodity. This limitation hinders the model capability to address questions related to technology-specific energy policy. However challenging the disaggregation of specific electricity technologies may be, the provision of a well-tested framework for creating a model which is multi-regional within a country made the TERM model framework the most suitable for this research. The model framework and the specific model of this research will be described in detail in the next section.

The TERM-BR, a multi-regional model previously used to analyse aspects of sugarcane and soybeans related policy in Brazil, will be used as the base-model of this research. TERM-BR is the Brazilian version of TERM, which is a bottom-up multi-regional CGE since it treats each region as a separate economy. The model is a collection of 27 state regional models, which are linked by trade and factor movements between regions, and 127 sectors (Ferreira et al., 2015). Each regional model has its industries and final demand sectors following cost-minimising agent behaviour, when choosing the optimal input mix of commodities or primary factors. Its database relies principally on the 2005 Brazilian Input-Output tables, combined with regional data sources, and data for the household disaggregation, PNAD and POF.

TERM-BR10 (Diniz, 2019) followed TERM-BR by calibrating the model to the 2010 national accounts database and by being the first to include a disaggregated electricity sector module in the TERM framework. Hence, it was clearly the frontier of knowledge this thesis builds on. TERM-BR10 is a multi-period recursive dynamic CGE model with 136 activities represented in each of the 27 Brazilian states, with 10 household types and 10 labour grades according to wage levels determined by PNAD.

4.3 The TERM-BR E15 Model

The TERM-BR E15 Model is the model calibrated for this research with the 2015 National Accounts (Input-Output tables) data for Brazil, the most recent available by the time of this study and electricity data for the same year. Based on the latter, the electricity sector and commodity were disaggregated into different sources and a transmission and distribution sector, and substitutions were introduced. The disaggregation was done in order to be compatible with the most relevant sources analysed, and also reflecting the structure of the electricity mix which change substantially from 2010 to 2015 when alternative renewable sources, mostly wind power, gained ground.

TERM-BR E15, like its predecessors, is a bottom-up multi-regional multi-period recursive-dynamic CGE model for Brazil. It has 136 activities represented: the 126 traditional sectors of national accounts, plus the nine generation sources which were disaggregated specifically for the purpose of this research, Transmission and Distribution of electricity and Natural Gas distribution as a separate sector. each of the 27 Brazilian states is a separate region, with 10 household types according to their income and 10 labour grades according to wage levels determined by POF and PNAD. For simulation purposes, in this thesis, the 136 sectors have been aggregated into 40 sectors (Appendix A).

Each region operates independently in terms of production of goods, production-factor remuneration. Regions are integrated through inter-regional trade, estimated in the initial database through the gravitational method established by Horridge (2003), and factor mobility through labour-force migration according to relative prices. As mentioned, inter-regional trade matrices which total row and column totals are consistent with the use of each region are obtained through gravity formulas in which trade volumes follow an inverse power of distance between a chosen port for each region.

Sectors are divided into tradable and non-tradable. Tradeable sectors are freely traded between all the regions. In contrast, the non-tradable are mostly services which are constrained to the region where they are produced and therefore there are no trade flows between regions to such sectors. However, the output of non-tradable sectors moves in line with the regional economy. That is, if a tradable sector from a region experiences growth, demand for the regional non-tradeable tends to expand. Table 4.1 shows the main sets of the model.

Index	Set name	Description	Size
s	SRC	(dom,imp) Domestic or imported (ROW) sources	2
c	COM	Commodities	136
m	MAR	Margin commodities (Trade, Transport)	2
i	IND	Industries	136
o	OCC	Skills	10
d	DST	Regions of use (destination)	27
r	ORG	Regions of origin	27
p	PRD	Regions of margin production	27
f	FINDEM	Final demanders (HOU, INV, GOV, EXP);	4
h	HOU	Household income levels	10
u	USER	Users = IND union FINDEM	140

Table 4.1 TERM BR E15 model set list

The production functions use a combination of intermediary inputs, excluding electricity, electricity generation intermediary inputs, and primary production factors, namely capital, labour, divided in ten wage categories, land and natural resources as a production factor. This combination is determined by a fixed-coefficient Leontief production function. The combinations between intermediary inputs are determined by a Constant Elasticity of Substitution (CES) and can be domestic or imported. When domestic, a CES also determines from which of the five regions in the country the input will be pursued.

The same process happens for the electricity sector, when combining the nine disaggregated renewable and non-renewable sources through a CES. Finally, primary production factors are also combined by a CES determining proportions of capital, labour and land and other natural resources. The share of each source in electricity generation is subject to changes accordingly to relative prices under a CES system. The elasticity of substitution equals to five, therefore highly elastic between sources. This structure is shown in Figure 4.1 below.

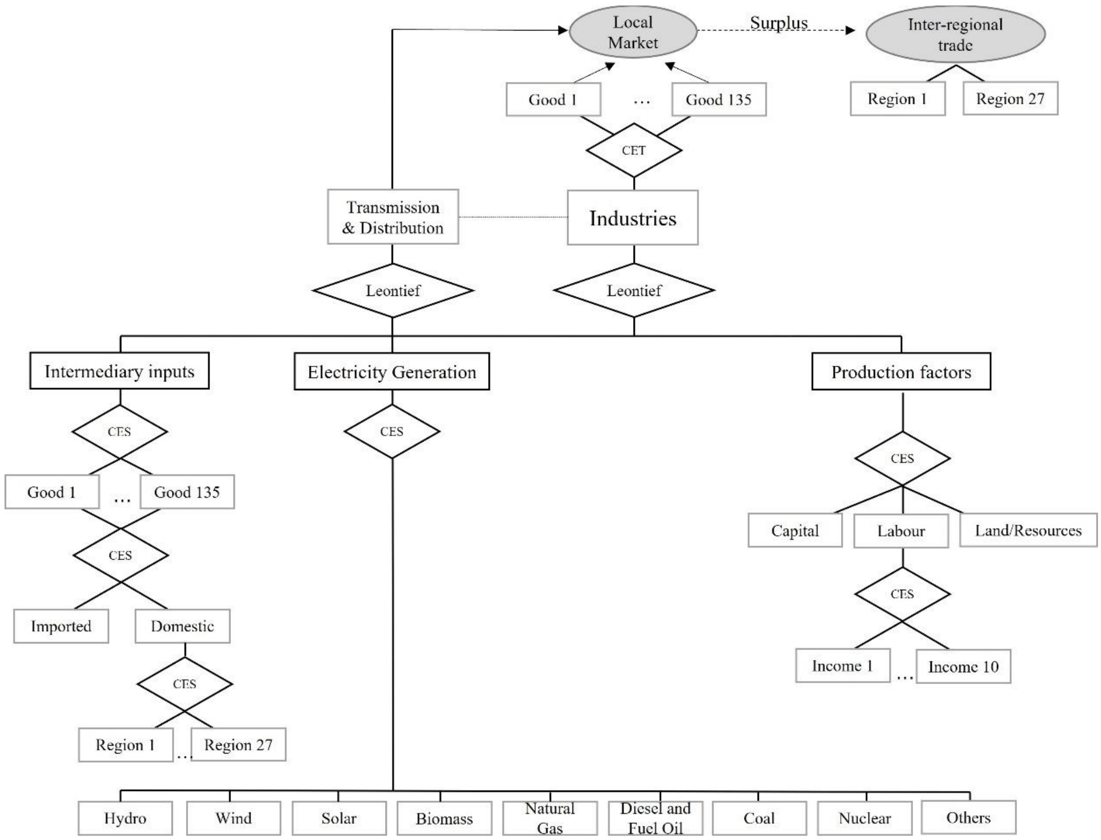

Figure 4.1 Production Function of the TERM-BR E15 Model

4.3.1 Production technology

Industries combine intermediary inputs and primary factors of production. Their choices are constrained by a two-level nested production technology: the first level is the choice between these two categories, which is done at a fixed proportion, the so-called Leontief function:

$$Q = min(\delta I, \beta F)$$

Where:

Q is production

δ and β are parameters

I are the intermediary input

F are primary factors of production.

The second level is the choice between different intermediary inputs (the commodities produced by all the other sectors) and the choice between the three production factors: capital, labour (ten skill levels) and land and other natural resources. Both choices in the second level are determined by a Constant Elasticity of Substitution (CES) function, as follows:

$$Q = F \times (\alpha_K K^{\rho} + \alpha_L L^{\rho} + \alpha_R R^{\rho})^{\frac{\upsilon}{\rho}}$$

Where:

Q is quantity produced

F is total factor productivity

α_i is the share parameter of factor i so that $\sum_{i=1}^{n} \alpha_i = 1$

ρ is the substitution parameter where $\rho = \frac{\sigma - 1}{\sigma}$

σ is the elasticity of substitution

υ is the degree of homogeneity of the production function.

4.3.2 Local final demand

Each of the ten household income groups in each region maximise a Stone-Geary utility function subject to its income constraint:

$$U = \prod_{i} (q_i - \gamma_i)^{\theta_i}$$

Where:

U is their utility;

q_i is the consumption of good i;

γ_i and θ_i are parameters for good i;

The Stony-Geary function implies a subsistence level of consumption, and its optimizations leads to a Linear Expenditure System (LES) in which the demand for each good is a linear function of the price of all available goods and their income:

$$q_i = \gamma_i + \frac{\beta_i}{p_i}\left(y - \sum_j \gamma_j p_j\right)$$

Where:

p_i is the price of good i

y is total expenditure.

4.3.3 Capital and investment allocation

Capital allocation between industries and regions is determined by the maximization of the investment rate of return. The model recursive dynamic determines that the investment of a period less capital depreciation equals capital stock in the following period:

$$K_{j,t+1} = K_{j,t}\left(1 - D_{j,t}\right) + I_{j,t} - S_{j,t}$$

In which:

$K_{j,t+1}$ is the capital stock of industry j in the period $t+1$

$K_{j,t}$ is the capital stock of industry j in the period t

$I_{j,t}$ is the investment of industry j in the period t

$D_{j,t}$ is the depreciation rate of industry j in the period t

$S_{j,t}$ is the shifter for decreases in capital accumulation.

4.3.4 Labour allocation

Labour allocation is determined by real wage, through labour supply and demand in each region. When real wage grows more in a region relatively to other regions, it will attract migrant workforce, while regions where real wage decreases will experiment outwards migration flows. Thus, imbalances in the labour market, for example, increased labour demand, may be neutralised either by a local wage rase that leads the region back to equilibrium in this market, or by workforce migration flows from other regions. Real wage is determined as follows:

$$\left(\frac{W_t^r}{W_t^{*r}}-1\right)=\left(\frac{W_{t-1}^r}{W_{t-1}^{*r}}-1\right)+\varphi\left(\frac{D_t^r}{D_t^{*r}}\right)-\left(\frac{S_t^r}{S_t^{*r}}\right)$$

In which:

W_t^r is the real wage in region r in period t

φ is a parameter so that $\varphi > 0$

D_t^r is labour demand in region r in period t

S_t^r is the labour supply in region r in period t

* Denotes the equilibrium level.

$$\frac{S_t^r}{S_t^{*r}}=\frac{\frac{(W_t^r)^\omega}{\sum_{r=1}^n (W_t^r)^\omega s_t^r}}{\frac{(W_t^{*r})^\omega}{\sum_{r=1}^n (W_t^{*r})^\omega s_t^{*r}}}$$

In which:

s_t^r is the share of region r national labour in period t

ω is a parameter so that $\omega > 0$.

Labour is the only factor that is considered to have a degree of mobility both in the short and long term.

4.3.5 Import and export demands

The substitutability between regionally produced output and imports from other regions follows an Armington CES function in each of the regions, in which:

$$q = A(\alpha m^\rho + (1-\alpha)d^\rho)^{\frac{1}{\rho}}$$

Where:

q is total demand (domestic and imports)

A is the shift parameter

m is import

d is domestic

α is the share parameter;

ρ is the substitution parameter where $\rho = \frac{\sigma-1}{\sigma}$;

σ is the elasticity of substitution;

And the function is homogeneous of degree 1.

So that the optimal import/domestic ratio is:

$$\frac{m}{d} = \left(\frac{p_d}{p_m}\frac{\alpha}{(1-\alpha)}\right)^{\sigma}$$

Where:

p_d is the domestic price

p_m is the import price.

Imports are therefore determined by the sales of regional goods and the relative price of regional products over imported goods. Regionally produced and import good added compose total supply for intermediate consumption and final demand in each of the regions. Similarly, exports from different regions depend on the regional demand and relative prices.

4.4 Data

The main database for the model calibration has been the National Accounts (mainly Input-Output tables) for the year 2015, which were the most recent data published by the National Institute of Geography and Statistics (IBGE, 2023b) by February 2023. National Accounts are comprehensive economic datasets that require numerous government resources to be produced. However, in EMDEs such as Brazil, Input-Output tables are not published for every year but rather with five-year gaps and four-to-five-year delays. Hence, the Input-Output table for 2015 was published in 2019; up to February 2023, an Input-Output table for 2020 had not been published.

Using National Accounts from 2015 is not considered a data fault given that economic structures, the emergence of significant new sectors, major shifts between sectors, or their interactions with other sectors do not normally change in five years. That is, there is usually no structural economic change in a five-year period. Hence, several models whose analyses are published are still calibrated with the 2010 or even 2005 Input-Output database.

CGE models generally use National Accounts as their database. So, the main effort involved was to calibrate the TERM-BR model to the most recent published data for Brazil with the disaggregation of natural gas and the electricity sector into nine sources and transmission and distribution, the regional disaggregation, the disaggregation of households into ten income bands and the disaggregation of labour into ten skill levels (occupations).

4.5 Electricity sector disaggregation

Disaggregation efforts in the Input-Output database involve disaggregating the production (MAKE) and the USE matrices, as well as taxes and margins. The official Input-Output tables published by the IBGE for the year 2015 aggregated in a single commodity and in a single industry gas fuels (natural gas processing and urban gas fuel distribution – liquified petroleum gas (LPG), piped natural gas (NG) and electricity generation, transmission and distribution (T&D). Thus, the first step towards disaggregating electricity is defining and subtracting the amount of gas fuels within the single sector, isolating the electricity sector to disaggregate it into technologies then.

The datasets used for this process were the following:

- Auction electricity prices from the Chamber of Electricity Trade (CCEE, 2020)
- National Energy Balance 2016 – Base-year 2015 from EPE (EPE, 2016)
- LPG prices from the National Petroleum, Gas and Biofuels Agency (ANP) - (ANP, 2015)
- Natural gas prices, quantities, exchange rate, margins and taxes from MME (MME, 2019, 2015)

The two main sectors using LPG and NG are households, as cooking fuels, and transformation industries. Therefore, the disaggregation of gas fuel from the single sector focused mostly on these sectors. Subtracting gas fuel was done by calculating the value of household LPG and NG use (using the National Energy Balance (NEB) quantity and ANP price data) and the proportion of natural gas and electricity used by each of the industry sectors (using the National Energy Balance data).

The equation below shows the treatment to household energy consumption, subtracting LPG and NG to isolate electricity consumption as such.

$$E^h = EG^h - (c^h_{GLP} \times p^h_{GLP} + c^h_{NG} \times p^h_{NG})$$

Where:

E^h= household electricity consumption

EG^h= household aggregate electricity, NG and GLP consumption (IBGE, 2021b)

c^h_{GLP}= household GLP consumption – from NEB (EPE, 2017)

p^h_{GLP}= LGP household price from ANP (ANP, 2015)

Similarly, NG contained in the aggregated sector is mostly used by transformation industries.

$$NG_i = \frac{g_i}{(g_i + e_i)} \times EG_i$$

Where:

i = industrial sector

NG_i= Sector i NG consumption

EG_i = Sector i NG and electricity consumption aggregated

g_i = % NG consumption of sector i total energy consumption

The next step was to calculate weighted-average electricity prices for each source from auction procurement results:

$$P_j^{MWh} = \frac{p_{i,j}^{MWh} \times q_{i,j}^{MWh}}{\sum_{i=1}^{n} q_j^{MWh}}$$

Where:

P_j^{MWh} = Weighted-average price of a MWh generated by source j in all projects

i = Electricity generation project procured in auction

j = Electricity source.

Then, prices were applied to quantities from the National Energy Balance (NEB) in order to obtain the percentage of the electricity good production value corresponding to each of the sources. These percentages were then applied to the IO data for the electricity sector, yielding the production value of electricity generated by each of the sources.

$$GPV_j^{NEB} = MWh_j^{NEB} \times P_j^{MWh}$$

Where:

GPV_j^{NEB}= Gross Production Value of electricity generated by source j according to NEB quantities

MWh_j^{NEB} = Quantity of electricity generated by source j in 2015 according to NEB data.

$$S_j^{NEB} = \frac{GPV_j^{NEB}}{\sum_{j=1}^{9} GPV^{NEB}}$$

Where:

S_j^{NEB} = Share of source j in the total 2015 gross production value of electricity according to NEB quantities.

$$GPV_j^{IO} = S_j^{NEB} \times (GPV_{ElectGen}^{IO})$$

GPV_j^{IO} = Gross Production Value of electricity generated by source j disaggregated from the Input Output aggregate data

$GPV_{ElectGen}^{IO}$= Gross Production Value of electricity generation in the 215 Input Output data.

To do this, the electricity sector was disaggregated into two main industries: 1) Generation; and 2) Transmission and Distribution (T&D). The intermediate consumption of the aggregate electricity industry's own product is considered to be the value of Generation. Assuming therefore that the value contained in the cell of the Use matrix, where the electricity *industry* intersects with the electricity *commodity,* is the flow between electricity generated by power plants of each of the sources and the means through which it is consumed, T&D. Therefore, T&D consumes all electricity generation commodity by each of the sources. All other industries then consume solely the T&D commodity. Only within the electricity industries that transactions occur from generation to T&D. No other sector demands from the generation sources. This is especially plausible in Brazil, since the system is entirely integrated.

With the assumption above, the aggregate value of generation was disaggregated by source applying the percentages obtained through the weighted average of generation and prices explained in step 3.

Production data disaggregation, in turn, considered the same value for Generation as the use matrix, and distributed this production value among generation sources (a diagonal matrix for generation). The remaining value of the electricity sector was attributed to T&D.

Imports, exports, taxes and margins followed the same logic as intermediate consumption.

4.5.1 Jobs, wage, and gross value-added disaggregation

The disaggregation of jobs and wages was done in two main steps. The first step used data from the Annual Social Information Report (RAIS, from the acronym in Portuguese) (MTE, 2020) to disaggregate the Input-Output sector into Natural Gas, Electricity Generation and T&D occupations. This is the most disaggregated occupation dataset available for Brazil.

Then, the U.S. Bureau of *Labor* Statistics Occupational Employment Statistics (2020) data for employment per electricity generation source was used to disaggregate the number of jobs of the aggregated electricity sector. It was used as a proxy due to the lack of similar data for Brazil. The factor of employment per MW installed was applied to installed capacity of each source in Brazil in 2015. Naturally, this would not result in the total number of jobs in Brazil, due to differences in labour productivity. In order to neutralise such factor, the proportions of each source were applied to the RAIS data.

$$L_s^{Br} = \left[\frac{\frac{L_s^{US}}{MW_s^{US}} \times MW_s^{Br}}{\sum_{s=1}^{9} \left(\frac{L_s^{US}}{MW_s^{US}} \times MW_s^{Br} \right)} \right] \times L_{EG}^{Br}$$

Where:

L_s^{Br} is the number of jobs per electricity generations source s in Brazil

L_s^{US} is the number of jobs per electricity generations source s in the US

MW_s^{Br} is the installed capacity of electricity generation source s in Brazil

MW_s^{US} is the installed capacity of electricity generations source s in the US

L_{EG}^{Br} is the total number of jobs in electricity generation in Brazil.

It is important to show that the resulting employment and wages per electricity generation source in the base year do not follow the same proportions as the share of each source in total generation. Some sources employ proportionally more or less relative to generation. Thermal power plants employ more full-time equivalent (FTE) workers relative to how much electricity they generate than hydropower. Biomass employs more relatively, and wages are higher than in other sources. Wind employs less than other sources, but wages are higher proportionally, which is also valid for solar PV. Figure 4.2 shows the shares of each electricity generation source in total electricity generation, jobs in FTE and wages in the model's base year of 2015.

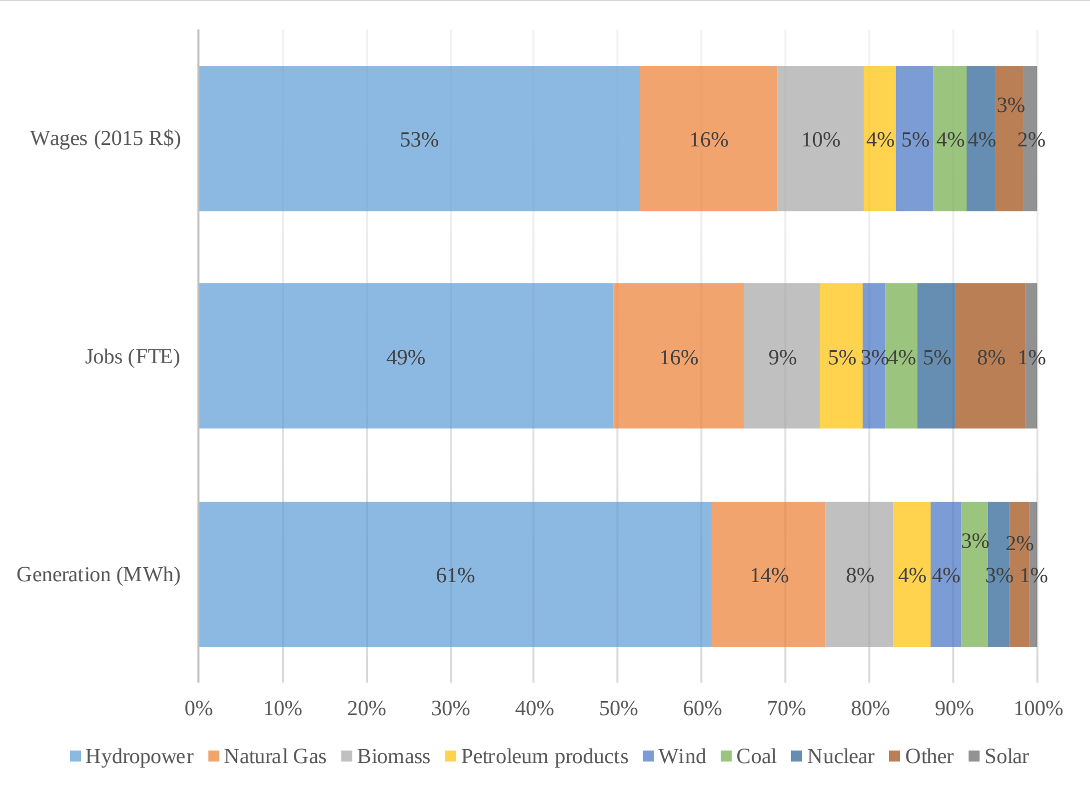

Figure 4.2 Share of electricity sources in generation, jobs (full-time equivalent - FTE) and wages in the base year (2015)

4.5.2 Regional disaggregation

Official regional-level Input-Output data is only available for Brazil in highly aggregated sectors (18 industries), and crucial variables for the model, such as trade and transport margins, are missing. Thus, building a complete regional share matrix was needed in order to regionalise the official national Input-Output tables for 2015. This matrix was built for 136 sectors and 27 Brazilian states.

15 sectoral databases were used to disaggregate the production of each commodity into 27 territories, namely:

1. Annual Industrial Survey (PIA/IBGE): Industrial commodities state shares only for SE and S regions
2. Annual Services Survey (PAS/IBGE): Service commodity state shares
3. Agriculture and Livestock Gross Production Value Survey (Ministry of Agriculture, livestock and food supply, Brazil): Agriculture and livestock state shares
4. Municipal Livestock Survey (PPM/IBGE): Fishery and Aquaculture state shares
5. National Energy Balance 2016 – Base year 2015 (EPE) – Electricity generation state shares
6. Electricity Statistical Yearbook 2016 – Base year 2015 (EPE) – Electricity generation regional tariff differences
7. Regional accounts: Financial services, construction, trade, household services state shares
8. Central Enterprise Registry - CEMPRE (IBGE): Electricity and gas distribution state shares, industrial sectors for states not in the PIA
9. National Oil and Gas Agency Yearbook 2020: Petroleum and Gas extraction state shares; Fuel refinery state shares; Ethanol production state shares
10. Brazilian Vegetable Oils Industry Association statistics: Vegetable oil production state shares
11. Brazilian Forestry Industry Association: Cellulose pulp production state shares
12. National Mining Agency (ANM): Aluminium production state shares
13. Brazilian Steel (Aço Brasil) Institute Statistical Yearbook – Iron and steel and steel products state shares
14. Brazilian Chamber of Construction Industries (CBIC): Cement production state shares
15. Sugar Cane Industry union (UNICA): Sugar production state share.

It is necessary to highlight that this has been a relevant data-gathering effort, which created a systematised database for state-level production regionalisation of 136 groups of goods which production process is similar. All of these databases are published in Portuguese only, which highlights the importance of local knowledge and understanding of the country's statistical system.

4.6 Simulations

For the simulations, modelling has been conducted with an aggregation of the 136 sectors of the TERM-BR E15 model into 40 relevant sectors (listed on Appendix A). The relevant steps for simulations are described in the following sections.

4.6.1 Model database update

The year of the database to which the model was calibrated is 2015. However, official statistics have been released for national real GDP growth, real investment growth, real government expenditure growth, imported and exported volumes variation (Table 4.2) and regional economically active population growth (Table 4.3**)** from 2016 to 2019. These were used as historical shocks to update the model according to what is known to have been observed from the database year until the latest official statistics published. The electricity capacity expansion scenarios were then implemented as shocks into the CGE model from 2020 to 2050.

	2016	*2017*	*2018*	*2019*
Real Investment	-3.8%	2.0%	2.3%	2.2%
Real Government expenditure	-12.1%	-2.6%	5.2%	3.4%
Exported volume	0.2%	-0.7%	0.8%	-0.4%
Imported volume	0.9%	4.9%	4.1%	-2.4%
Real GDP	-2.5%	2.7%	3.8%	3.1%
Population	0.0%	0.0%	0.0%	0.0%

Table 4.2 National macroeconomic shocks 2016-2019

	2016	*2017*	*2018*	*2019*
North	1.35%	1.29%	1.24%	1.19%
NE	0.63%	0.59%	0.56%	0.53%
South	0.72%	0.70%	0.67%	0.65%
SE	0.71%	0.69%	0.66%	0.63%
CW	1.42%	1.37%	1.33%	1.29%

Table 4.3 Economically active population growth per region 2016-2019

Therefore, the data shown in Table 4.2 and Table 4.3 were used as historical shocks to update the model according to what is known to have been observed from the database year until the latest official statistics published. The electricity capacity expansion scenarios were then implemented as shocks into the CGE model from 2020 to 2050.

4.6.2 Macroeconomic closure

CGE models have more variables than equations, thus, a set of variables must be exogenously determined. The choice of exogenous variables when running specific simulations depends on the modeller's discretion, following common practices, for example, for differences between the short and long term according to the theorical background of the model.

The macroeconomic closure used for the simulations conducted in this research was a long-run closure. This basically means that the dotation of production factors is endogenous and therefore not fixed as in the short-run case. This feature is particularly relevant for the capital formation dynamics (shown in Section 4.3.3). In the case of the simulations conducted for this research, investment in electricity generation sectors were left as exogenous (variable *xinvitot(ELECIND,DST)* see Appendix C for the full closure code) in order to apply shocks to them. The latter were determined by the energy system models results, which will be explored in Chapter 5.

4.6.3 Solution method

The multi-regional CGE model is solved using the GEMPACK (General Equilibrium Package)[14] suite of softwares specific for CGE models. The GEMPACK includes the RunDynam Programme for recursive-dynamic models, which was used since the multi-regional CGE model of this research is recursive-dynamic.

The equations of the TERM-BR E15 model were linearised, following the Australian tradition of CGE model solution. The model has around 405 thousand equations, and the condensed version of the model around 34 thousand equations. The method employed to solve it in the simulations of this research was the Gragg method with three solutions, two steps in the first, four steps in the second and six steps in the third (Gragg: 2-4-6 steps extrapolation). Multi-step solution methods are often used to calculate an accurate solution of the underlying (usually nonlinear) levels equations of CGE models. The modeller usually needs to carry out three separate multi-step calculations and extrapolate them.[15]

4.7 Expert Elicitation

While the main method of this research is CGE modelling, modelling efforts have their own limitations associated mostly with simplifying assumptions that may fail to reflect relevant social aspects. The energy transition will require multi-level governance, particularly if it aims to create socioeconomic co-benefits, which involve

[14] The GEMPACK software was created developed by the Centre of Policy Studies (CoPS) based in Victoria University, Melbourne.

[15] See the GEMPACK manual for more details of multi-step solutions.

accompanying policies (Hofbauer et al., 2022). Therefore, the expert elicitation of this thesis aims to gather insights from policy and decision makers, that is, experts operating in the electricity sector as such, government departments and planning agencies, private companies and researchers thinking the future of electricity generation in Brazil. These actors have provided their views on how to use the CGE modelling results in policy and decision making and, importantly, the barriers to harnessing the potential socioeconomic co-benefits suggested by modelling results.

The insights gathered from the expert elicitation were grouped into themes related to each of the three research questions of this thesis. The results of the expert elicitation are explored in dedicated sections in Chapter 6 (Section 6.7) for research question (i) on macroeconomic impacts, Chapter 7 (Section 7.3) for research question (ii) on industrial and sectoral impacts, and 8 (Section 8.3) for research question (iii) on distributional impacts. This section will detail the use of expert elicitation as an additional analytical tool combined to the main method of this thesis, the multi-regional CGE modelling.

4.7.1 Expert Elicitation participants

The expert elicitation has been used to identify trends and address the limitations of modelling results in informing the right policy mix at the different governance levels required. Policymakers, electricity sector agents and other experts have been consulted to provide insights that are typically outside of the modelling scope. The planning phase of the expert elicitation consisted of mapping the institutions whose experts are relevant for the purpose, aiming at conducting five to ten interviews. However, the acceptance of invitations exceeded the target, and the following institutions accepted to participate, from which 13 participants were effectively involved in this expert elicitation:

Institution	***Sector***	***Participants***	***Code***
Bank of the Northeast – NE Regional Development Bank	Public Development Bank	1	DFI
National Bank for Economic and Social Development (BNDES)	Public Development Bank	3	DFI
Energy Planning Programme, Federal University of Rio de Janeiro	Academia	1	AC
Federal Government Energy Research Company (EPE)	Public Planning Agency	1	GOV
ABEEOLICA– Brazilian Association of Wind Energy	Electricity Companies Association	1	ELS
Vestas Wind Systems Brazil	Private company	1	ELS
Centre for Regulatory and Infrastructure Studies - Getúlio Vargas Foundation (FGV)	Energy-system Think Tank	1	ELS
International Renewable Energy Agency - Brazil expert	Multilateral Energy Agency	1	ELS
National System Operator (ONS)	Electricity System Operations	1	ELS
Agora Energiewende Brazil Expert	Energy-system Think tank	1	ELS
Eletrobrás	Public Electricity Utility	1	ELS
	Total	**13**	

Table 4.4 Expert elicitation participants

Table 4.4 lists the institutions and categories of participants, along with the abbreviation by which they are referred to onwards:

DFI is Development Finance Institution

AC is Academia

GOV is Government Agency

ELS is Electricity Sector

Participants are distinguished by a number appended to the category abbreviation (e.g. DFI1, DFI2, ELS1 etc.). Attributing abbreviations to each of the participants allows for an indication of the specific areas where experts act without compromising their anonymity. This is important to reflect the different perspectives and possible biases, which will influence participants’ responses. In Chapters 6,7, and 8 (expert elicitation reporting Sections 6.7, 7.3 and 8.3) experts are referred to by these abbreviations which, within each category they are distinguished by a number appended to the category abbreviation (e.g. DFI1, ELS2, etc.).

4.7.2 Expert Elicitation interviews

Expert elicitation interviews consisted of 60-minute meetings over *Zoom* which started with a brief presentation of the research aim, the modelling approach, the main characteristics of the three electricity capacity expansion scenarios, their energy mix in 2050, the regional distribution of electricity capacity expansion and the TERM-BR E15 modelling results for scenarios' impacts over regional GDP, household consumption and wage levels across the three scenarios.

Then, five questions were asked to guide the discussion. The aim of the questions was to address not only how modelling results can be used to inform policymakers in their decision process, but also the relevant aspects which fall outside of the modelling scope or complement the limitations of the modelling. This is the case, for example, when they discuss education and capacity building needed to ensure the near full employment that a CGE model achieves due to its theoretical structure. Another relevant example is the chance that has been given for the experts to express their views on the assumptions of the scenarios, and how the structure of electricity sector investment could be different if long-term assumptions had been different.

Participants were given the chance to discuss their views on the modelling results that were presented and respond to the five questions as they wished, in any order, prioritising their views on the relationship between electricity generation, socioeconomic development and resource availability. The five questions shared with the interviewees were the following:

1. *In your opinion, can positive modelling results for socioeconomic impacts on the NE mean long-term regional development? Can we couple the objective to maintain the renewable profile of the Brazilian electricity mix with a long-term regional development objective?*
2. *How can Brazil overcome the barriers to investing in non-hydro renewables enough to achieve more ambitious scenarios in which renewables reach 100% of the electricity mix in 2050?*
3. *In your view, how can the socioeconomic results shown be used to inform multi-objective public policy that promotes long-term benefits that are economic, social, environmental and to energy security across Brazilian regions?*

4. *What is the part each of the different Brazilian regions play in long-term electricity capacity expansion (2050)?*
5. *In your opinion, which sources should be prioritised in the electricity capacity expansion until 2050? What is the role for hydropower?*

Most experts responded at least partly to all of the five questions, but the flexibility of the interview design allowed them to explore aspects that were not framed within the questions, and originated additional questions posed by the researcher.

4.7.3 Expert Elicitation analysis

The expert elicitation interviews were recorded, and a thematic analysis of the issues raised by experts was conducted. Thematic analysis is a qualitative research method that consists of analysing qualitative data by identifying and reporting repeated patterns (Braun and Clarke, 2006; Kiger and Varpio, 2020). Thematic analysis is considered a flexible method to analyse qualitative data, given that it is not necessarily tied to a particular theoretical perspective (Maguire Moira, 2014).

The thematic analysis of this research consisted of identifying, interpreting, and making sense of patterns, or common themes raised by experts in their responses related to the three research questions of the thesis (Section 1.1), complementing the CGE modelling results and discuss responding to each of them. Identifying patterns is particularly relevant when they are not part of the questions asked, that is, when experts raised common issues adjacent to the scope of the questions that were asked as such. The themes which were identify as patterns in speeches of the expert elicitation participants were the following, divided by objective:

Macroeconomic Impacts of Electricity Capacity Expansion Scenarios

1. The uncertainty around macroeconomic benefits translating into regional development.
2. The natural, unintended, regional economic acceleration of electricity capacity expansion investments in any electricity source.
3. Barriers to the investment in renewable electricity without exploring further the hydropower potential in the Amazon basin.

4. The potentialities to be explored by each of the regions that raise opportunities for diversifying the mix, allowing for portfolio management to mitigate risks to the system and regional investment distribution.
5. The potential impact of hypothetical offshore wind deployment on shifting the regional distribution of wind power investment to the SE.
6. Tax income not being channelled to investment in the region because there is a misalignment between tax collection and plant deployment.

Industrial and Sectoral Impacts of Electricity Capacity Expansion Scenarios

7. The need for industrial strategies to develop power plant supply chains to increase regional socioeconomic co-benefits.
8. Wind plant component logistics: wind blade and tower manufacturers are in the NE already. Although generators are in Santa Catarina. Prohibitive logistics of using Brazil’s road transportation infrastructure to transport blades.
9. Renewable electricity potential to turn the NE into an important region for manufacturing industries exports.
10. Hypothetical hydrogen production as a propeller for even further investment in the NE, exporting hydrogen to Europe from Ceará, and potentially, exporting wind blades produced in the NE.

Distributional Impacts of Electricity Capacity Expansion Scenarios

11. The regional divide: policies that are clearly distributive to the NE region may not be accepted by other regions, given for example the losses to the SE, the dominating region.
12. The confronting ideas that income distribution is a natural co-benefit of electricity capacity expansion versus the need for coordinated, multiple-objective policy.
13. The view of the electricity system as exogenous, separated from the rest of the economy, and which interests must be secured even above other infrastructure sectors.
14. Bottlenecks to increasing the share of non-hydro renewables in the electricity mix while promoting regional equality is divided into two categories:

   a. Planning and socioeconomic: creating supply chains, taxation, capacity building etc.
   b. The challenge of intermittency to system operation, the role of storage and further investment opportunities to the NE.

15. Power plants land lease as a factor of further income concentration.

The relevant views brought by the participants of the expert elicitation on each of the 15 themes will be explored and discussed in the expert elicitation sections of each of the three results chapters: 6, 7 and 8.

4.7.4 Ethics and data protection

The expert elicitation received ethical approval under the BSEER Research Ethics Committee – Low Risk Application, UCL Data Protection registration number: Z6364106/2021/08/35 social research. For the Research Ethics application and approval, see Appendix E.

4.8 Chapter 4 conclusions

This chapter presented the detailed methodology of the multi-regional CGE model for Brazil calibrated for this research, the TERM-BR E15. The latter has the crucial feature of a disaggregated electricity sector into nine generation sources as separate sectors (Hydropower, Solar PV, Wind, Natural Gas, Biomass, Nuclear, Diesel and fuel oil, Coal, and Others) a Transmission and Distribution sector. Chapter 4 has shown the production function of the TERM-BR E15 model, its main equations, databases, and datasets used in the calibration of the model. Moreover, this chapter has explored the implementation of the long-term electricity system scenarios as simulations in the TERM-BR E15 CGE model as a soft-link with three energy-system models for Brazil. The long-term electricity capacity expansion scenarios used have been obtained from three modelling groups based in Brazil. The details of the scenarios used will be described in the next chapter.

Finally, Chapter 4 introduced the complementary method of this research, the expert elicitation, in which 13 experts of Brazil's electricity sector and its interface with socioeconomic development were consulted. The expert elicitation served to discuss the CGE modelling results with senior experts, not only to increase the impact of this research, but also to enlighten the discussion of how these modelling results will be seen and can be used in policy and decision-making.

5. LONG-TERM ELECTRICITY CAPACITY EXPANSION SCENARIOS AND ASSOCIATED INDUSTRIAL INCENTIVES

In order to respond to the three research questions, this thesis performs a soft link between three energy-system optimisation models (ESOMs) and the multi-regional CGE model TERM-BR E15. The soft link consists of turning the results for electricity sources' capacity expansion scenarios from ESOMs into investment shocks to each of the electricity generation sources in every region of the CGE model as explained in Section 4.6. Chapter 5 therefore explains the scenarios used in this thesis to estimate their regional long-term socioeconomic impacts, and their implementation to the CGE model.

Each of the three scenarios have different approaches to climate-related objectives. The baseline scenario (described in Section 5.1) is an official scenario modelled by the EPE, an energy planning agency of the federal government. It has no climate objective, neither in terms of emission reduction, nor penetration of renewable energy sources. The objective of the baseline is to meet the projected demand for 2050, considering higher constraints to wind and solar energy intermittency. Therefore, it follows a technological pathway that increases hydropower and natural gas the most across the three scenarios. Section 5.2 describes the two scenarios which consider climate policies. The Alternative Renewable scenario (described in Section 5.2.1) aims to achieve the maximum penetration of variable renewables in the mix until 2050. The Climate Policy scenario's objective (described in Section 5.2.2) is to achieve economy-wide net zero emissions in Brazil in 2050.

Then, Section 5.3 provides more information on the regional distribution of electricity installed capacity between the five Brazilian geoeconomic regions over time. Section 5.4 analyses the CO_2 emissions associated with each of the energy-system scenarios, and Section 5.5 follows with the explanation of how the electricity capacity expansion of these scenarios were translated into shocks to the CGE model. Section 5.6 follows with the presentation of the industrial strategy scenarios applied additionally to the energy-system scenarios. Section 5.7 provides a critical view of the limitations of the energy-system scenarios, uncertainty and the robustness of the results found by linking the two types of models (ESOM and CGE). Finally, Section 5.8 concludes Chapter 5 by summarising the scenarios.

5.1 Baseline

The Baseline in this particular modelling framework means the most conservative electricity capacity expansion pathway, reflecting current and recently launched policies and strategies benefiting fossil fuel sources and limiting the expansion of solar and wind power. This baseline is also a capacity expansion scenario resulting from an ESOM, which are implemented as shocks to the CGE model.

The scenario chosen as the baseline is the EPE's National Energy Plan 2050 scenario in which wind and solar are limited to 50GW each, in terms of total installed capacity from 2015 to 2050. Hydropower capacity expansion considered refers only to hydropower potential not interfering in protected areas, but still considering new large hydropower plants in indigenous and *quilombola* communities' land (additional 30GW of hydropower installed capacity).

EPE uses the Model for Investment Decision (MDI) (EPE, 2020d), which is a partial equilibrium, system-cost minimising optimisation model. Like other system-cost minimising models, it minimises electricity capacity expansion costs (the sum of investment costs and operation costs) to meet a given projected demand. Regions are represented as subsystems, each with their own respective demand, which can be entirely or partially met by imports through transmission lines, constrained by a maximum interchange capacity, a unit cost for transmission line expansion, and estimated transmission losses. The system is represented by existing power plants, planned and procured installed capacity, and candidate projects for expansion.

In the Baseline scenario, there is no additional hydropower capacity installed from 2029, coal installed capacity is reduced in 2030 and phased out 2045, while fuel oil is phased out in 2030 due to cost optimisation in the model, rather than emission reduction policies (Figure 5.1).

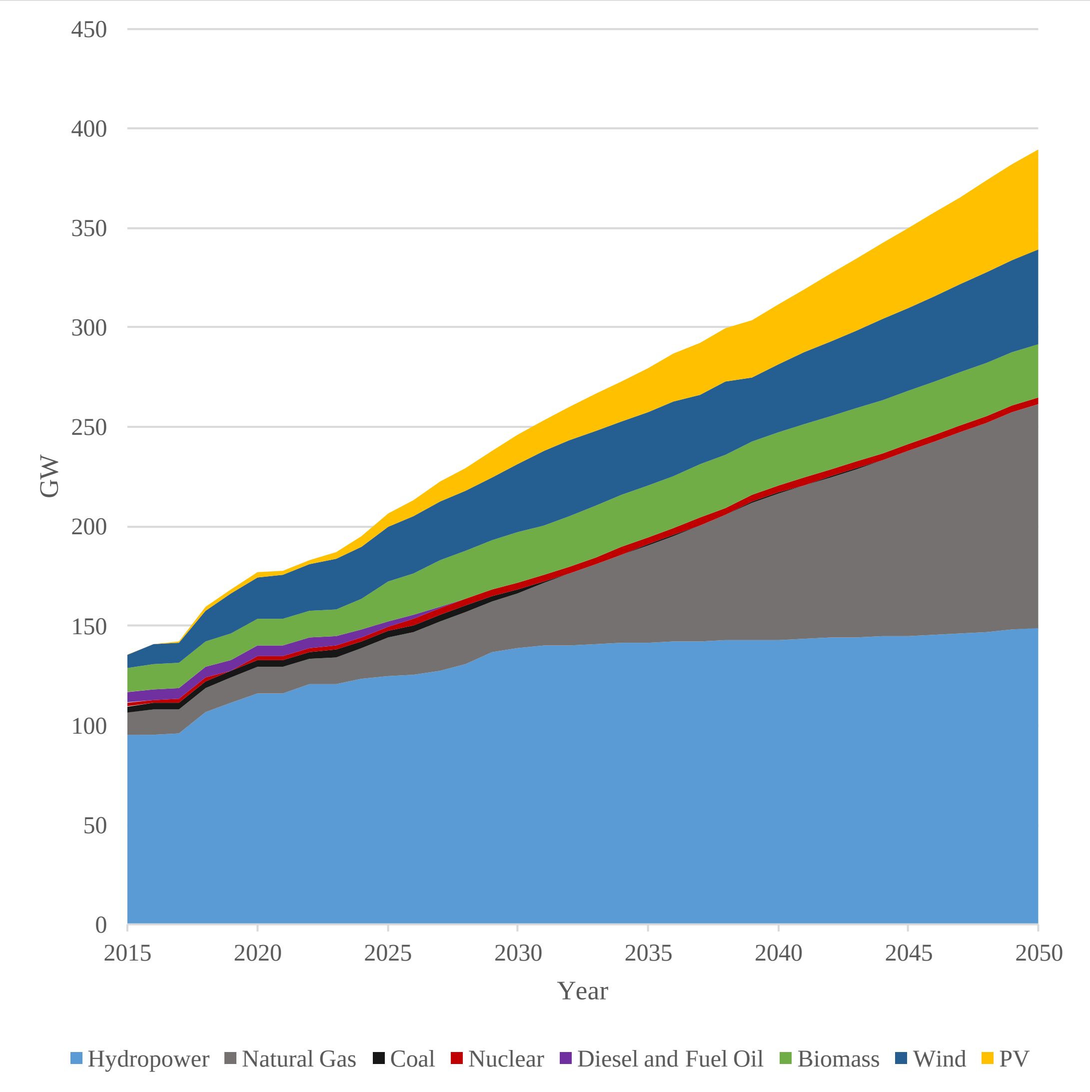

Figure 5.1 PNE 2050 Baseline scenario installed capacity per source 2015-2050

Source: Author's calculations using data provided by EPE (2020a).

The Brazilian electricity mix in the baseline scenario would still have hydropower as the main source, but with a share of 38%, nearly 45 p.p. lower than its share in 2012. Natural gas would be the main source after hydropower, reaching 112,3GW of installed capacity, 29% of total, as seen on Figure 5.2, increasing 21 p.p. from 2015, when its share was 8%. Wind power would increase its share modestly, from 5% to

12% between 2015 and 2050, and solar PV would come from zero in 2015 to 13% in 2050. This reflects the decrease in wind and solar power costs, observed and adjustments in projections, given that in a least-cost optimising energy system model they would still sum 25% of the mix even in the absence of emissions constraints, and the presence of a constraint to intermittent power sources.

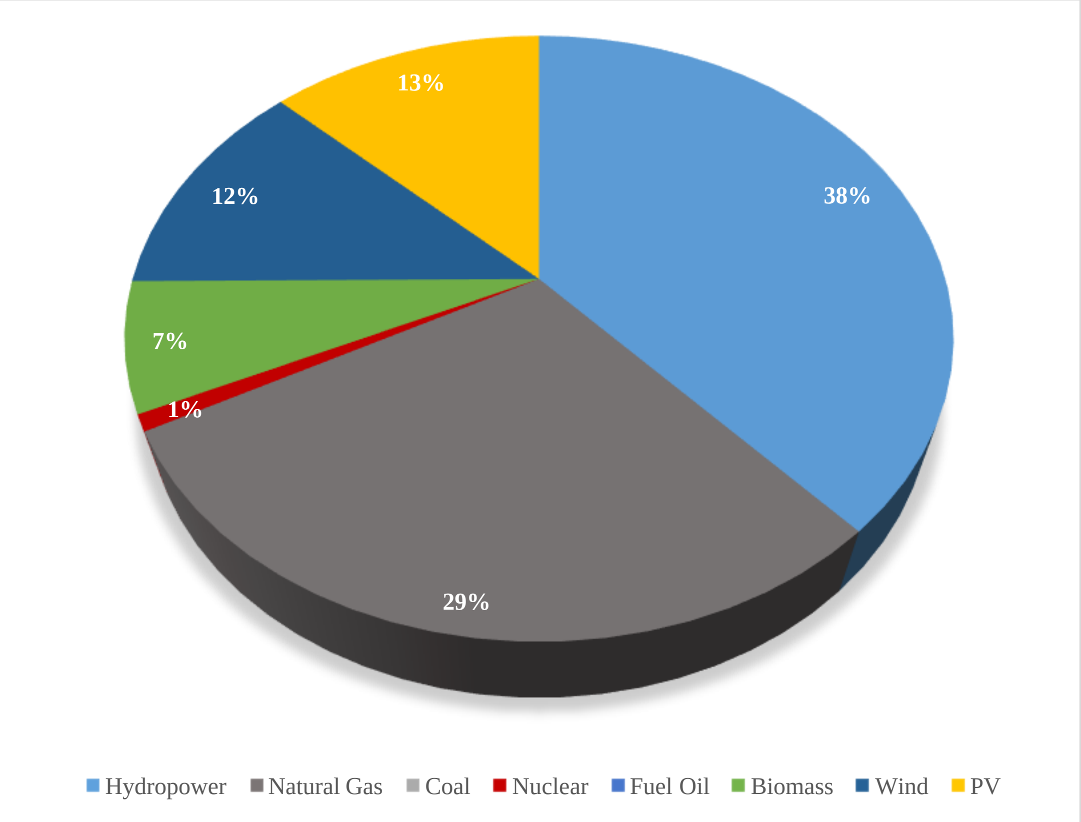

Figure 5.2 Share of electricity generation sources in installed capacity in 2050 – Baseline scenario

Source: Author's calculations using data provided by EPE (2020a).

In the Baseline scenario, wind power in the NE starts at 88% of total wind installed capacity and increases to 100% in 2050, given the intermittency constraints and the superior wind generation potential in the NE region. Solar PV, in contrast, starts with 72% of its installed capacity in the NE, but this share falls to 12% in 2050 given constraints to transmission of solar power, particularly distributed, which makes it less costly to install closer to the load. This phenomenon can also be observed in the next scenarios.

5.2 Policy scenarios

Two alternative scenarios were modelled, representing two different approaches to climate policy: the first one, produced by PSR through electricity-system modelling, represents efforts specifically to include the most possible intermittent renewables in the Brazilian electricity system in the long run, which will be called hereafter *Alternative Renewable (AR)* scenario. The second policy scenario, produced by Cenergia, is the result of modelling of economy-wide climate policy, from which results for the power sector were selected. This scenario will be hereafter referred to as *Climate Policy (CP)*. Thus, these two scenarios differ in their objectives, and their capacity expansion trajectories reflect these differences, which will be explained as follows.

5.2.1 Alternative Renewable scenario (AR)

The Alternative Renewable (AR) scenario was modelled through the PSR Energy Consulting and Analytics (hereafter PSR) chain of tools, a complex modelling framework for the electricity system, for the period between 2022 and 2050 with the aim to include the maximum possible of variable renewable sources, solar and wind power. The chain of tools includes: the OPTVALUE tool, the OptGen model, the SDDP model and the *The Time Series Lab* (TSL) tool. This is the most detailed modelling framework for the power sector available, considering hydrological risks, several aspects of variable renewable integration including storage options.

OPTVALUE is a tool for financial analysis of electricity projects, which calculates the Internal Rates of Return (IRR) or electricity price depending on the type of contract, whether prices are variable or pre-determined. It accounts for the risk of projects, including hydrological risk associated with the hydropower dam levels (PSR, 2022b).

OptGen is a least-cost optimisation model for long-term expansion planning which determines electricity capacity expansion in size and point in time, as well as the expansion of the transmission network. OptGen combines long-term system needs with a short-term operation optimisation representing hourly variation of alternative renewables and other short-term constraints such as hydropower reserve requirements in order to account for the integration of intermittent renewables. OptGen is the only model for the Brazilian power system that co-optimises Generation, Transmission and

Dynamic Probabilistic Reserves, which is relevant in the presence of variable renewable resources. It allows for flexibility-related options such as storage options like batteries (PSR, 2022b).

SDDP is a stochastic dispatch model for the power system and transmission network used for short, medium and long-term operation modelling. SDDP has representations of hydropower plants with each reservoir represented in detail including impacts of specific climatic phenomena such as El Niño, thermal plants, transmission networks, natural gas networks, batteries and other fast-response storage, and variable renewable energy which is modelled through a specific tool, the TSL (PSR, 2022b). The TSL produces scenarios of intermittent variable renewable energy sources using historical generation data for solar and wind power (PSR, 2022b).

This modelling framework is much more detailed in terms of transmission lines and distribution centres than previous ones and considered storage option. Therefore, it allowed more solar and wind power in the NE than the other two models, rather than prioritising the SE and South regions. It also imposes greater constraints to hydropower given hydrological risk modelled through the PSR tools. In the AR scenario, total additional hydropower installed capacity would be 14.8GW, from which only 3.41GW correspond to large hydropower plants (Figure 5.3). This is the scenario in which hydropower has the smallest share of total installed capacity among the three scenarios: 28% in 2050 (Figure 5.4).

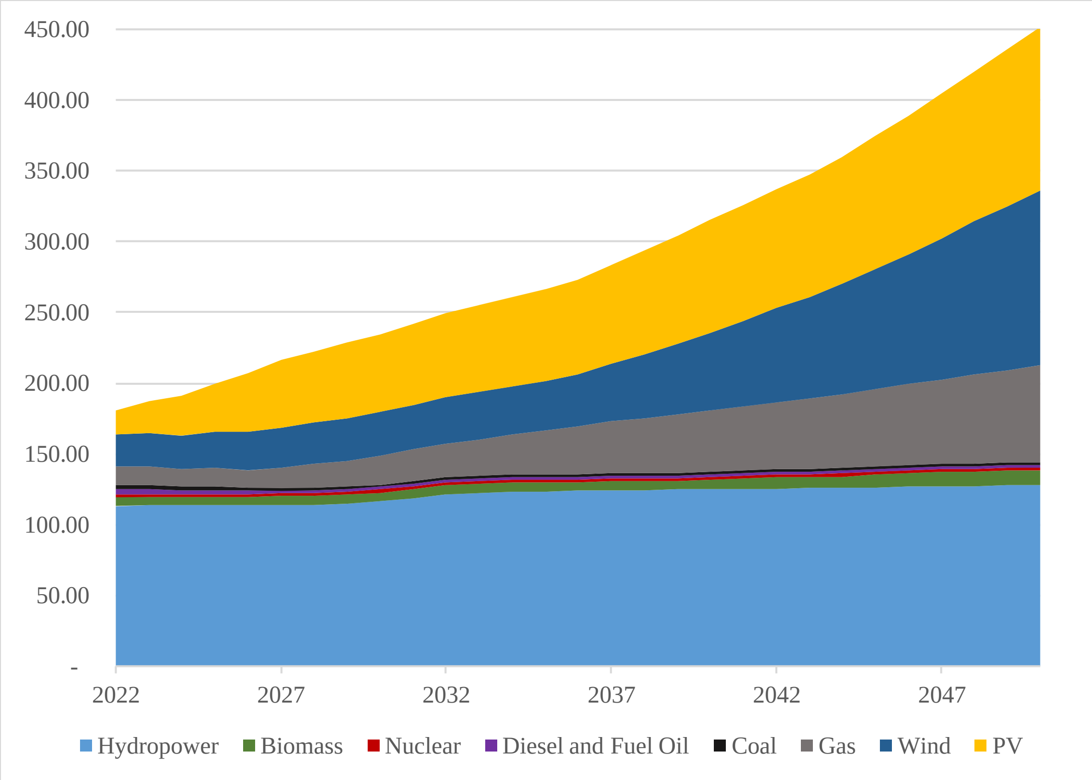

Figure 5.3 Alternative Renewable scenario installed capacity per source 2015-2050

Source: Author's calculations using data provided by PSR in private communications.

Constraints to hydropower expansion have a clear impact on total renewable installed capacity in 2050. This is the scenario in which the total sum of renewables in installed capacity is the smallest: 83% renewables in 2050.

Variable renewables, on the other hand, have their largest share in the AR scenario, as expected: over 53% of total, 26% solar and 27% wind power (Figure 5.4). This is also the scenario with the largest participation of wind and solar installed capacity in the NE in 2050: 81% of wind power capacity is in the NE and 41% of solar power capacity is in the NE.

Natural gas remains a relevant source for electricity generation in the Alternative Renewable scenario due to the need for firm energy after hydropower capacity ceases to expand. Its share increases from 8% in 2022 to 15% in 2050 (Figure 5.3 and Figure 5.4), evenly distributed among the five regions with around 20% in each of them.

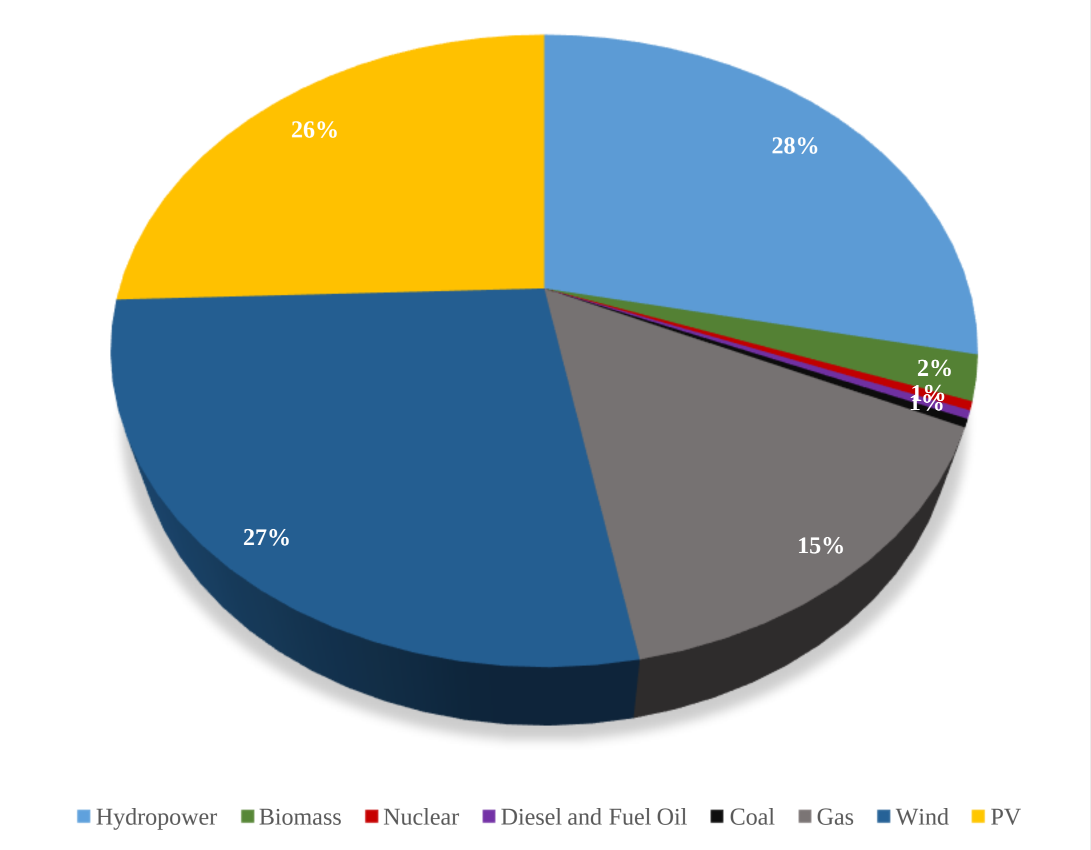

Figure 5.4 Share of electricity generation sources in installed capacity in 2050 – Alternative Renewable scenario

Source: Author's calculations using data provided by PSR in private communications.

The share of biomass in total installed capacity decreased from 3.5% in 2022 to 2% in 2050. The reason for this reduction is higher investment costs (CAPEX and OPEX) in OptGen, obtained through the OPTVALUE tool, when compared to natural gas, onshore wind and solar power.

5.2.2 Climate Policy scenario (CP)

The Climate Policy (CP) scenario comprises the period between 2010 and 2050 and considers that Brazil achieves its NDC emission reduction targets for 2030 (to reduce GHG emissions by 50% below 2005 levels) and the economy-wide net zero emission target by 2050, following the International Energy Agency (IEA) Net Zero roadmap (IEA, 2021b). The main measures adopted in the energy sector were to electrify the road transport sector following the IEA (2021b) key milestones in transforming the global transport sector, but considering a five-year delay for Brazil (Table 5.1).

The Climate Policy scenario was modelled through the country-specific energy-system and land use model called Brazilian Land Use and Energy System (BLUES) model (IAMC, 2021; Rochedo et al., 2018). BLUES is a perfect-foresight, least-cost optimization model for the Brazilian energy system, including electricity generation, agriculture, industry, transport, and the buildings sectors. It accounts for CO_2, CH_4 and N_2O emissions associated with land use, agriculture and livestock, fugitive emissions, fuel combustion, industrial processes and waste treatment (IAMC, 2021). BLUES regional division is the following: one overarching region, Brazil, and five sub-regions according to the geoeconomic division of Brazil, presented in Section 1 (North, NE, CW, SE and South). Over 1,500 technologies are considered across sectors, specific for each of the five regions (IAMC, 2021).

BLUES	***Sales Share of electric vehicles with a five-year delay from IEA Roadmap***					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**
Battery electric vehicles	**5%**	**35%**	**64%**	**76%**	**88%**	**100%**
Motorcycle	40%	63%	85%	90%	95%	100%
Buses	3%	32%	60%	73%	87%	100%
Light Commercial	0%	36%	72%	81%	91%	100%
Heavy trucks	0%	15%	30%	53%	76%	99%

Table 5.1 Climate Policy scenario assumptions for road transport 2015-2050

Source: Author's calculations using data provided by Cenergia in private communications.

The five-year delay assumption was used given that, in 2020, electric vehicles sales were 4.6% of total globally but only 0.1% in Brazil, so they considered a five-year catch-up period. Such electrification of the transport sector is particularly relevant given that 65% of total load transportation is done by diesel-fuelled heavy trucks (EPL, 2018). Mostly for this reason, the transport sector currently accounts for half of the energy sector emissions, or 10% of total emissions in Brazil (Instituto E+, 2022).

In the CP scenario, new hydropower capacity ceases to be installed by 2020 already (Figure 5.5). Total additional hydropower capacity is 28.6GW from 2010 to 2050, from which 25GW installed between 2010 and 2020, meaning that merely 3.6GW would be installed between 2020 and 2050. The participation of natural gas remains near constant throughout the time horizon, between 6% and 8% of total, while biomass decreases due to competition with other land uses such as carbon sinks, from 20% in 2015 to 5% in 2050. Wind and solar power increasingly become half of total installed capacity.

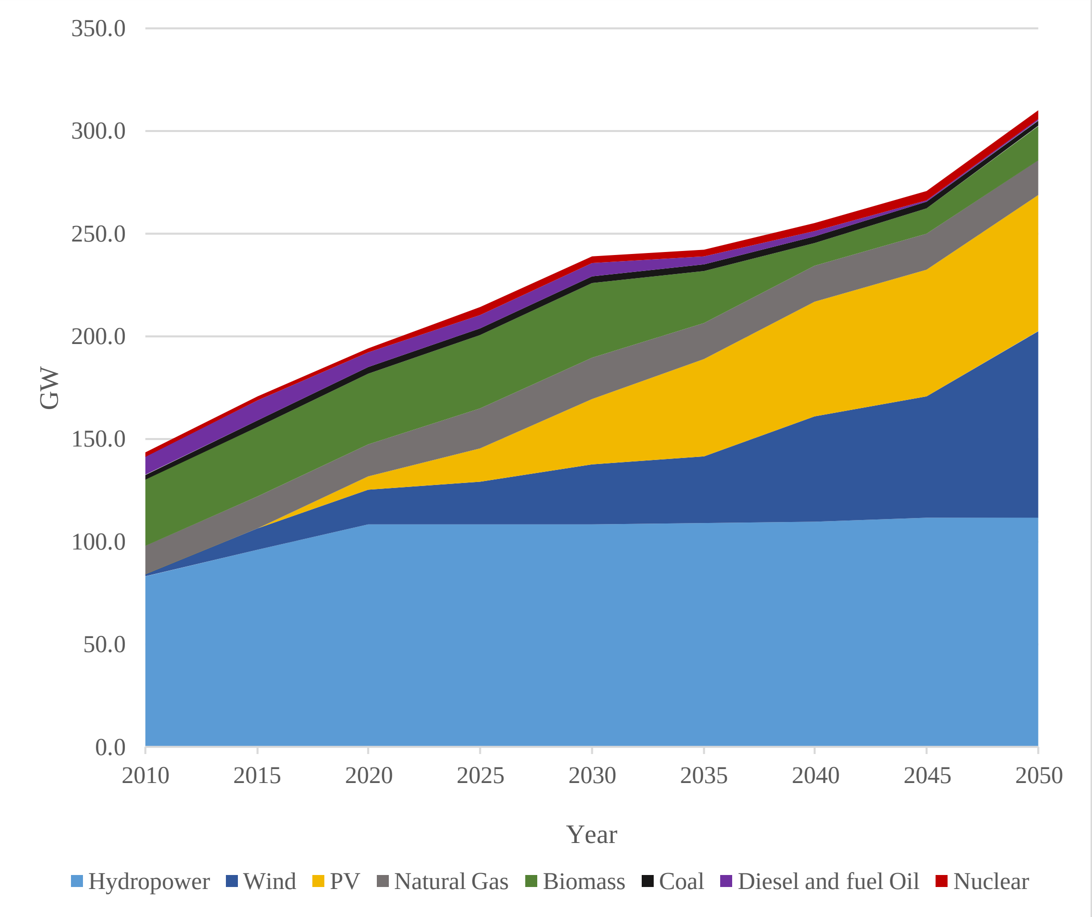

Figure 5.5 Climate Policy scenario installed capacity per source 2015-2050

Source: Author's calculations using data provided by Cenergia in private communications.

In the CP scenario, the electricity mix would be 92% renewable in 2050. Similar to the baseline, in the Climate Policy scenario, hydropower keeps a share of 36% of the total installed capacity in 2050 (Figure 5.6). Coal maintains its share of 1% of the electricity mix, due to regional restrictions to intermittency in the model (60% for each region) and therefore the need for firm electricity from non-variable sources. In this scenario, the emissions from coal and natural gas are abated in the land-use system, exogenous to this analysis. Nuclear power from 2GW in 2015 to 4.2GW in 2050, reaching 1% of the electricity mix, all of which in the SE region.

Wind power reaches 29% of the mix in 2050 from 7% in 2015 with 91GW, 52% of which in the NE region, 29% in the SE and 16% in the South region.

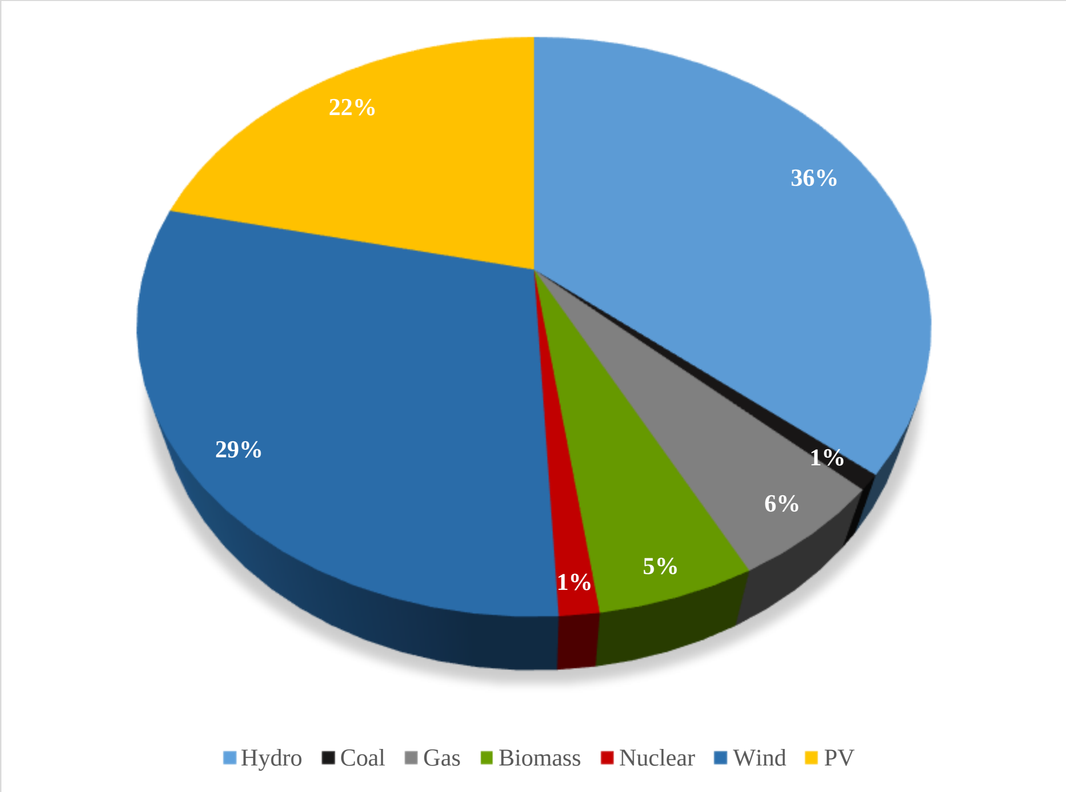

Figure 5.6 Share of electricity generation sources in installed capacity in 2050 – Climate Policy scenario

Source: Author's calculations using data provided by Cenergia in private communications.

In the CP scenario, solar PV starts at 0.01% of the mix in 2015 and reaches 22% of the mix in 2050 at 66GW. Half of these would be installed in the SE due to assumptions related to transmission costs. These costs lead the model to choose proximity to load over higher irradiation from the NE, where 28% of the solar PV installed capacity in 2050 would be installed. The remaining PV installed capacity would be 11% in the South region, 6% in the CW region and 5% in the North region.

5.3 Comparison of installed capacity regional distribution over time

The regional distribution of the electricity installed capacity and its variation over time is vital to this analysis. Each of the different scenarios, with their different underlying assumptions, create particular regional allocations for the new electricity plants to be installed until 2050. This is especially relevant here, because the region where new plants are installed are the regions receiving new investment, and therefore experiencing economic effects of this new infrastructure projects.

From Figure 5.7, Figure 5.9 and Figure 5.8[16] it is visible that, within the three scenarios used, the more alternative renewables are prioritised, the more the share of the installed capacity in the NE region increases.

In the Baseline (Figure 5.7), natural gas is the main expansion source and hydropower still increases 30GW. Hence, the SE region not only remains in the first place in regional share of total installed capacity, but also increases this share from less than 30% in 2020 to 44% in 2050. The NE remains in the second position, due to what is seen as an inevitable expansion of solar and wind power due to the improvement of their economic efficiency over time, allowing them to participate in auctions with lower-price bids, for example.

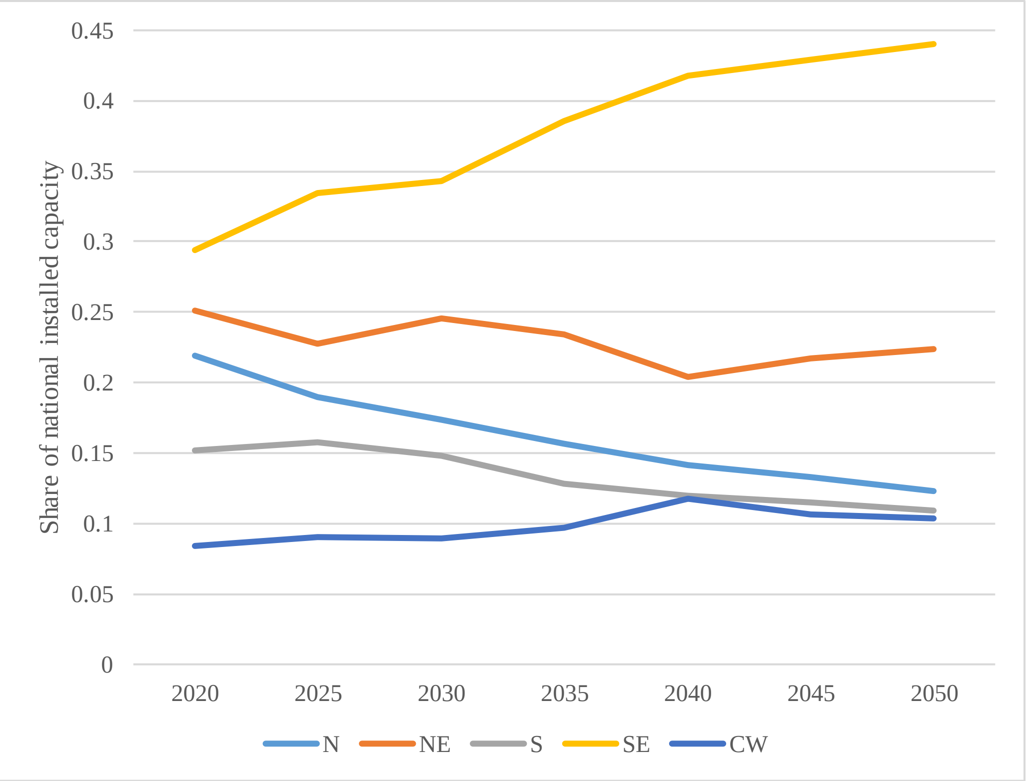

Figure 5.7 Baseline scenario regional distribution of installed capacity over time

Source: Author's calculations using data provided by EPE (2020a).

The Alternative Renewable scenario, in which alternative renewable use is maximised, is the only one presenting a structural change in regional distribution of installed

[16] The starting point is not the same for all scenarios because the starting year of the different modelling efforts is different, creating variations in *ex-ante* projections for 2020.

capacity (Figure 5.8). Indeed, in the Alternative Renewable scenario, in 2050 81% of the wind installed capacity and 42% of the solar installed capacity are in the NE. Given that these two sources sum 53% of the national total by the end of the time horizon, the NE increases its share of national installed capacity from 24% in 2022 to 38% in 2050, surpassing the SE and taking the lead in 2040.

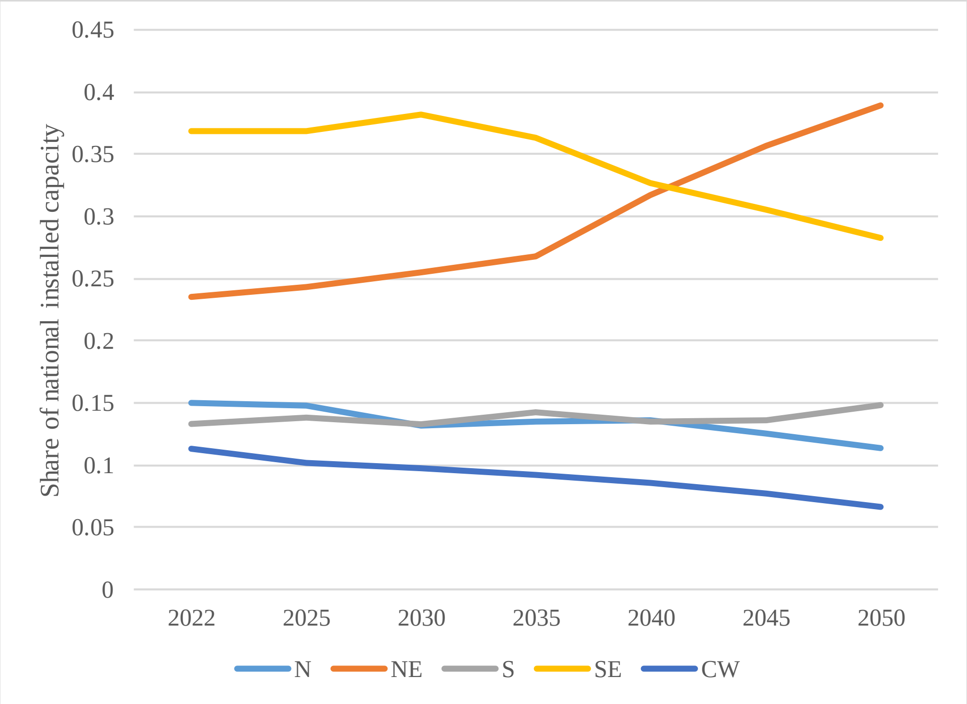

Figure 5.8 Alternative Renewable scenario regional distribution of installed capacity over time

Source: Author's calculations using data provided by PSR in private communications.

Finally, the Climate Policy scenario, in which wind power reaches the highest share of installed capacity by the end of the period, the regions where the wind investment goes increase their share in national installed capacity, mostly the NE, but, to a smaller extent, the South as well. However, the SE still remains first, despite the decrease in its share from 36% in 2020 to 31% in 2050.

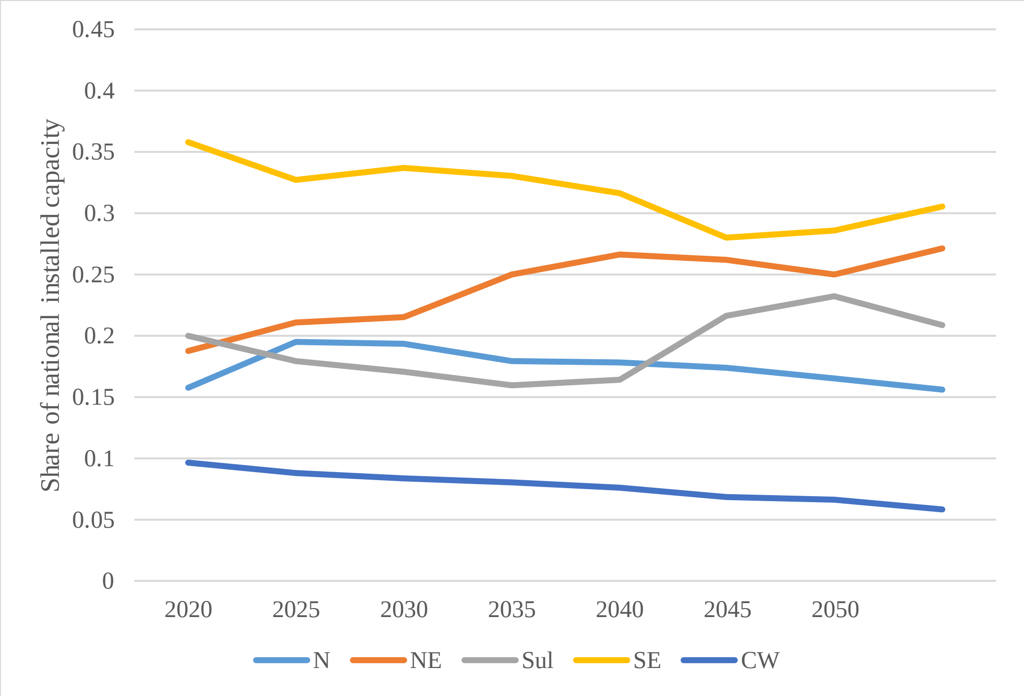

Figure 5.9 Climate Policy scenario regional distribution of installed capacity over time

Source: Author's calculations using data provided by Cenergia in private communications.

The North region is known by its large hydropower plants such as the Belo Monte dam, discussed in Chapter 2, among other relevant hydropower projects such as Santo Antonio e Jirau, under construction along the Madeira River in the state of Rondônia. However, the future limitations to hydropower are reflected, to different degrees, in all three scenarios. Hence, the North region either loses share or remains stable in all three scenarios, depending on their underlying assumptions for the start of the period.

The Centre-West region, in turn, has never been particularly relevant in terms of electricity generation. Indeed, in the operation of the SIN, the Centre-West region is integrated with the SE, forming a single subsystem. The sources present in this region are hydropower, biomass and to a lesser extent solar. The alternative scenarios consider a timid installation of solar in the Centre-West. However, it remains the last region in terms of installed capacity across all scenarios, increasing from 8.4% to 10.4% in the Baseline, due to hydropower expansion, and decreasing from around 10% to around 5% in both policy scenarios.

5.4 Capacity expansion scenarios carbon dioxide emission comparison

Clearly, scenarios pursuing larger shares of renewable sources in electricity capacity expansion result in lower emission levels in the long run. Hence, the baseline scenario, given the domination of fossil fuel electricity generation sources, especially natural gas, reaches 183 $MtCO_2$ emitted in 2050, which is five to nine times higher than the emissions of the policy scenarios in 2050.

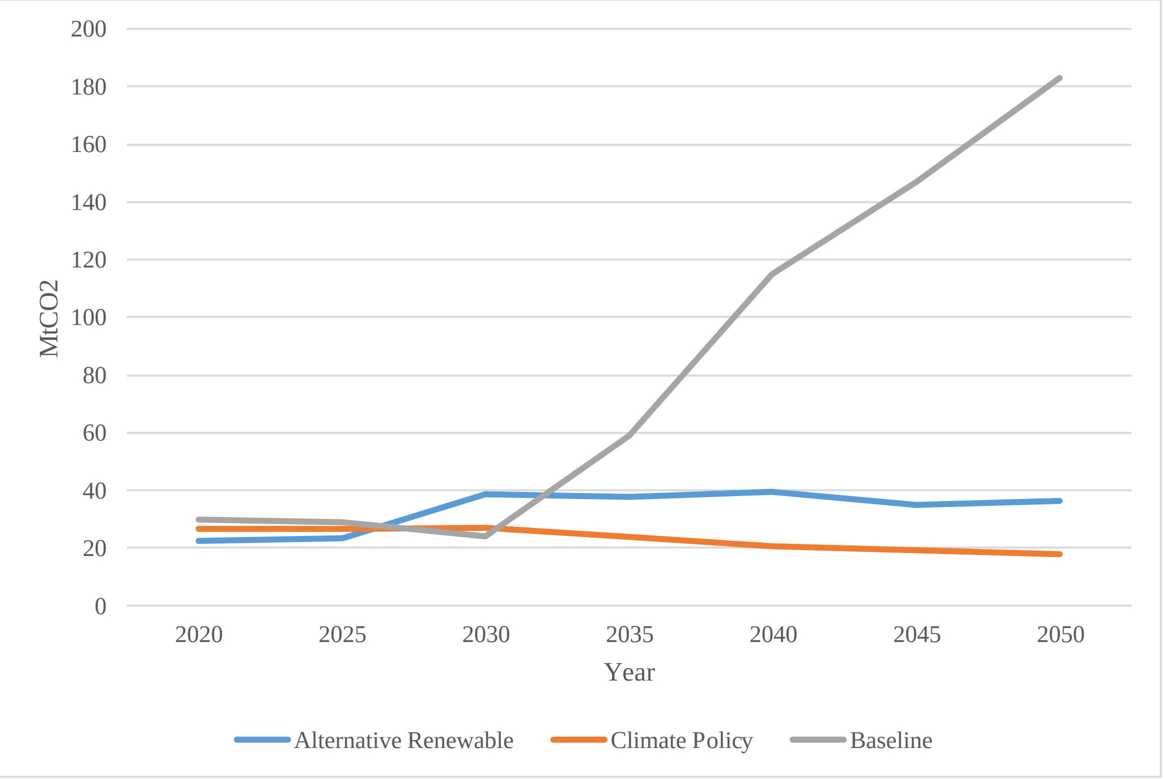

Figure 5.10 Electricity sector carbon dioxide emissions per scenario – $MtCO_2$ 2020 to 2050

Source: Author's calculations using data provided by EPE (2020a) and by PSR and Cenergia in private communications.

Noticeably, the emissions of the Alternative Renewable scenario in 2050 are higher than those of the Climate Policy scenario. This occurs because of the use of natural gas as firm power, a backup to the system's operation. Given that the electricity system model used by PSR accounts for hydrological risks, hydropower generation is lower in this modelling result than in the BLUES model, which does not consider such risks. The PSR modelling framework considers system volatility within hours of a day, hence it is more adherent to the actual challenges of the system's operation and therefore reaches scenarios with higher fossil-fuelled firm power.

5.5 Electricity capacity expansion implementation to the CGE modelling simulations

The energy-system modelling scenarios described in Sections 5.2.1 and 5.2.2 were translated into shocks that were applied to investment levels of the electricity generation sectors of the CGE model. From all three partial equilibrium models, the inputs obtained were results for installed capacity by electricity generation source, as seen in section 5.

Results from the three models were compatibilised with the CGE model structure. First, electricity generation sources from each of the modelling frameworks were aggregated into the same level of disaggregation of the TERM-BR E15 model. Then, since the BLUES model runs into five-year steps, a linear annual variation was assumed within each five-year period in order to break them into annual steps.

Once each of the partial equilibrium models' scenarios were in the standard electricity-source aggregation and annualised, regional growth rates for the installed capacity of each of the sources in each of the five Brazilian regions (North, NE, South, SE and CW) were calculated. In order to apply this as shocks to the CGE model, the capital stock level for the electricity sectors in 2019 was used as the base year capital stock, to which the annual growth rates were applied.

The capital and investment allocation equation of section 4.3.3 was used to determine the variation of investment needed in the TERM-BR E15 model, given depreciation levels, to ensure such capital stock variation observed in the electricity-system scenarios. This means that electricity capacity expansion from energy-system models translate into the capital stock of electricity generation sources in the CGE model. In the latter, capital stock varies each year through investment.

It is important to notice that the concept of investment used here is the macroeconomic concept of investment spending rather than the financial concept of investment. That is, spending on productive physical capital such as machinery and construction of buildings as part of total spending, adding to the economy's total physical capital. Investment spending, as expenditure over a period of time, is a component of that period's GDP and leads to variations in the amount of capital (Krugman and Wells, 2015). Investment is the expenditure flow that alters the stock of production capacity, or capital stock. While the purchase of a stock or existing asset is, in contrast, what is meant by the financial concept of investment.

Linear geometric capital stock growth rates were calculated for each source in each region. Positive rates were applied as shocks to electricity sector composite total investment[17]. Negative shocks occur when capital accumulation (installed capacity) decreases in the cases of coal, diesel and fuel oil and wind power in the South region (the latter in the baseline only). In these cases, such degrowth rates were applied to the capital accumulation shifter[18], to the electricity sector composite.

5.6 Industrial strategy scenarios

Arguably, socioeconomic impacts of power plant investment in a region are intrinsically related to the extent to which their supply chain is developed locally. Particularly in EMDEs, sustainable and inclusive economic development depends on local capabilities for renewable energy deployment. It is widely argued that technological development co-evolves with socioeconomic development, and thus, those who manage to create and maintain an industry with an innovation system attain better socioeconomic conditions (Grottera, 2022; Vasconcellos and Caiado Couto, 2021; Walz et al., 2017). This idea is also consistent with financing policies used by BNDES to several energy sources for the last four decades.

Moreover, participants of the expert elicitation consulted in this research were in wide agreement that there should be accompanying industrial strategies to electricity capacity expansion in order to create long-term socioeconomic and development co-benefits of renewable energy investment.

Therefore, two additional simulations were implemented to analyse the alignment of the expansion of industrial power plant component manufacturing with the deployment of renewable electricity in the policy scenarios presented in Section 5.2.

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[17] Variable xinvitot(ELECIND,DST).

[18] Variable faccum(ELECIND,DST).

These simulations were implemented as additional shocks to each of the policy scenarios: Alternative Renewable and Climate Policy.

Markedly, the main differences between the three long-term electricity capacity expansion scenarios used is in the penetration of wind and solar power. Since biomass does not achieve any substantial share of total installed capacity, the industrial strategy simulations focused on wind and solar power supply chain industries. Moreover, the industrial components of biomass-fired power plants such as pumps, boilers, heat exchanger, etc. are already produced domestically (Milani et al., 2020; Soria et al., 2015).

The simulations consider hypothetical incentives to industrial segments that are relevant to wind and solar PV supply chains. This is done by applying a 1% reduction in taxes that operate as federal taxes, hence tax collection is centralised in the national government. This is important, since was tax collection at the regional level, different regions could implement the same mechanism at the same time. Therefore, tax reduction incentives here are considered a decision of the federal government. This is consistent with the current tax system in Brazil, in which most taxes incurring over industrial production and power plant deployment belong to the federal level. Moreover, this is consistent with the literature that indicates not only that industrial policy is crucial to retain the socioeconomic benefits of the energy transition in EMDEs, but also that local content requirements as such are detrimental to the economy (Hansen et al., 2020; Kuntze and Moerenhout, 2013; Morris et al., 2021).

The two industrial strategy additional scenarios are therefore the following:

1. National Renewables supply chain policy (Ind REN): The first industrial policy scenario considers a 1% national incentive to domestically produced industrial goods demanded by the wind and solar PV electricity generation sectors. This does not target the NE region and aims to estimate the impacts of incentivising the participation of the national industry in renewable power plant supply chain.
2. Incentive to the industrial segments that are most relevant to power plants in the NE region (Ind NE): The second industrial policy scenario considers a 1% incentive to help develop industrial segments that are relevant in the supply chain of power plants in the NE, namely: Metallurgy, which produces most

structures, Electronics, encompassing the manufacturers of several crucial components such as inverters and semiconductors, and Machinery and Equipment, which comprises, for example, motors, wind blades, components of the nacelle and solar PV silicon cells. This scenario incentivises these specific industrial segments in the NE region only.

The implementation of the two industrial policy simulations as shocks to the multi-regional CGE model are explained in the next chapter, section 5.6.1.

5.6.1 Industrial policy implementation to the CGE modelling simulations

Industrial policy options described in Section 5.1.8 were implemented in the CGE model through specifically designed shocks. The shock to incentivise specific industrial segments supplying to wind and solar domestically was implemented by applying a 1% reduction in total federal taxes (variable *tuser_d*) on domestically produced goods supplied to the wind and solar power sectors by the metallurgy, electronics and machinery and equipment manufacturing sectors to every year of the 2020 to 2050 period.

The shock to incentivise the development of relevant industrial segments in the NE region was implemented by applying a 1% reduction in federal taxes (the same variable *vari*) on goods produced in the NE region by the metallurgy, electronics and machinery and equipment manufacturing sectors of the 2020 to 2050 period.

The following chapters will present modelling simulations results grouped into the responses to the three research questions of the thesis, stated in Section 1.1. Chapter 6 explores the estimates of the national and regional macroeconomic impacts of scenarios with higher shares of renewable electricity sources in comparison to a baseline scenario in Brazil up to 2050. Chapter 7 analyses sectoral impacts and industrial policy options to build capabilities in Brazil and in the Northeast region to retain a larger share of the socioeconomic benefits of renewable energy deployment. Finally, Chapter 8 assesses the distributional impacts of the different profiles of electricity generation capacity expansion in the long term in Brazil and its regions, analysing impacts on workforce by wage level and households by income group.

5.7 Limitations of the energy-system scenarios, uncertainty, and the robustness of results

Markedly, energy-system optimization models have their own limitations which are reflected in the scenarios used in this research. For example, energy technologies' costs are normally exogenous in ESOMs and there is some rigidity to long-term cost assumptions. This means that ESOMs do not model the innovation process endogenously and normally use conservative assumptions for new technologies' cost reductions over time (Grubb et al., 2021b).

Moreover, dealing with the intermittency of alternative renewable sources, notably solar and wind, is still challenging for ESOMs in the long-run (Pfenninger et al., 2014). This means that the ESOMs still rely on traditional representations of firm-power sources and still assume little penetration of energy storage, for example. Therefore, the scenarios used do not reach 100% renewable electricity sources in 2050.

It is not the purpose of a macroeconomic, multi-sectoral CGE model with strong socioeconomic detail such as the TERM-BR E15 to be detailed enough on the electricity system to create its own electricity generation and capacity expansion scenarios.

Achieving the most up-to-date energy-system modelling results for the electricity sector in Brazil until 2050 from the three existing models for the country, which belong to three different institutions, was a crucial accomplishment of this thesis. It required evoking the Brazilian Access to Information law, through which public institutions are obliged to provide information, including the data of the detailed results of the scenario from EPE for the baseline of this thesis. However, the greatest challenge consisted of using strong networking efforts to obtain the private scenarios from the Cenergia laboratory, and from PSR Energy Consulting and Analytics. Thus, the scenarios obtained for this thesis are the best possible existing long-term electricity system scenarios for Brazil.

However, notably, the energy-system scenarios used in this thesis present the limitations that are inherent to the approach of energy-system analysis that are not addressable within the scope of the thesis. Sections 5.7.1and 0 will provide critical reflections on the aforementioned approach and on uncertainty and the robustness of results, respectively.

5.7.1 Critical reflection on the approach to energy systems analysis

In analyses where the economic effects of a perturbation beyond the boundaries of the energy system are central to the research questions, it is necessary to employ CGE models to capture both the bottom-up technical detail of ESOMs with the top-down economy-wide consistency of a CGE (DeCarolis et al., 2017). This is clearly the case of this thesis. Hence, the links between the ESOMs and the CGE model are reasonable and justified. However, linking ESOMs with CGE models introduces complexities, and potential inconsistencies.

The energy-system scenarios used in this thesis were modelled through three different ESOMs (concept explained in Section 3.4.1) and linked to the CGE model through careful consideration of which data should be transferred between the models, as recommended by DeCarolis et al. (2017). In general, ESOMs' scenario developers predefine the desired energy-system outcomes, for example lower or higher emissions profiles for a specific sector such as the electricity sector, as is the case of this research. The desired outcomes are linked to and influenced by the key concerns and discussions of the time (Trutnevyte et al., 2016).

Notably, the three energy-system scenarios which socioeconomic impacts are assessed in this thesis were not modelled for the specific research questions of this research, but rather the modelling groups' policy and target interests. The energy-system scenarios were modelled to respond to policy interests of each of the modelling groups and chosen to be used in this thesis according to availability and fit to the research questions: the baseline is an official scenario that reaches a more fossil-based electricity mix in 2050 and acts as a counterfactual to the two alternative scenarios that reflect different ways to tackle emissions in the electricity system. The AR scenario has a specific renewable energy sectoral focus, and the CP scenario aims to reduce emissions across the economy, including the electricity sector.

The fact that the three energy-system scenarios were not created through the same ESOM diminishes their comparability. The different background assumptions are reflected in the absolute increase of installed capacity in 2050. The Climate Policy scenario has lower GDP growth background assumptions for the increase of energy demand, and higher energy efficiency assumptions across the energy system, which makes its total installed capacity in 2050 lower than the baseline and the Alternative Renewable scenarios.

5.7.1.1 Limitations of using external energy-system scenarios

It is not the scope of this research to build or modify ESOMs as such, but rather estimate the differences in socioeconomic impacts of the investment spending in different electricity source combinations in the long run. Still, had it been possible to control the assumptions and the development of the ESOMs which generated the scenarios used, it would have been possible to work with assumptions that would possibly have been an even better fit to the research questions posed here.

The main examples are the role of storage in the electricity system and the introduction of green hydrogen in the system. The former would impact results by allowing more integration of variable, intermittent renewable sources, which could reach 100% or near 100% renewable sources in 2050, and the latter would increase, potentially massively, the demand for zero (or near zero) emission electricity. The absence, or the constraints, to the availability of storage in scenarios has led to a significant share of natural gas in the electricity generation installed capacity in 2050 even in low carbon, renewable energy policy scenarios.

This issue relates to the rigidity to long-term cost assumptions for new technologies, such as batteries, and the lack of an endogenous technological progress or innovation process in models (Grubb et al., 2021b). Therefore, scenarios reflect the background assumptions that storage technologies costs will remain high in the long run, and the system will need gas power plants as a back-up. Therefore, this thesis would have benefited from the possibility of working more closely with the energy-system modelling groups running and developing the ESOMs in Brazil to propose the flexibilization of such assumptions. A sensitivity analysis of varying storage and green hydrogen costs in the long term could have allowed for more scenarios with higher penetration of these two technological options.

5.7.1.2 Spatial considerations

Apart from the importance of formulating the research questions of the analysis to adopt the best modelling practices in order to respond to them, researchers need to set spatial boundaries (DeCarolis et al., 2017). In the case of this thesis, explicitly modelling the differences within sub-regions of the country is critical. Therefore, the availability of sub-national regional scenarios was central to the ESOM scenario choice. Having ESOM scenarios for each of the five geoeconomic regions of Brazil allowed for the macroeconomic modelling of regional socioeconomic effects of electricity capacity expansion of the various combinations of energy sources and ultimately answer the thesis' research questions.

5.7.1.3 Effective Communication

Another guiding principle for ESOM-based analysis is effective communication of scenarios in light of the limitations of the modelling framework to help policymakers and other decision makers draw useful insight (DeCarolis et al., 2017). The need for early stakeholder engagement in energy-system scenario analysis is increasingly recognised by the literature (DeCarolis et al., 2017; Hofbauer et al., 2022; Trutnevyte et al., 2016).

This guiding principle has been followed by this thesis through the conduction of an expert elicitation process. Since the ESOMs which generated the energy-system scenarios used for the research are external, discussing their insights and limitations with the decision-makers in the expert elicitation did not allow for changes in the energy-system scenarios as such. However, these discussions made the assumptions behind the energy-system scenarios transparent to decision-makers and allowed this thesis to incorporate their views and considerations into the macroeconomic modelling. The main example of that is the inclusion of industrial policy scenarios as a demand of decision-makers who participated in the expert-elicitation.

5.7.2 Critical reflection on uncertainty and the robustness of results

Assessing the long-term future of the economy and the energy system is inherently related to multiple uncertainties. The uncertainty related to technological innovation and cost trajectories of new technologies over time was introduced in sections 5.6 and 5.6.1. But beyond technological aspects of uncertainty, there is a combination of various other deeply uncertain factors such as the availability of natural resources and socio-economic dynamics over time. Therefore, it is critical to understand that modelling long-term projections do not precisely forecast the future, and it must be clear that a single projection fails to represent the full spectrum of possible energy-system and economic futures (DeCarolis et al., 2017). This is true both to ESOMs and to macroeconomic models.

The literature addresses two main types of uncertainty: parametric and structural uncertainty. Parametric uncertainty refers to the input values for the parameters of the models, while structural uncertainty is the imperfect mathematical representation of the structural changes of systems over time.

5.7.2.1 Uncertainty quantification options

Scenario analysis is a fundamental alternative approach to forecasting in terms of addressing uncertainties by assessing alternative future developments. Each scenario represents a storyline about how the future may unfold along with a set of exogenous assumptions consistent with the storyline in the models. Scenario analysis helps addressing parametric uncertainty by varying assumptions around the relevant parameters of the modelling runs, and structural uncertainty by varying the model formulation to address scenarios' elements (DeCarolis et al., 2017).

Another widely used practice is Global sensitivity analysis, which is available to address both parametric and structural uncertainties by identifying the parameters which variations have the largest effect on the modelling results. Predefined probability distributions or plausible ranges can be applied to the input parameters simultaneously to understand which of them are the main drivers of results variations.

Finally, stochastic optimisation is an approach to deal parametric uncertainty. It addresses the limitation associated with the fact that parameters are determined ex ante, that is, values are assigned to parameters previous to model runs. It does so by attributing probabilities to decision variables through event trees. However, uncertainty increases with time stages, and therefore stochastic optimisation is more challenging the longer the time horizon of the analysis. For this reason, applications with stochastic optimization are more suitable to near-term analyses (DeCarolis et al., 2017).

It is important to notice that this thesis does not include uncertainty analysis within the parameters and the structure of each of the ESOMs which generated the scenarios because the objective of thesis is the assessment of economic impacts through the CGE model. Given the individual nature of the thesis, the incorporation of the ESOMs teams into the effort of the work done here was not possible. However, the thesis deals with the uncertainty of the energy-systems by assessing the impacts of three scenarios, modelled by three different groups, with three different ESOMs.

Notably, the fact that the three energy-system scenarios were not developed by the same institution or ESOM is not necessarily a flaw, since it can partially address uncertainty. Trutnevyte et al., (2016) highlight that scenarios choice benefits from using scenarios developed by multiple organiastions to address uncertainty, despite the lack of consensus in relevant assumptions such as future oil prices and GDP growth. Trutnevyte et al. (2016) also point out that researchers can address the challenge to incorporate potential influence of governance and the perspectives of the various relevant decision-makers by combining quantitative and qualitative scenario-model dialogue. This is addressed in this thesis by the addition of the expert elicitation process.

5.7.2.2. The robustness of CGE modelling results

The robustness of CGE modelling results is impacted by uncertainties that are inherent to long term analysis of economic systems, particularly the structural uncertainty embedded in the model calibration for a base year in which the economy is considered to be operating in equilibrium. Structural uncertainty is a limitation of CGE models when looking at time frames long enough for structural change to occur in the economy. For example, sectors that are not shocked may change substantially across the decades until 2050 which hinders the capacity of the CGE model to project accurately the feedback effects between all sectors of the economy, which impacts economy-wide results.

Uncertainty is CGE modelling projections is addressed in the literature by assuming variations in the shocks implemented, instead of implementing a single shock (Phimister and Roberts, 2017). This is done in the thesis by implementing a series of energy-system scenarios as shocks. Parametric uncertainty is normally addressed by varying the elasticities of the model, such as the elasticity of substitution between the several electricity generation sources. This requires an effort of alternative elasticity estimation that has not been possible within the scope of this thesis. Therefore, future work should focus on addressing these uncertainties.

5.8 Chapter 5 conclusions

Chapter 5 served to provide a detailed description of the three electricity capacity expansion scenarios, as well as the two industrial strategy scenarios simulated in addition to the non-hydro renewable energy policies considered. Table 5.2 compares the three scenarios for the electricity system capacity expansion until 2050, their main assumptions, model used to obtain them, and the resulting electricity mix in 2050.

	Baseline	**Climate Policy**	**Alternative Renewable**
Description	National Energy Plan - official planning to meet demand projections up to 2050	Cenergia lab from the Federal University of Rio de Janeiro, results from the BLUES (Brazilian Land Use and Energy System) model. Results to the electricity sector are obtained among multi-sectoral climate policy considering for example transport electrification.	Highly specialised electricity sector consulting firm, does electricity-system specific modelling considering very detailed aspects of load, transmission, hydrological stress, etc.
Main aim	Project supply to meet future demand in scenarios considering national challenges.	Model how to achieve net zero emissions in the Brazilian economy as a whole in 2050.	Maximum integration of variable renewables in the Brazilian electricity mix up to 2050.
Assumptions	50GW constraint to wind and solar (each) in 2050 considering constraints to transmission expansion. Hydropower expansion constrained to areas not interfering in conservations units or indigenous lands.	All NDC measures achieved in 2030 and GHG neutrality in 2050 following the IEA Net Zero by 2050: A Roadmap for the Global Energy Sector with a 5-year delay to the world share of EVs. 100% EVs in 2050.	Renewable plants are modelled using the TSL™ tool, developed by PSR, which, based on historical data on wind speed, temperature and irradiation (NASA / MERRA2), emulates hourly output of renewable power plants. In order to capture the entire available portfolio of renewables, several wind and solar farms are modelled, with different capacity factors and daily generation profiles. The average capacity factor by technology and state is shown in the table below.
Power sector results summary	Electricity mix: 32% hydro, 11% wind, 11% solar, 17% gas, 11% other thermal in 2050.	Electricity mix: 36% hydro, 29% wind, 21% solar, 5% gas in 2050	Electricity mix: 28% hydro, 27% wind, 26% solar 15% gas in 2050.

Table 5.2 Summary of the electricity capacity expansion scenarios until 2050

6. MACROECONOMIC IMPACTS OF ELECTRICITY CAPACITY EXPANSION SCENARIOS

The concern of economic loss is one of the main barriers to governments' willingness to implement renewable energy policies and system changes, as it would be to move to a solar and wind power-based electricity system in Brazil. Barriers are particularly relevant in EMDEs, many of which argue they cannot endure the potential negative impacts of the energy transition on their long-term economic growth and development process.

The modelling analysis of this research allows for a detailed analysis of net impacts, across the economy, on GDP and other macroeconomic aggregates of the different long-term pathways for the electricity mix. These results are the response to the underlying research question (i) of this thesis, described in Section 1.1.

Scenarios modelled have different objectives. They reflect the relevance of hydropower in the long term, wind and solar power deployment and the long-term role of thermal power plants, primarily natural gas-fired plants, in the electricity system. Accounting for net impacts is crucial in this context to compare scenarios for electricity installed capacity in the whole of the economy, including price feedback, as opposed to the typical analysis of employment creation of a set of projects of a specific technology.

Chapter 6 and the following chapters (Chapter 7 and Chapter 8) explore the impacts of the six policy scenarios on socioeconomic indicators corresponding, respectively, to each of the three underlying research questions outlined in Section 1.1. The scenarios reported are (i) Alternative Renewable electricity capacity expansion scenario (AR), (ii) Climate Policy Renewable electricity capacity expansion scenario

(CP), and each of them combined with (i) national renewable supply-chain industrial policy (+Ind REN) and (ii) industrial policy to targeted segments in the NE region (+Ind NE).

Chapters 6, 7 and 8 present cumulative results relative to the baseline. They show and discuss how AR and CP electricity capacity expansion trajectories impact socioeconomic variables compared to baseline impacts. The macroeconomic aggregates analysed in this Chapter are GDP (Section 6.1), real investment (Section 6.2), capital stock (Section 6.3), aggregate employment (Section 6.4), and export and import volumes (Section Export volume and Section 6.5 respectively). Then, this chapter compares the results encountered with similar analysis from the literature in Section 6.6.

Section 6.7 explores the insights raised in the expert elicitation relating to macroeconomic effects. The section develops the six themes presented in Section 4.7.3, showing the views of experts on how the macroeconomic results obtained would be used in policy and decision-making. Section 6.8 discusses the combination of modelling results with expert insights on the macroeconomic impacts of electricity capacity expansion scenarios. Finally, Section 6.9 summarises the findings of the chapter.

6.1 Real GDP[19]

On aggregate, national modelling results show that AR energy (mainly solar and wind) and CP associated with industrial incentives would not significantly impact GDP growth. The long-term renewable electricity policy's cumulative impacts on national GDP growth until 2050 are negligible. Figure 6.1 shows that although GDP would grow the most in the Baseline in 2050, the largest difference to a policy scenario from 2020 to 2050 is a 2.2% negative cumulative difference. This is the case of the CP scenario with industrial policy in the NE (CP +Ind NE).

Generally, scenarios following the CP capacity expansion pathway result in the lowest GDP cumulative growth. In the other scenarios, the cumulative difference from 2020

[19] Real in economic terms denotes having discounted inflation, as opposed to nominal, which is absolute GDP growth not accounting for price increase effect.

to 2050 would be less than 2%[20]. From 2020 to 2050, GDP would increase by 157.64% in the baseline and around 156% in most policy scenarios. Thus, modelling results do not indicate any significant GDP loss from pursuing renewable electricity capacity expansion in Brazil.

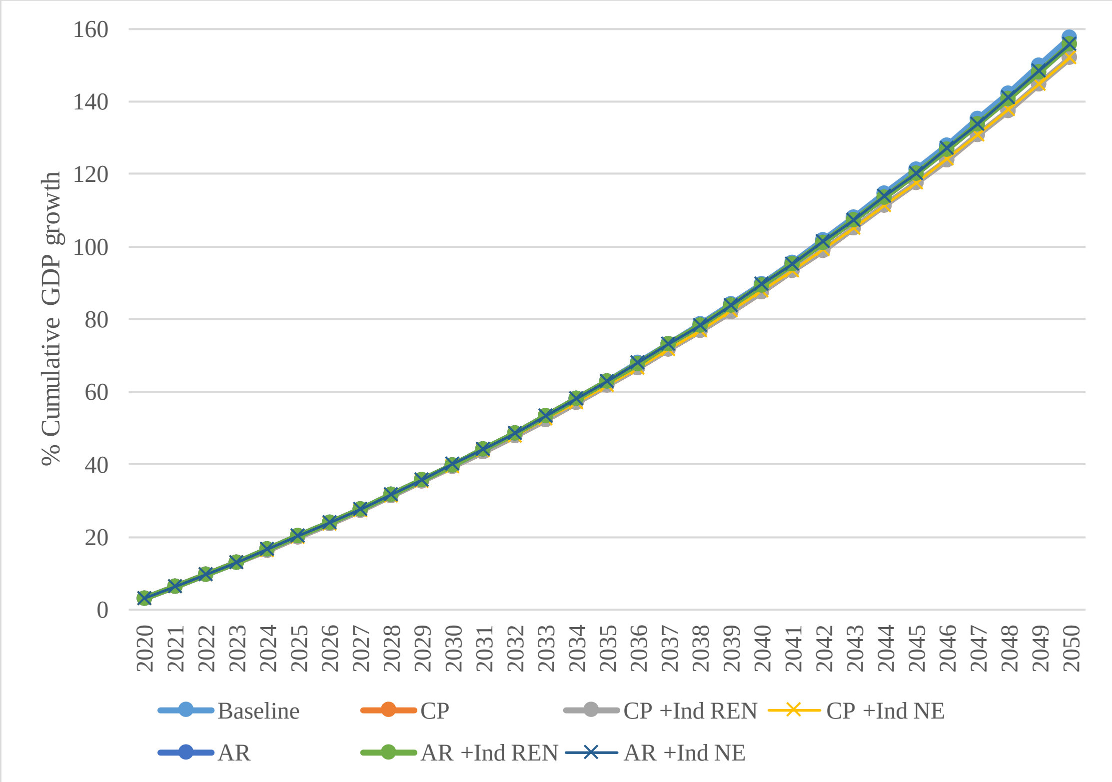


Figure 6.1 Cumulative absolute real GDP growth per scenario - 2020 to 2050

Regional deviations to the baseline in cumulative GDP growth show more significant positive impacts on the NE region in AR scenarios, particularly when associated with the industrial policy (Figure 6.2). The GDP of the NE region would grow 5% above the baseline cumulatively until 2050 in the AR capacity expansion scenario associated with an industrial incentive to the regional industrial segments relevant to power plants supply chains (NE AR +Ind NE). The AR Scenario (NE AR) and the AR combined with national renewable supply-chain industrial policy (NE AR +Ind REN) yield a 2% cumulative increase in the NE region GDP by the end of the period.

[20] It is important to notice this is not a reduction in one year growth, but rather a cumulative difference in total growth from 2020 to 2050.

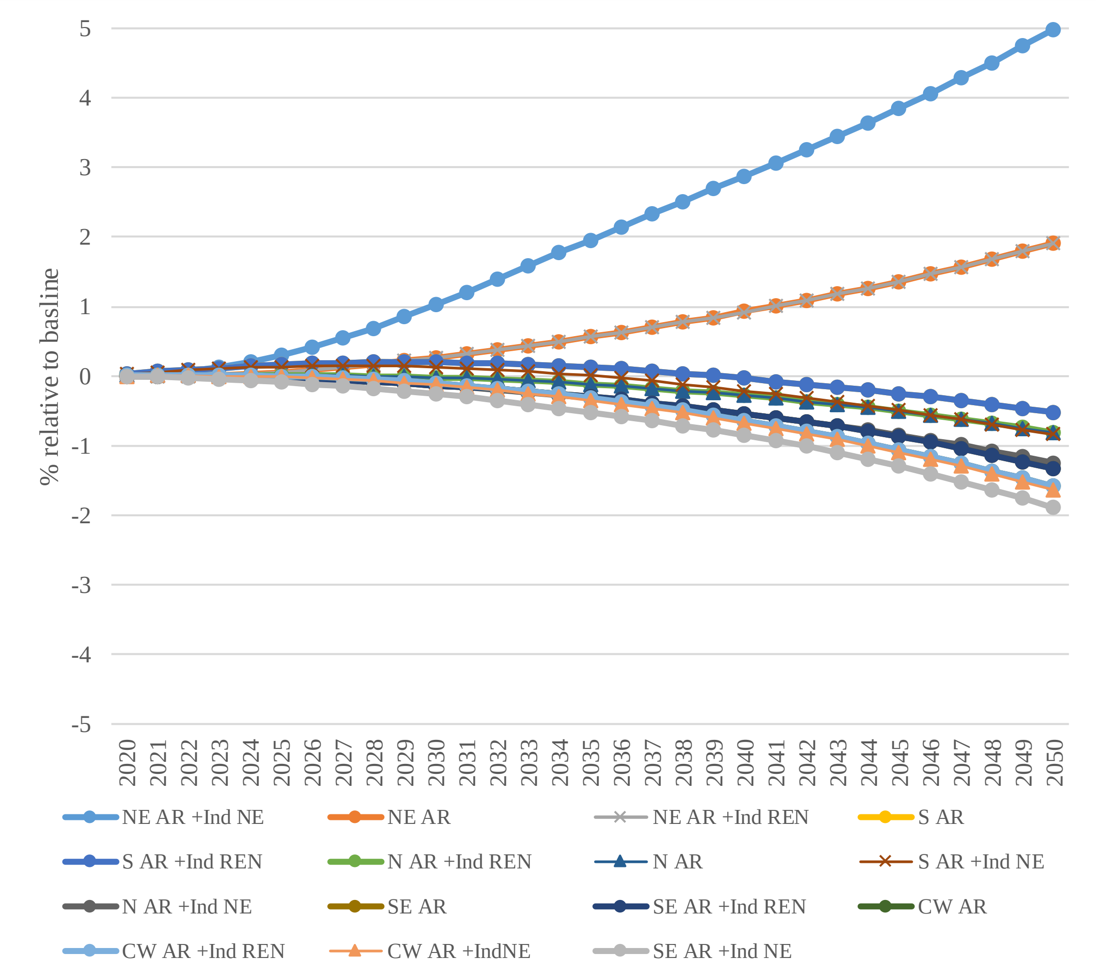


Figure 6.2 Regional real GDP growth in AR scenarios – yearly cumulative variation relative to baseline - 2020 to 2050

The other regions would have a GDP growth between 0.5% and 2% lower than the baseline, showing that no significant GDP loss occurs nationally or regionally. The slightest impact, close to zero, is observed in the South region, which receives the second largest wind power installed capacity and produces industrial goods down power plants' supply chains. The negative variation relative to the baseline occurs because the South region also benefits from fossil-fuel plant deployment, with part of the thermal plants installed in the region. But most thermal plants would be installed in the SE region, which proximity to the South also means greater demand for the industrial goods manufactured in the South.

The SE region is the main loser in GDP growth related to the electricity capacity expansion of the AR scenario. The SE loses the most when this scenario has an industrial incentive to targeted industrial segments in the NE region (-1.89% GDP growth in 2050 relative to the baseline). The reasons for the relative loss are: (i) the SE is receiving the most fossil-fuelled installed capacity, hence benefitting from scenarios with the more significant deployment of such technologies and (ii) the SE is the most industrialised region and therefore has a relative economic loss in the presence of industrial segments elsewhere.

The electricity capacity expansion scenario from the modelling of multisectoral CP shows slightly smaller gains and slightly larger losses than the AR scenario. Figure 6.3 shows regional results for all six scenarios. Once more, the most significant GDP gains were in the NE region, especially when combined with the regional industrial incentive to segments relevant to power plants supply chains. The NE had a 2.3% GDP gain until 2050, arguably a small gain. However, we should notice that the region that is customarily left behind and has the lowest economic gains, in this case, has the largest gains relative to a scenario based on traditional technologies and the other four regions.

In scenarios with no direct incentive to the NE industry, the NE experiences a GDP growth slightly lower than the baseline: around -0.75%. The South region also experiences a lower GDP growth, between 1.35% and 1.67% lower than the baseline.

In the case of the CP scenarios, the SE region does not stand out. The curves representing the three scenarios following the CP capacity expansion stay in the middle of the graph, with GDP variations between 2.10% and 3.05%. They stay in the middle because, in this scenario, the SE region receives most of the installed solar power capacity since it is close to the load, and the state of Minas Gerais has solar irradiation levels close to those of the NE region. The CW region faces similar negative impacts to the SE: a GDP growth of around 3.5% lower across all scenarios.

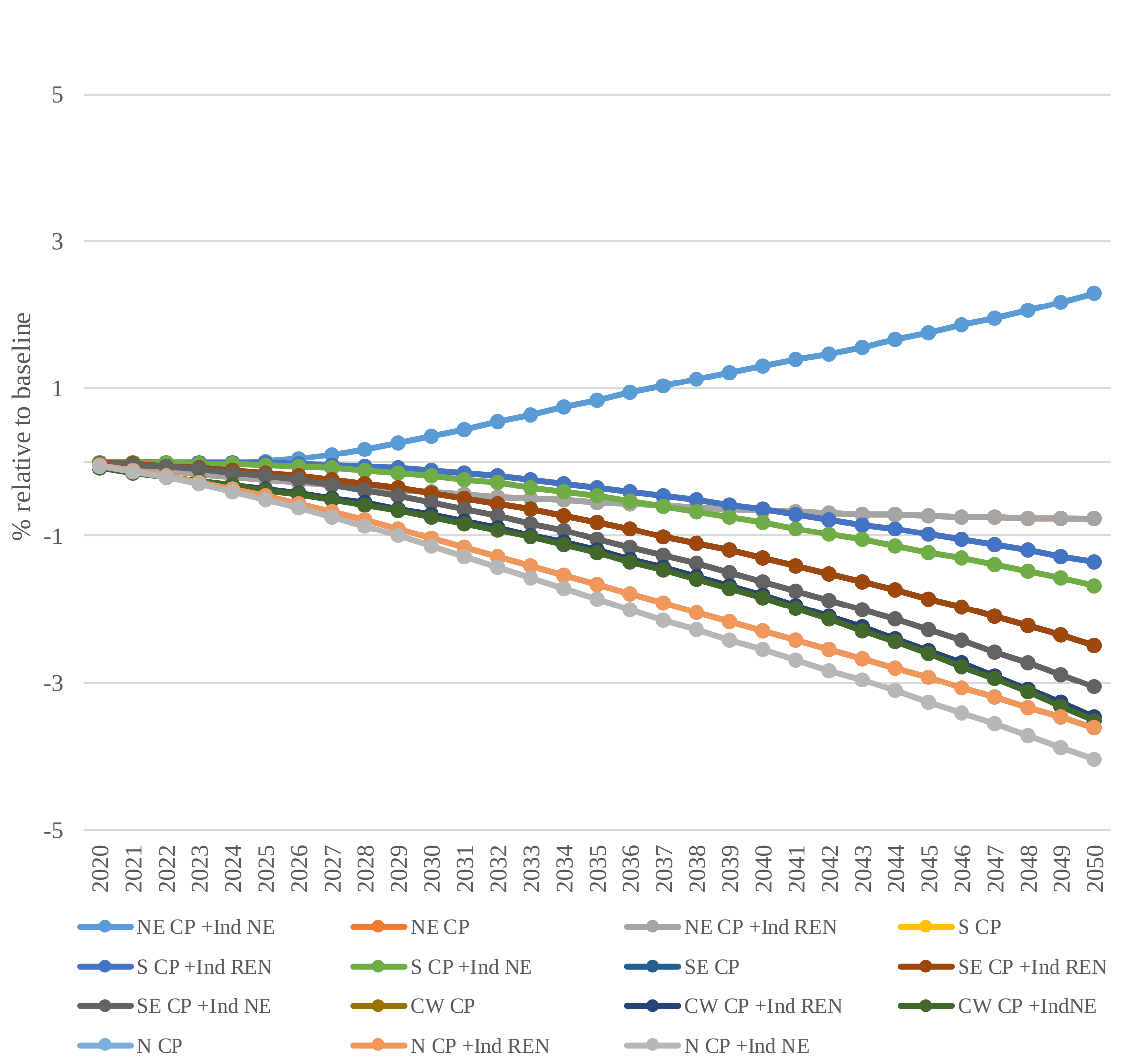


Figure 6.3 Regional real GDP growth in CP scenarios – yearly cumulative variation relative to baseline - 2020 to 2050

In the CP scenario capacity expansion, regardless of industrial incentives, the region which loses the most GDP growth is the North region, with variations between -3.61% and -4.03% relative to the baseline. The North loses the most because the investment in hydropower, to which the North region is the most relevant, ceases, and the North region is not industrialised and therefore does not supply power plants in other regions of the country.

These are the lowest levels of GDP growth observed across scenarios and geographical levels, both national and regional. The North region is the second least developed in Brazil. Hence, this outcome would be a reason for concern. Pursuing the CP scenario could involve compensation policies for the North region.

6.2 Real investment

Real investment is an indicator of the impacts that investment in electricity capacity expansion creates in the investment across all sectors of the economy. That is the extent to which electricity capacity expansion creates a need for production capacity expansion in the other aggregated sectors or the whole economy. Multi-sectoral results are analysed both at the national and regional levels. Figure 6.4 shows the economy-wide impacts on real investment at the national level.

National economy-wide real investment levels until 2050 are slightly lower than the baseline in most policy scenarios. In the AR scenario combined with a regional industrial incentive in the NE region (AR +Ind NE), the real investment trajectory is the closest to the baseline, with a 1.22% lower level than the baseline in 2050. Noticeably, the negative impact is smaller than 0.5% until 2042. The other two AR scenarios follow: with no industrial policy associated (AR) and with an industrial incentive no national wind and solar supply chains (AR +Ind REN). They show a 2.3% loss relative to the baseline in 2050. In these two scenarios, impacts only surpass 0.5% in 2035.

The scenario with incentives to the NE industrial sectors (CP +Ind NE) has the highest economy-wide investment level among CP capacity expansion trajectories, 3.66% lower than the baseline in 2050. On the other hand, the CP scenario, with no industrial policy, and the CP capacity expansion trajectory associated with the national industrial incentive for solar and wind supply chains (CP +Ind REN) have similar and the most negative results across scenarios: 4.72% lower than the baseline in 2050, and over 0.5% loss starting in 2024.

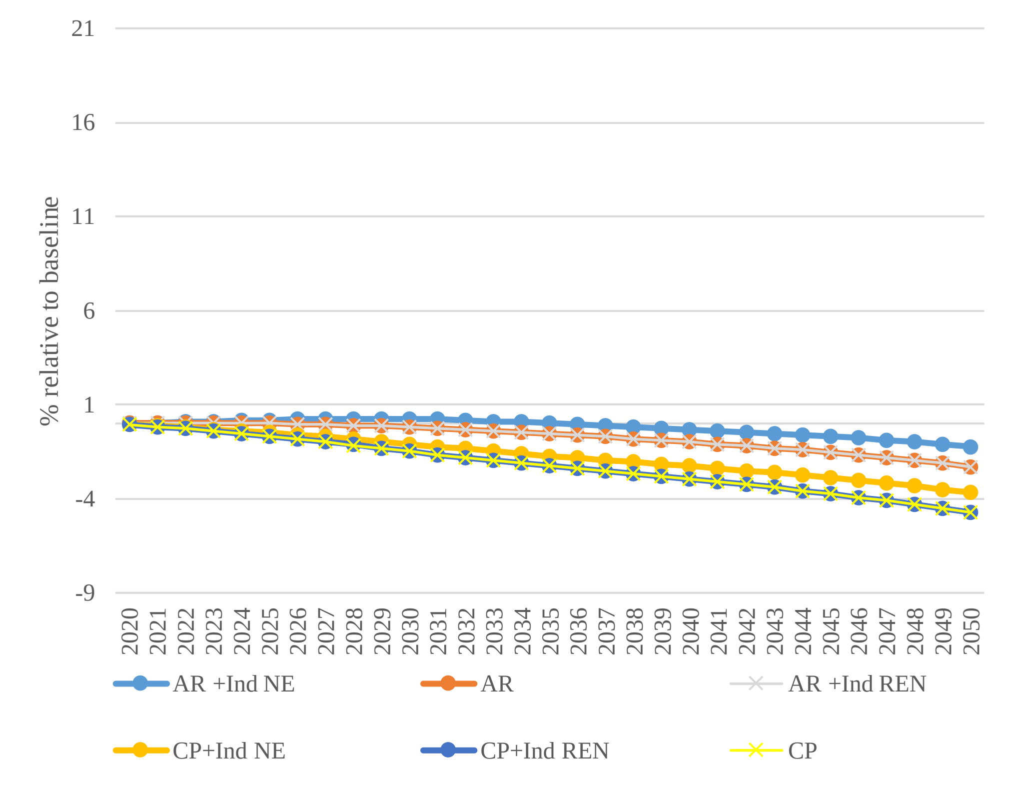


Figure 6.4 National real investment growth relative to baseline per scenario

Regional impacts on real investment have clearer winners and losers in each scenario than in the baseline. The NE is the region that benefits the most from both the AR and the CP capacity expansion trajectories when combined with regional industrial policy (AR +Ind REN and CP +Ind REN). Figure 6.5 presents the regional real investment results over time for the AR capacity expansion trajectories, with and without industrial policy options. Figure 6.6 shows the regional real investment results over time for the CP capacity expansion trajectories, with and without industrial policy options.

The result for the AR trajectory with regional industrial policy in the NE (NE AR +Ind NE scenario, Figure 6.5) is the most considerable positive impact on real investment across all scenarios and geographical levels. It would bring a 21.14% real investment gain to the NE region until 2050 and a 10% increase starting from 2034.

The NE would also benefit from the AR capacity expansion trajectory, with no perceivable difference between the scenario with no industrial policy (NE AR) and national industrial policy for wind and solar supply chains (NE AR +Ind REN). In both scenarios, real investment would increase by 4.32%.

Similar to the impacts on GDP, in the AR capacity expansion trajectory, the SE region loses the most. But in this case, with a higher percentage than GDP loss: 5.9% lower than the baseline in 2050 in the AR trajectory with industrial incentives in the NE (SE AR +Ind NE). Therefore, we can attribute the loss in the SE to the substitution between the SE and the NE production of manufacturing goods. Noticeably, the Ind NE industrial policy scenario considers an incentive to industrial segments in the NE that are relevant to renewable power plants' supply chain but is not constrained to the goods supplied to these users only. In contrast, the Ind REN industrial policy scenario simulates the implementation of a national industrial incentive but only for those goods directly used by wind and solar power.

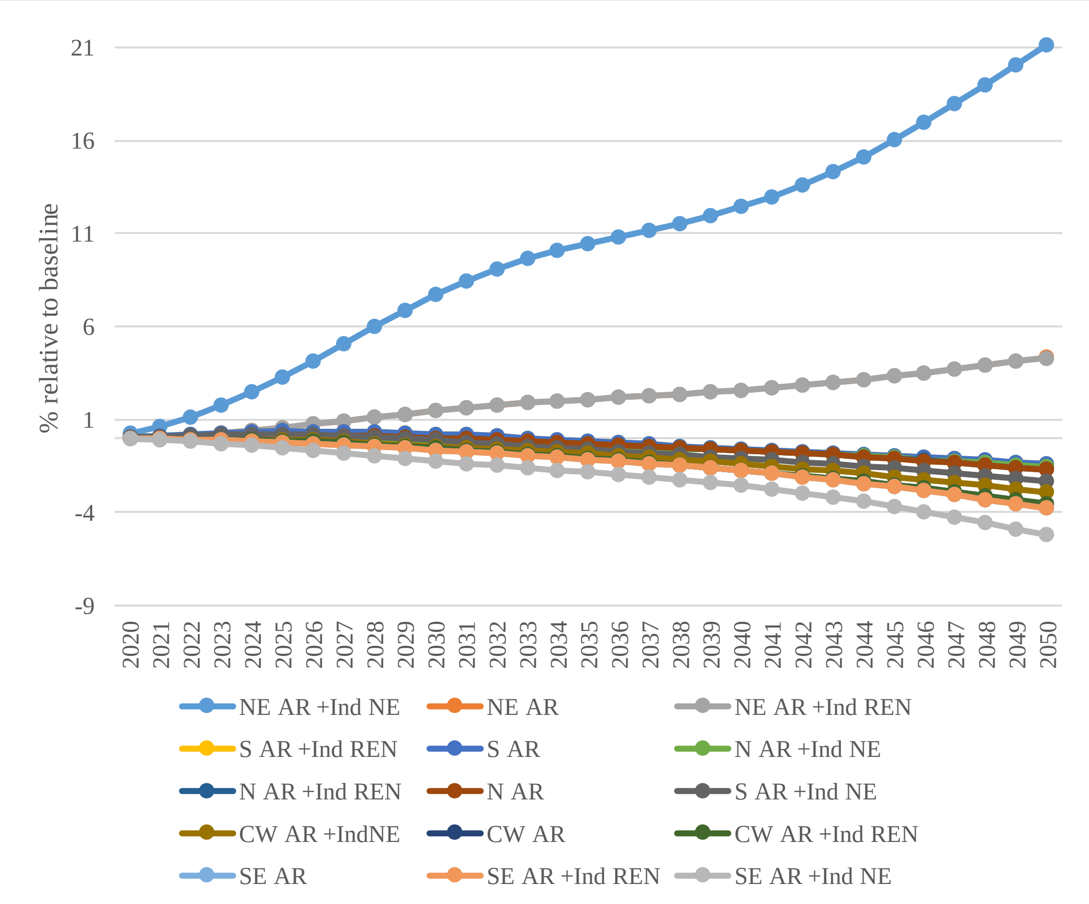


Figure 6.5 Regional real investment growth relative to baseline in AR scenarios - 2020 to 2050

Results of the CP capacity expansion pathway associated or not with industrial incentives are similar to those results of the AR trajectory in terms of the main winners and losers. Although, as observed in most of the variables reported, CP trajectory scenarios yield lower benefits or more significant losses depending on the variable and the scenario.

The NE region has a 15.47% real investment gain in 2050 in the CP capacity expansion trajectory with the regional industrial incentive in the NE (NE CP +Ind NE on Figure 6.6). All other scenarios and regions experience lower real investment growth than the baseline. The NE is again the region which experiences the slightest loss, with a 1.11% decrease in real investment in 2050 in the CP capacity expansion trajectory with the national industrial incentive to wind and solar components (NE CP +Ind REN).

The largest loss is once more in the SE region in the scenario where the CP capacity expansion pathway has the regional industrial incentives in the NE: a 7.24% lower than the baseline real investment level in 2050. This investment loss relates to the incentive to industrial segments in the NE, which, in the long term, creates additional manufacturing capacity in the NE, which in the baseline occurs in the SE, hence the lower growth relative to the baseline.

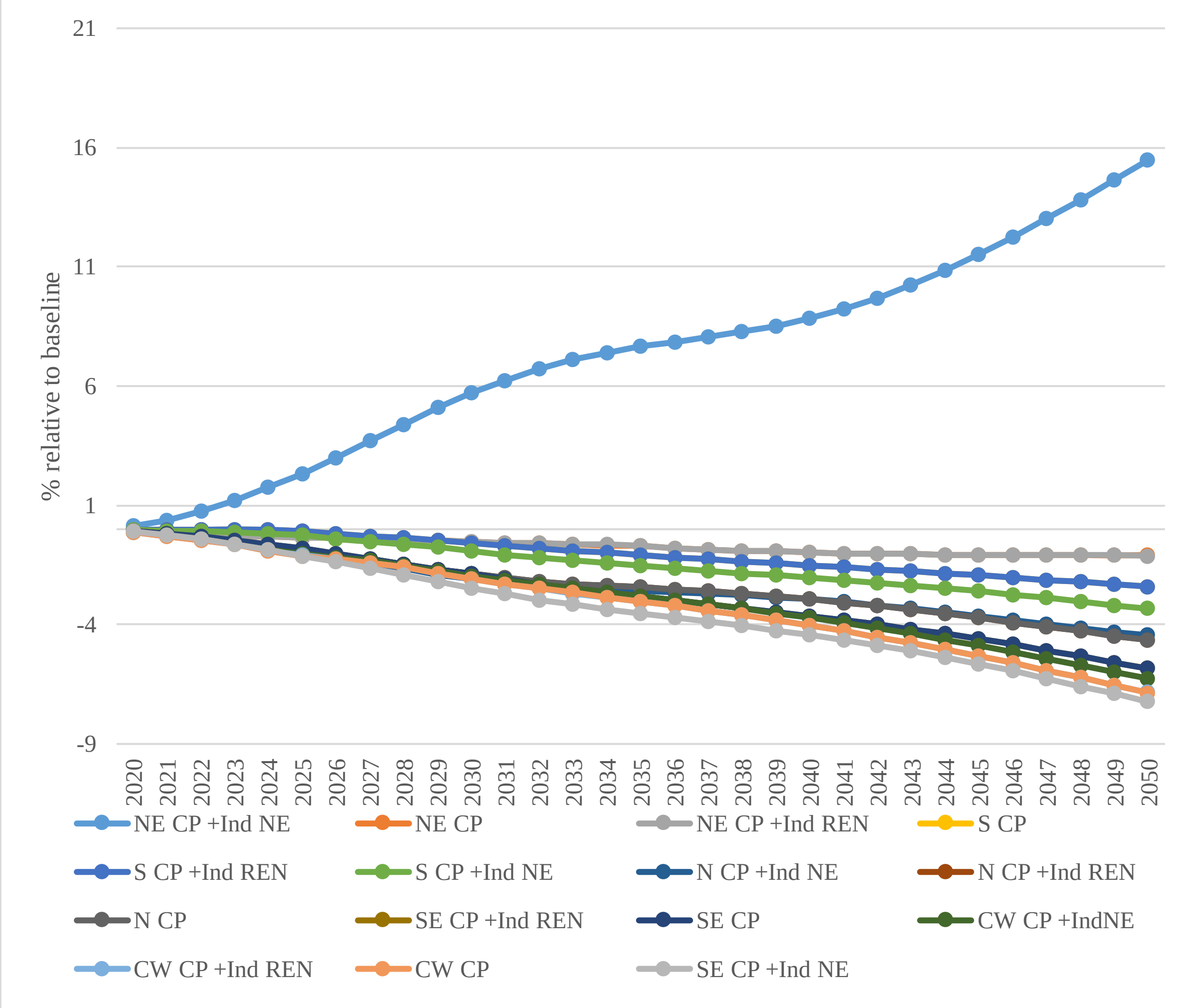


Figure 6.6 Regional real investment growth relative to baseline in CP scenarios - 2020 to 2050

The South region comes second in experiencing the mildest impacts across the three scenarios within the CP capacity expansion trajectory: between 2.4% and 3.33% lower than the baseline in 2050. Regions without an outstanding potential for wind and solar electricity or manufacturing industrial goods lose real investment. The CW and the North regions, whose economies are mostly agriculture and livestock, experience real investment growth between 4.64% and 6.85% lower than the baseline.

6.3 Aggregate employment

Figure 6.7 shows that national aggregate employment variations relative to the baseline are close to zero across scenarios, as expected, given the theoretical basis of a CGE model, as discussed in Section 3.4. The most significant variation observed is

0.11% lower than the baseline in the AR and CP capacity expansion trajectories combined with regional industrial policy in the NE (AR +Ind NE and CP +Ind NE).

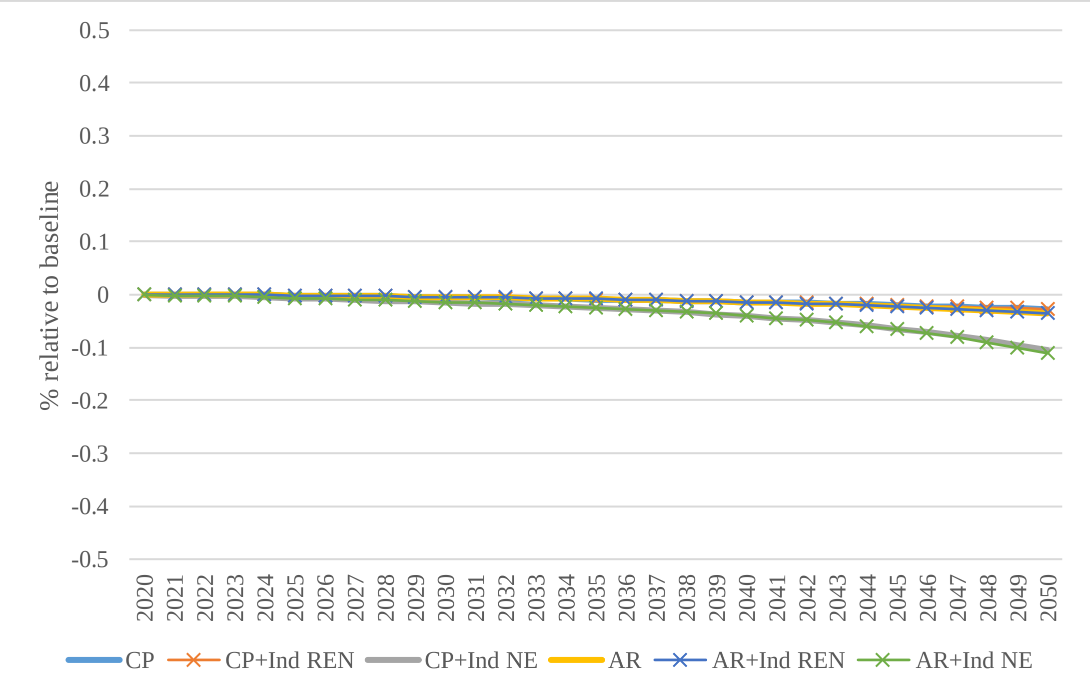


Figure 6.7 National aggregate employment growth relative to baseline per scenario - 2020 to 2050

Regional results show more nuances in job creation, given that the national total entails regional winners and losers. The different wage bands also show nuances, reflecting the different skill levels of the workforce, which Chapter 8 explores. Markedly, impacts on employment do not surpass 1% cumulative in 2050, given the full employment assumption of the Walrasian theory and its full employment assumption.

Once more, scenarios following the AR electricity capacity expansion show more positive results than those of the CP trajectory, combined or not with industrial incentives. The NE also benefits the most, particularly in the AR regional industrial incentive scenario (NE AR +Ind NE). It is the only result presenting a variation over 0.5% for national and regional results, including positive and negative variations. In this scenario, the NE yield a 0.56% cumulative gain in employment creation, despite the national loss of this scenario being the largest.

The NE is the most benefitted in the other two scenarios within the AR pathway: in the absence of industry incentives (AR) and with the national incentive for wind and solar components (AR +IND REN). The NE in these two scenarios receives the second highest gain, although close to zero: 0.16% in 2050.

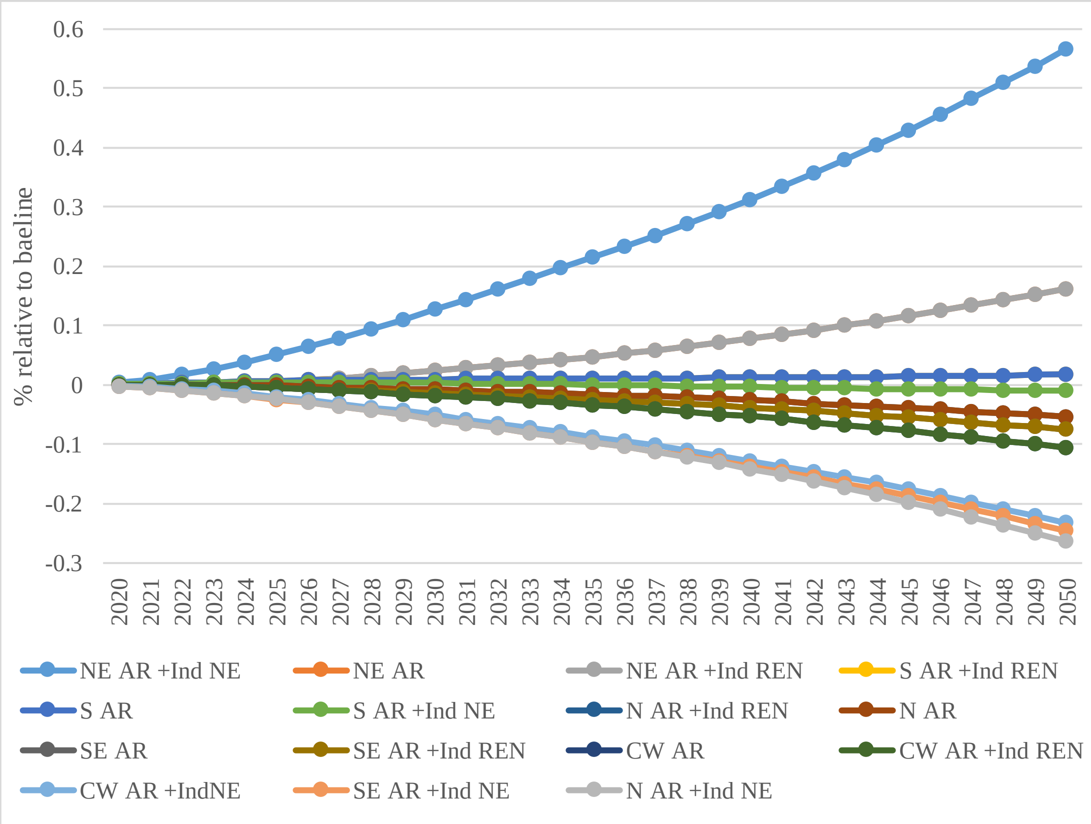


Figure 6.8 Regional aggregate employment growth relative to baseline in AR scenarios - 2020 to 2050

The South region comes next in terms of benefits, or milder losses in aggregate employment, like GDP and real investment. Impacts on South employment were near zero (between 0.001% losses and 0.01% gains). The SE, CW and North regions stayed in the middle with zero and 0.1% lower than baseline in scenarios with no industrial policy (AR) and with national industry policy for wind and solar components (AR +Ind REN). The largest negative impacts within scenarios following the AR capacity expansion occur in the same three regions, SE, CW and North, in the presence of an industrial policy focused on the NE. Since national results are close to zero, there must be losers to compensate for winners.

Scenarios following the CP capacity expansion trajectory showed similar trends. The NE also benefits the most, notably in the presence of regional industrial incentives. In this case, aggregate employment in the region increases by 0.53% above the baseline.

Once more, results for the other two scenarios in the NE region came second in terms of benefits but close to zero impact: 0.12% increase relative to the baseline.

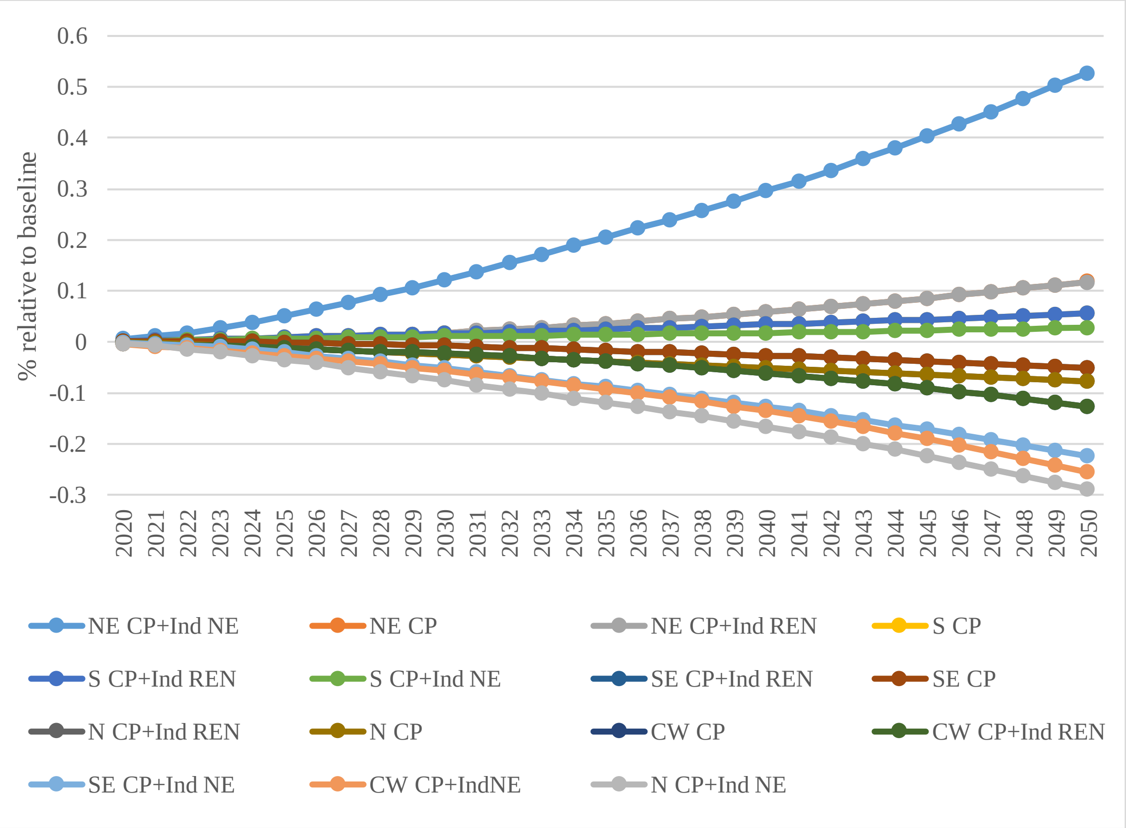


Figure 6.9 Regional aggregate employment growth relative to baseline in CP scenarios - 2020 to 2050

The South region, similar to the AR scenarios, is virtually not impacted, with slight benefits in job creation: from 0.028% gains relative to baseline in the scenario with an industrial incentive to the NE region to 0.057% in the other two scenarios following the CP capacity expansion. On the other hand, the SE, CW, and North regions are again the main losers in CP scenarios, with negative variations between 0.05% and 0.18% in the absence of industrial policy and 0.22% and 0.28% lower than the baseline in the case of regional industrial incentives in the NE.

6.4 Export volume

The interactions between one economy and the rest of the world through trade are another macroeconomic aggregate that influences policymakers. The influence occurs mainly in EMDEs, where the currency usually is devaluated relatively to those of the advanced economies. This is and has historically been the case in Brazil. However, it is crucial to notice that impacts on exports may reflect higher domestic demand for goods relative to the external demand or variations in the trade terms, particularly the exchange rate.

Impacts over exports at the national level, although small, are noticeably positive except for the AR scenario without industrial policy (AR) and with targeted national industrial incentives (AR +Ind REN) (Figure 6.10). Positive impacts may indicate a higher national demand for domestic goods. In these two scenarios, there was a slightly negative impact relative to the baseline: aggregate exports would grow 0.28% less than the baseline. However, among the four scenarios that would experience above the baseline export growth, only the CP scenario with industrial incentives to targeted segments in the NE (CP +Ind NE) region would have a difference to baseline higher than 1%, with 1.17%.

Most scenarios experiencing above-the-baseline growth start the trajectory with a loss relative to baseline and start gaining in 2033. The AR scenario with the industrial incentive to targeted sectors in the NE (AR +Ind NE) was the only scenario to create positive export impacts relative to the baseline across the whole period from 2020 to 2050, reaching 0.57% above the baseline in 2050.

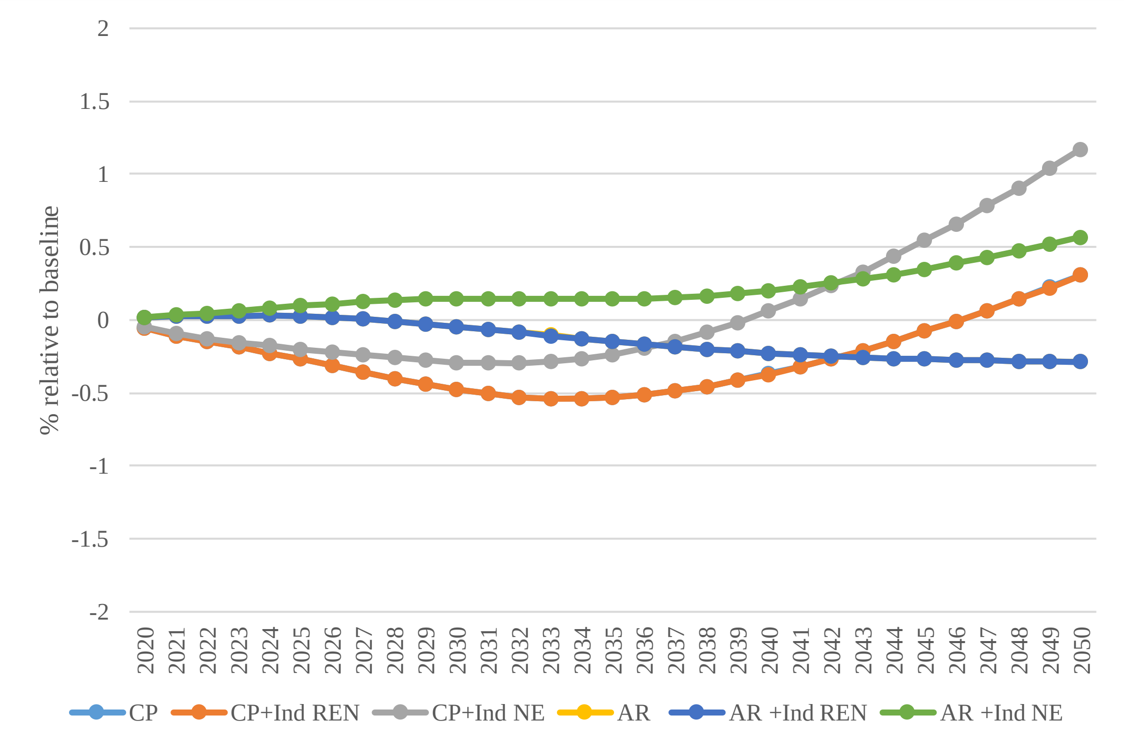


Figure 6.10 National export volume growth relative to baseline per scenario

The simulated scenarios significantly impact regional participation in the production of exported goods relative to the baseline, as shown in Figure 6.11 and Figure 6.12. The NE region exports the least good compared to the baseline, which is a vital sign that it internally consumes the goods it produces instead due to the increased demand. For example, the results of the NE varied from 4.54% below baseline in the AR with no industrial policy scenario (NE AR) to 15.90% below baseline in the AR scenario with regional industrial incentives (NE AR +Ind NE). The variation is consistent with the hypothesis that the more incentive to the NE economy relative to the rest of the country, the more it consumes local goods.

In contrast, the SE and South regions maintain the current pattern in the Brazilian economy and experience the highest export increase relative to the baseline across scenarios. Moreover, exports are notably higher in the AR scenario with regional industrial incentives, which is again consistent with the broader idea that it gains room within national exports once the NE starts retaining locally produced industrial goods, mainly through increased regional demand.

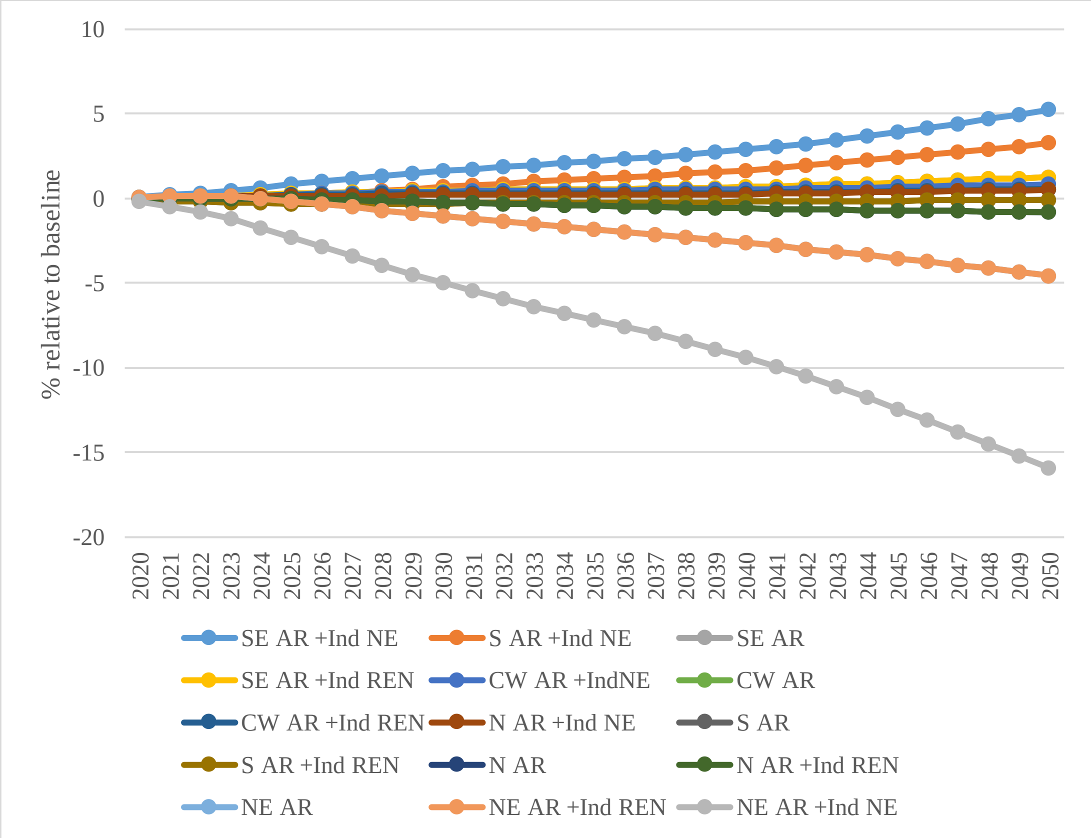


Figure 6.11 Regional export volume growth relative to baseline in AR scenarios

The levels and ranking of impacts on exports are similar between the two groups of scenarios. Again, the SE and South regions in the CP scenario considering industrial incentives in the NE (SE CP +Ind NE and S CP +Ind NE) yield the most export growth: 5.39% and 2.54% above the baseline, respectively. However, the NE region also reduces its exports the most, like in the AR scenarios. Indeed, the NE region in the scenario in which industrial incentives occur in the NE only (NE CP +Ind NE) has the most negative deviation from the baseline: 13.33% below the baseline level in 2050.

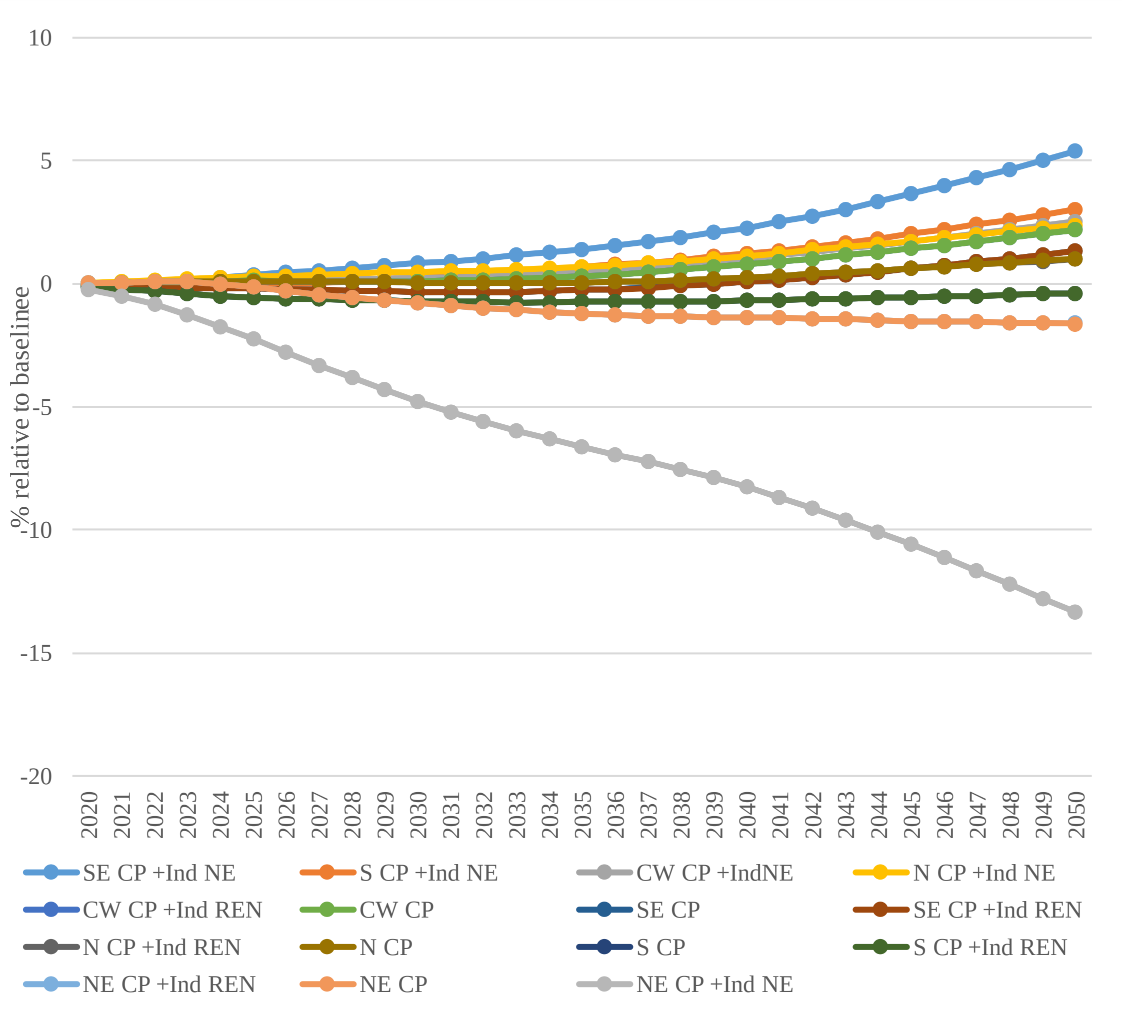


Figure 6.12 Regional export volume growth relative to baseline in CP scenarios

6.5 Import volume

On the other side of the trade balance, imports, on the national level, would suffer close to zero impacts across scenarios: from a loss of around 0.34% relative to baseline in 2050 (AR, AR +Ind RE, CP and CP +Ind REN scenarios) to a gain of 0.33% in the scenarios accounting for an industrial incentive in the NE (AR +Ind NE and CP +Ind NE).

Markedly, the imports trajectory in the CP +Ind NE scenario, imports growth decreased from 2020 to 2034 relative to baseline and started increasing since, maintaining the trend until 2050. On the contrary, in the Alternative +Ind NE scenario, the increase in growth relative to baseline was nearly constant across the period. The constancy indicates that the industrial incentive in the NE causes the retention of goods the region would have exported otherwise and also slightly increases imports to meet the additional demand.

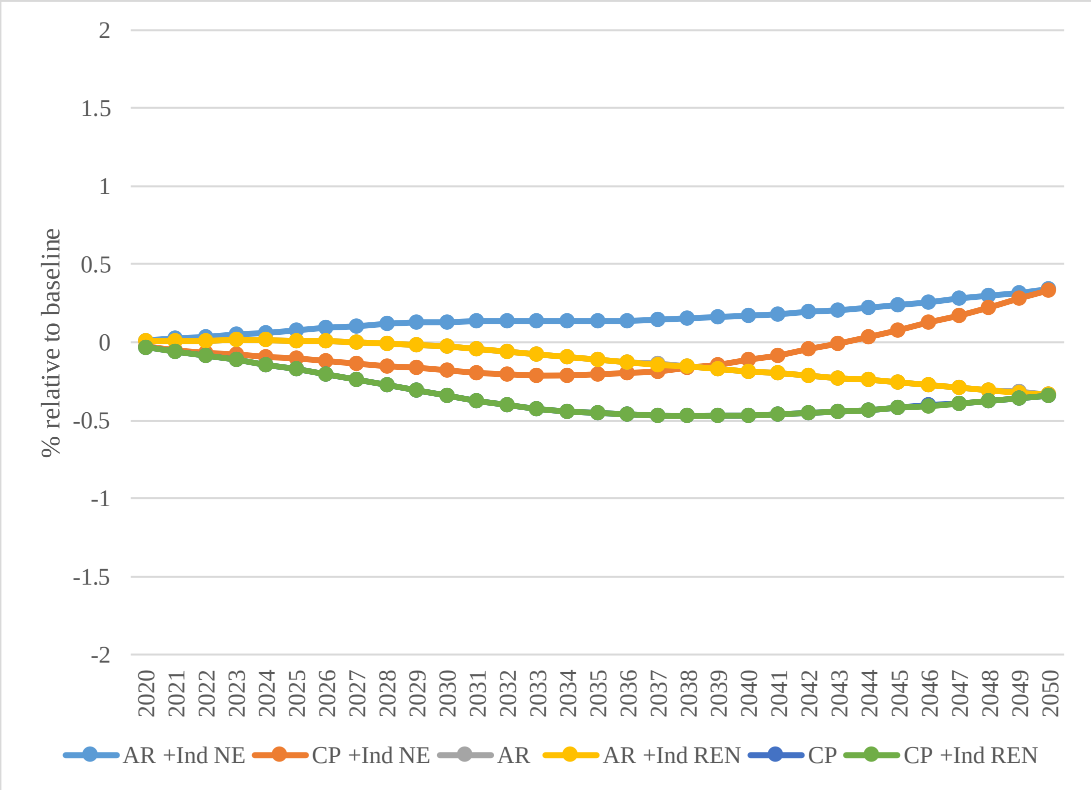


Figure 6.13 National import volume growth relative to baseline per scenario

Regional results provide more insight into the process of creating additional demand in the NE through regional industrial policy. However, it is essential to note that such an industrial policy simulated would be a federal-level regionally targeted policy instead of a policy implemented by state governments. Hence, it would be the central government would control it. Therefore, it would not be possible for other states to create the same incentive and cause the same effects in other regions.

It is clear from Figure 6.14 and Figure 6.15 that the NE region pushes the increase in national imports relative to the baseline observed in the scenarios with industrial incentives in the NE. A 13.39% increase in the AR capacity expansion trajectory and a 12% increase in the CP trajectory relative to baseline when combined with industrial incentives in the NE (NE AR +Ind NE and NE CP +Ind NE).

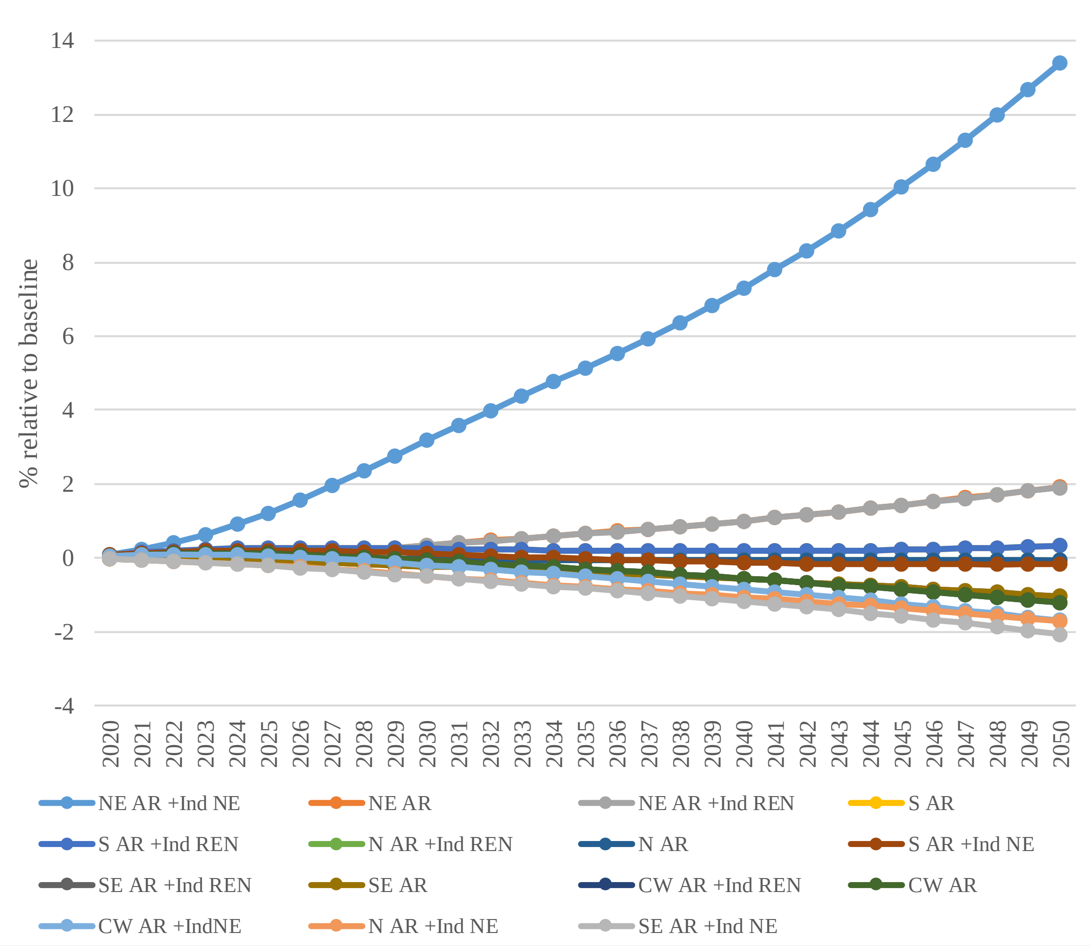


Figure 6.14 Regional import volume growth relative to baseline in AR scenarios

In all three combinations of the AR Capacity expansion trajectory with industrial policy options, the NE increases its import levels relative to the baseline. In the absence of renewables-related additional industrial policy (NE Alternative) and with national renewable-related industrial incentives (AR +Ind REN), imports increase in the NE would be around 1.9% more than the baseline in 2050.

The South region does not experience virtually any impact on imports, with deviations to the baseline varying from -0.18% in the scenario where there is the industrial incentive to the NE (S AR +Ind NE) to 0.32% in the scenario with the national industrial incentive to wind and solar supply chains, in 2050. As expected, the regions which experience mild GDP negative variation also have a slight decrease in imports due to the reduced demand: impacts on the CW and North regions range from 1.2% below the baseline to 1.72% below the baseline in 2050. The SE region, also following its GDP trajectory relative to the baseline, imports less: Between 1.71% and 2.07%

lower than the baseline. The latter refers to the scenario considering industrial incentives in the NE (SE AR +Ind NE). Hence, the SE can absorb more of its production. It is also the scenario where demand decreases the most in the SE.

In the CP capacity expansion scenarios, as observed before, the trend to the NE region in the presence of regional industrial incentives was of meaningful increase. Imports supplying to the South region's consumption slightly increase, with an even higher difference to the baseline than for NE in the CP scenarios with and without industrial policy. Increases relative to the baseline range from 0.54% (S CP +Ind NE) to 1.04% (S CP), pushed by excess economic activity.

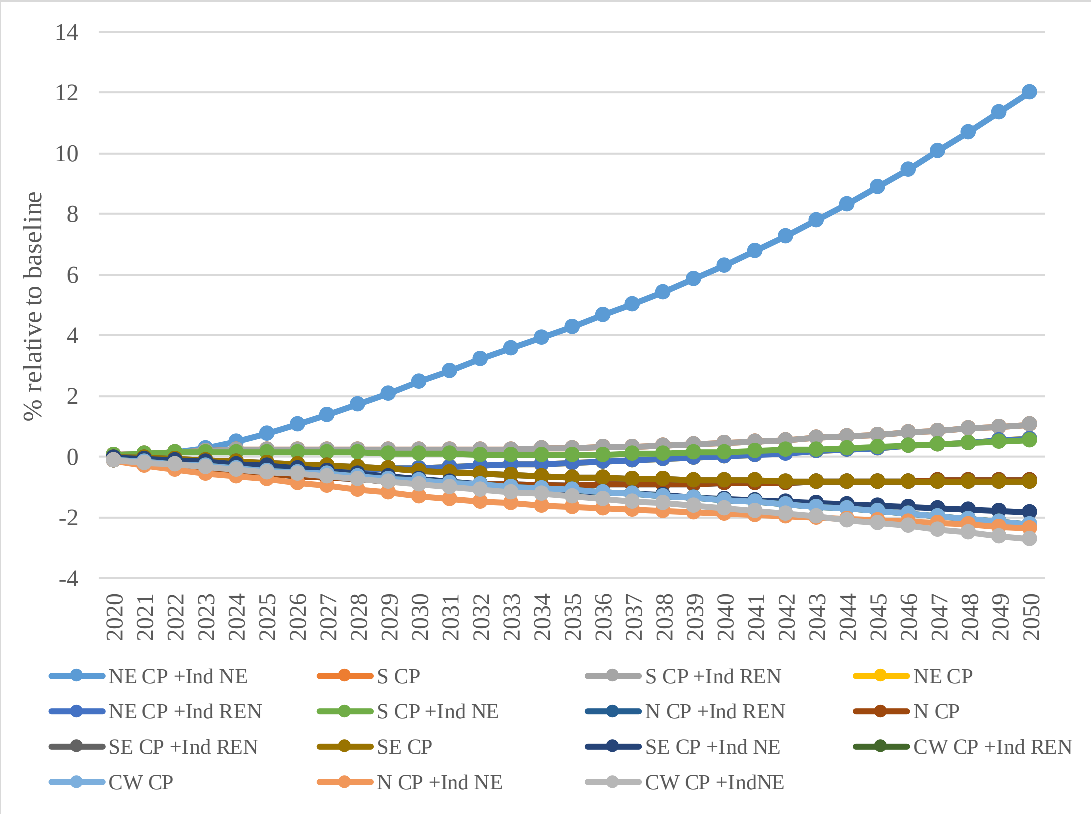


Figure 6.15 Regional import volume growth relative to baseline in CP scenarios

However, the impacts on the other four regions were different, pushed by their results over GDP. Impacts to the CW and North region are clustered at the lower end, ranging between 2.37% and 2.72% below the baseline, which is still of less relevance. Hence, one can conclude that the main implications for imports are indeed those of the NE region.

6.6 Results comparison with the literature

The impacts of increasing ARs capacity expansion on macroeconomic aggregates reported here are aligned with existing literature that has applied CGE models to conduct a similar analysis for EMDEs. For example, academic articles with a similar analysis for China also found similar GDP growth loss to the results presented in this chapter (Dai et al., 2018, 2016).

Chatri et al. (2018) analysed the increase of renewable electricity generation through fossil fuel subsidy removal in Malaysia with a static CGE model with electricity production disaggregated into coal, oil, natural gas and renewables (aggregated). They concluded that national real GDP would decrease slightly from 0.04% when fossil fuel subsidies are reduced by 10% to 0.36% when they are phased out. In addition, employment would decrease by 0.1% in the former case and 0.9% in the latter.

Kat et al. (2018) analysed the economic impacts of achieving Turkey’s NDC energy targets until 2030 with a more similar modelling structure: a recursive-dynamic CGE model with electricity disaggregated into the following technologies: coal, natural gas, hydropower, nuclear, wind, solar and others. They concluded that real GDP would decrease by 0.82% relative to the baseline in 2030.

Chunark et al. (2017) conducted a similar analysis for Thailand, in which they assessed the economic impacts of the NDC emission reduction targets for the electricity sector. They found GDP loss relative to baseline ranging from 0.2% in the scenario with a 20% mitigation target to 3.1% in the scenario with a 40% mitigation target in 2030. Table 6.1 compares studies and impacts on national GDP with the results discussed in this chapter.

Authors	***Year***	***Country***	***Objective***	***Time horizon***	***Cumulative impact on GDP***
Dai et al.	2016	China	Socioeconomic impacts of large-scale development of renewable energy	2050	0.27% loss
Dai et al.	2018	China	Socioeconomic impacts of achieving China's NDC energy targets through ETS	2030	6.47% to 1.2% loss, depending on the design of the ETS
Chatri et al.	2018	Malaysia	Socioeconomic impacts of reducing or removing fossil fuel subsidies	Static - no time horizon	0.04% loss (10% subsidy reduction) to 0.36% loss (phased out)
Kat et al.	2018	Turkey	Socioeconomic impacts of NDC energy targets	2030	0.82% loss
Chunark et al.	2017	Thailand	Socioeconomic impacts of NDC energy targets	2030	0.2% loss (20% mitigation target) and 3.1% loss (40% mitigation target).
This research	2050	Brazil	Socioeconomic impacts of increasing the renewable share of the electricity mix despite hydropower decrease	2050	1.5% to 2% loss

Table 6.1 Result comparison – National impacts on GDP in similar CGE analysis for EMDEs

6.7 Expert elicitation insights on macroeconomic impacts of electricity capacity expansion

It is clear from the modelling results that the regional distribution of electricity capacity expansion matters for the future of regional economies. Modelling simulations suggest that long-term policies aiming to increase non-hydro renewable sources have positive impacts on macroeconomic aggregates in the NE region. Moreover, they boost the economy even more when considering combinations of non-hydro renewable energy and CP with regional industrial incentives for targeted segments. However, experts, particularly those who perform modelling themselves (AC1, ELS1, ELS4, ELS7), agree that modelling results do not necessarily translate into regional development for the NE region. Nevertheless, these results are strong evidence that investing in non-hydro renewables is an opportunity to create regional development alongside electricity system planning.

6.7.1 Uncertainties on the translation of temporary economic acceleration into regional development

Most participants of the expert elicitation agreed that electricity capacity expansion investment of any kind creates temporary acceleration of economic activity, measured by GDP growth[21]. According to some of the experts (ELS4, GOV1, FDI2), the economic acceleration relates to the construction period of power plants rather than the operation period, although the latter is much longer than the former. This is because deployment mobilises the workforce during a period from 2 to 5 years, hence, for a short time (ELS4). It, therefore, creates an economic acceleration which makes a larger difference to the baseline in the smallest and least developed regions.

According to these experts, workers migrate to remote rural locations when enterprises exploit abundant natural resources like hydropower, solar and wind. There are socioeconomic co-benefits of higher consumption in the region where new businesses start, but they do not necessarily endure during the operation phase. However, it is important to notice that, when analysing long-term scenarios, such as the thirty-year time horizon of this thesis, new generation capacity is installed in several years across the period and therefore these cycles are reproduced several times. This suggests that

[21] AC1, GOV1, ELS2, ELS7, DFI1, DFI2, DF3

meeting future demand for electricity can accelerate regional economic activities, even if here is no structural change to these economies that translates into better socioeconomic conditions.

6.7.2 Bottlenecks to regional economic development

Four experts mentioned, for example, the fact that most taxation of electricity capacity expansion is done at the federal level, not by municipalities (DFI2, DF3, GOV1, ELS4). Hence, the new government revenue created by such investment spending goes to the federal government and very little can be done by local governments in terms of policies to retain socioeconomic benefits such as capacity building and local infrastructure.

One of the experts consulted (ELS4) declared to be critical of econometric analysis attempting to link socioeconomic impacts directly to power plant investment spending and electricity generation taxation. The fault they identified is in the tax distortion of the Tax on the Circulation of Goods and Services (ICMS) and the Industrialized Product Tax (IPI). Both of them are collected at the state level, however, they tend not to be channelled to regional development in the NE either.

The Industrialized Product Tax (IPI), in contrast, is collected at the state where electricity is generated, but it is a federal tax and, according to the expert (ELS4), there is no transparency in accountancy. The IPI is a federal tax over power plant deployment government needs to hold an account to states and municipalities. However, communities do not know how much of the IPI turns into resources to the municipality or how it returns to the community.

6.7.2.1 The income effect and the role of hydropower to the system

Experts have argued that sustained investment in renewable energy brings regional development through the income effect (ELS6, DFI1). That is, the economic acceleration caused by the new demand created by new jobs and wage spending. They draw on the experience and studies conducted for hydropower, since it is the most mature technology in the Brazilian energy mix, with a long history of projects mobilising substantial investment and accompanying socioeconomic studies. So, one expert (DFI1) gave the example of the of a large hydropower complex in the Amazon region called Santo Antonio and Jirau, which employs 40 thousand people, and the new demand created by the income of these workers incentivises the local economy.

Nevertheless, the intended economic dynamization happens on a trial-and-error basis. According to the same expert consulted (DFI1), there is not exactly a learning curve for promoting this process. Each case does not usually consider lessons from previous cases when trying to maximise gains to the particular territory emerging from such electricity investment.

Despite using the examples from hydropower, experts did not draw attention to the relative economic losses to the North region of climate and renewable policies focusing on solar and wind power. In the modelling simulation results presented previously, the North region experiences losses under CP and AR policies relative to the baseline. The latter is the scenario with the most significant hydropower capacity expansion, which would bring investments to the North. Four of the experts serving in the electricity sector operation were concerned that CP scenarios normally neglect important characteristics of variable renewables, meaning that wind and solar are variable sources and therefore do not provide the flexibility to the system that thermal power plants do (ELS1, ELS2, ELS3, ELS5).

Five of experts from this group suggested that hydropower has been demonised in Brazil, yet it is fundamental to the system due to its flexibility that allows it to play the role of storage (ELS1, ELS2, ELS3, ELS5, ELS7). Hydropower is also dispatched before thermal power in the system optimisation process because it is cheaper. They indicated that we should look at hydropower more carefully, with smarter projects including the reversible hydropower technology, considering recent rainfall changes and the impacts of reduced water availability over electricity generation. Additionally, most of them indicated that electricity capacity expansion should explore all regional vocations and potentialities, including fossil fuelled sources and not necessarily prioritising the NE.

6.7.2.2 The economic case for wind and solar power in the NE

The case of wind power in the NE is seen by these experts as a successful case for economic benefits due to its very large scale. Investment spending in electricity capacity is following a natural logic that channels them to wind and solar PV in the NE now and in the future, according to one of the experts who acts in an electricity company (ELS7). They raised that processes like these should be followed by initiatives to promote capacity building, supply chain development and retain some job creation benefits.

In the NE, several wind farms close to each other have formed clusters of investors who hold three or four farms in the same jurisdiction according to an expert consulted (GOV1). This creates synergies in the local economy when different investors join efforts to explore the local vocations. Hence, positive results to the NE economy can potentially mean long-term regional development, and the objective to maintain the renewable profile of the Brazilian electricity mix can arguably be coupled with a regional development objective. However, to date, we cannot assess whether the investment spending in electricity capacity expansion will create socioeconomic development or structural change in regional economies. Whether it will propel socioeconomic development or not depends on accompanying public policies and private strategies. Strategic choices can potentialise regional socioeconomic development, according to an expert consulted.

Regional development in the NE reinforces the objective from the federal constitution, as indicated by an expert (DFI2), given that the 1988 Brazilian constitution created a specific fund for this process. But more coordination between ministries and government agencies and institutions is needed in formulating public policies to integrate this objective with energy planning. It is important to notice however that, although there is a constitutional mandate to incentivise the NE economy and attempt to close the regional development gap, this could entice political discontent from other regions.

6.7.2.3 Regional trade-offs and new technological opportunities

There are clear trade-offs, evidenced by the modelling results. In order to incentivise the least developed regions, the most industrialised regions would lose relatively to business as usual in the long run. Solar power is seen, according to some of the experts, as more beneficial to the SE region than wind power given that there is very high solar irradiation in the northern part of Minas Gerais state, and the rooftop potential is the largest in the SE, where most of the population is concentrated (AC1, GOV1, ELS1, ELS7). Since most of the load is in the SE, consequently solar power investment becomes attractive in the SE. This is reflected in the baseline and the CP scenarios, in which most of solar power is installed in the SE, near most electricity consumption which therefore reduces the need for transmission line expansion in the optimisation problem.

One expert (DFI2) indicated a substantial bottleneck to the NE electricity generation potential, which is the expansion of transmission lines to connect the NE and the SE. According to them, while in some areas of the NE, there are no transmission lines, in the state of Ceará there is a vast semiarid area which is improper for agriculture or livestock, where transmission lines should be built. These new transmission lines would allow variable renewable electricity to be transmitted to the other regions, particularly while it cannot be stored in batteries or other forms of storage.

Finally, as discussed in Chapter 3, the development of a national supply chain of renewable power plants, manufacturing plant components nationally, was pointed out as crucial to promote development by all experts. This would avoid reproducing previous patterns of technological dependence from advanced economies. From modelling results, it is visible that a national industrial incentive only to those industrial goods supplied to wind and solar power plants have a very small positive impact on the economy in the long term. However, sectoral incentives in the NE indicate more structural changes.

6.8 Discussion

The experts consulted have indicated that positive modelling results obtained in this research as clearly useful to inform policymakers of the potential co-benefits and trade-off of the electricity sector transition. However, the aim to seize renewable electricity capacity expansion investment to pursue regional development requires coordination across multiple jurisdictional levels, government departments and agencies to combine multiple objectives. Additionally, achieving climate goals as such may demand that institutions originally created for other purposes incorporate climate responsibility or climate-related objectives (Hochstetler, 2021).

The main objectives involved are securing electricity supply, environmental protection, regional socioeconomic development and industrial development. Experts have raised, however, that multi-level policymaking is a significant barrier in Brazil, considering the different coordination challenges between ministries, local governments and federal agencies. For example, multi-level governance has also been the main hurdle for developing the Amazon region while deploying hydropower (Athayde et al., 2019; Doria et al., 2018).

However, renewable energy in the NE does not pose the same challenges as the Amazon region regarding potential environmental degradation and loss of environmental services due to the differences in technological potentials, geographical characteristics, and economic structures between the two regions. As discussed in Chapter 2 (Section 2.2), the potential for electricity capacity expansion in the North region is for hydropower. Large hydropower projects may displace indigenous communities from their traditional land by flooding extensive areas as well as causing biodiversity loss in the Amazon biome, which is different form the dry predominant biome of the NE, Caatinga (semiarid tropical savannah). The greatest technological potential in the NE, in contrast, is for solar and wind power generation. Moreover, the two regions have different climates, equatorial humid and semiarid climate respectively in the North and NE regions, which have contributed to shaping their different economic formations and current economic activities in place (Chapter 3).

Hence, discussing what development means to the different groups involved is necessary. Policymakers and the civil society should discuss whether development means purely increased capital stock and GDP growth, the growth of the set of macroeconomic aggregates analysed here, or variations in other indicators of sustained improvement in the living standards of communities. Renewable electricity capacity expansion will probably increase the NE region's GDP. However, we cannot expect the economic profile and structure of the NE region to change until 2050 purely by receiving renewable electricity investment.

Socioeconomic development and structural economic change are not natural consequences of the investment in renewables, as discussed in Section 3.3. Long-term optimisation of the electricity system in models used for planning does not include economic development in the objective function, and this aspect should be improved. At present, socioeconomic co-benefits are more a consequence than an energy policy objective. The centralised power system (SIN) seizes the potentialities of each of the regions regardless of regional development objectives. Therefore, we can influence energy planning from the perspective of socioeconomic benefits considering that the electricity sector institutions already address energy security and environmental benefits but not socioeconomic development.

6.8.1 Industrial development and structural economic changes

The centralised nature of the taxation of power plant deployment mentioned before allowed a modelling simulation of regional industrial policy, given that in TERM models, we use the simplifying assumption that taxation is also centralised. Federal taxation allows the central government to incentivise specific regions, such as the NE, without creating an effect through which other regions would implement the same incentive and neutralise relative benefits to the NE.

Development banks have had the opportunity to keep track of the different cases of infrastructure projects entirely or partly funded to understand the governance challenges and work with utility concessionaires and civil society to maximise socioeconomic benefits. It has been central for BNDES' policies to promote socioeconomic co-benefits of energy investment, even before the wind and solar power deployment started in Brazil, by trying to ensure economic dynamization around hydropower plants (Schaeffer et al., 2010). Efforts aim to promote socioeconomic development transversally across the regions, but ideally focusing on the potentialities of the NE and North regions since they are the two least developed. Wind farms are currently and projected to remain over 90% installed in the NE region (EPE, 2020a, 2020b). Manufacturing industries producing wind plant components are also moving to the NE, as discussed in Section 3.2.

6.9 Chapter 6 conclusions

Chapter 6 focused on the most reported results of CGE modelling: the impacts on macroeconomic aggregates. Hence, this chapter reported the impacts of the electricity capacity expansion scenarios, and the additional industrial policy scenarios, on Real GDP, real investment, aggregate employment, export volume and import volume from 2020 to 2050. The results reported in this chapter respond directly to the first underlying research questions presented in Section 1.1.

Results on real GDP variation relative to the baseline have shown that electricity capacity expansion leading to a low-emission mix in 2050, combined or not with industrial incentive options, do not corroborate the views that climate and renewable energy policies may cause significant GDP loss in the long term. However, macroeconomic impacts are not uniform across Brazilian regions, and the least developed region, the NE, experiences the most positive socioeconomic impacts of long-term policies aiming to increase non-hydro renewable sources in the electricity mix, while meeting the increased national demand for energy.

However, arguably, and according to all participants of the expert elicitation, turning the electricity capacity expansion investment spending into development depends on the development of the manufacturing segments of renewable plants' supply chain, which therefore justifies support to these sectors in the form of national or region tax incentives. The impacts of adding incentives to manufacturing sectors to renewable energy policy respond to the underlying research question (ii) of this thesis. Hence such modelling results and the discussion of sectoral impacts are the subject of Chapter 7.

7. INDUSTRIAL AND SECTORAL IMPACTS OF ELECTRICITY CAPACITY EXPANSION SCENARIOS

The analysis of socioeconomic impacts of electricity capacity expansion investment must consider not only the macroeconomic aggregates, or the direct impacts, but also impacts along the supply chains of power plants, and their components' supply chains in turn. This chapter explores the results of the latter, responding to the research question (ii) posed in Section 1.1.

The focus of the industrial incentive simulations were the following industrial segments of the CGE model (as described in Chapter 5): (i) Metallurgy, which produces steel structures (ii) Electronics, which manufactures various critical components such as inverters and semiconductors, and (iii) Machinery and Equipment, with the producers of motors, wind blades, components of the nacelle and solar PV silicon cells. These were therefore the industrial segments to which industrial incentives were simulated as shocks in the CGE modelling. The two industrial policy options considered were: (i) a 1% national incentive to nationally produced goods produced by these three sectors specifically demanded by the wind and solar PV electricity generation sectors and (ii) a 1% incentive to the three segments in the NE region only.

This chapter presents the sectoral impacts to industrial segments including the three sectors incentivised, as well as wood and cellulose and chemicals. The last two sectors were not incentivised in the modelling, and to a lesser extent participate in power plants supply chains. Hence, by presenting results to these five industrial segments, it is possible to compare the impacts over those segments which were incentivised and those which were not incentivised in the simulations.

Experts consulted in the expert elicitation of this research were notably emphatic with regards to the importance of sectoral incentives and industrial policy in order to propel the socioeconomic and development co-benefits of renewable energy investment. Thus, this chapter will provide insights from modelling simulations to the extent to which the different electricity capacity expansion mixes from 2020 to 2050 with and without the national or regional incentives to power plants' supply chain create co-benefits in other economic sectors.

In Section 7.1, the impacts of the six electricity capacity expansion trajectory combinations with industrial incentive scenarios will be presented over five indicators, namely: output by industrial sector (Section 7.1.1) , industrial real investment (Section 7.1.2), aggregate industrial employment (Section 7.1.3), sectoral exports and imports (Sections 7.1.4 and 7.1.5 respectively).

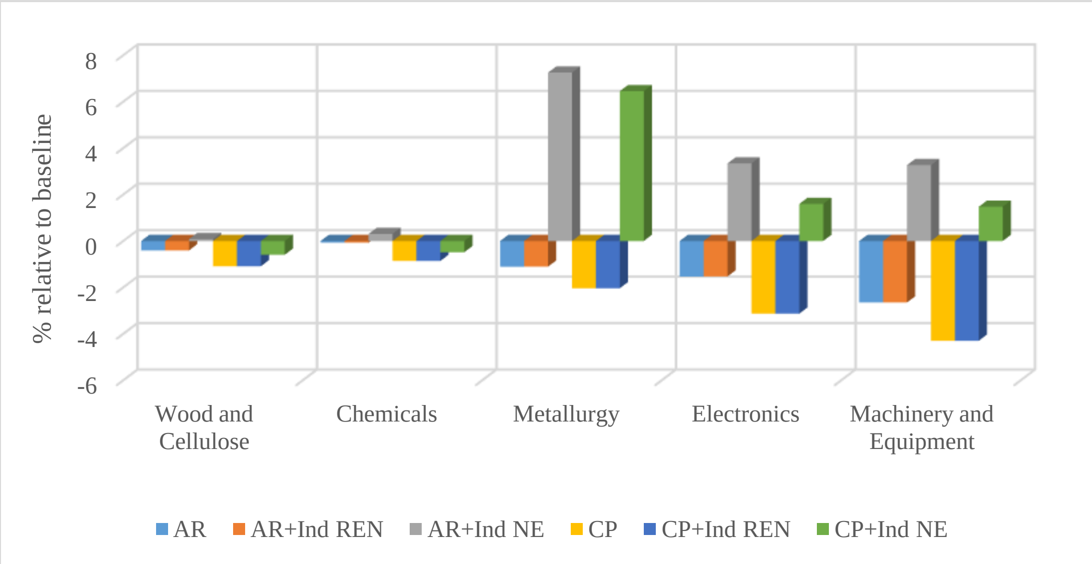
Section 7.2 focuses on the employment impacts in electricity generation sources as such. As discussed in Chapters 4 and 5, the investment variation of the electricity sectors is exogenous to the model and therefore implemented as shocks. The production of the electricity sectors (generation) follows the same trends; however, generation results are more accurate in energy-system models. Since the scenarios were obtained through the energy-system modelling frameworks shown in Chapter 5, this chapter presents the relevant results endogenous to the CGE model for the electricity sector, that is, aggregate employment.

Section 7.3 explores the points raised by experts consulted in the expert elicitation process on the need for industrial strategies to create a renewable power plant supply chain in Brazil to maximise the co-benefits of the energy transition in the electricity system. The four themes which were identified in the expert elicitation on the need for industrial strategies outlined in Section 4.7.3 are discussed. Then, Section 7.4 discusses the combination of industrial and sectoral impacts from modelling results with the expert elicitation insights. Finally, Section 7.5 concludes Chapter 7.

7.1 Manufacturing industries

7.1.1 Industrial output

On the national level, it is visible that manufactured goods production is negatively impacted relatively to the baseline by the AR and the CP capacity expansion pathways, unless there is targeted regional industrial incentive in the NE. The national incentive specific to wind and solar components (Ind REN) does not cause a notable reduction in negative impacts, as seen on Chapter 6.



Clearly, the industrial incentive to the selected sectors in the NE (Ind NE) has a much larger impact on industrial output than the national incentive to solar and wind components (Ind REN).

Sectors targeted (Metallurgy, Electronics and Machinery and Equipment) clearly benefit from the NE regional industrial policy even at the national level. Relevant positive impacts are observed for the incentivised sectors, only when there is an incentive in the NE region (Figure 7.1). National output in Metallurgy production capacity would be 7.25% higher than the baseline in the AR trajectory (AR +Ind NE) and 6.45% in the CP capacity expansion trajectory (CP +Ind NE). The analogous results for Electronics would be 3.34% above the baseline in the Alternative +Ind NE scenario, and 1.6% in the CP +Ind NE scenario. For Machinery and Equipment, results would be 3.27% and 1.48% above the baseline respectively. Again, the national incentive only to those goods produced by these sectors that are used by solar and wind power plants (Ind REN) does not create a substantive difference to the case without any industrial incentive.

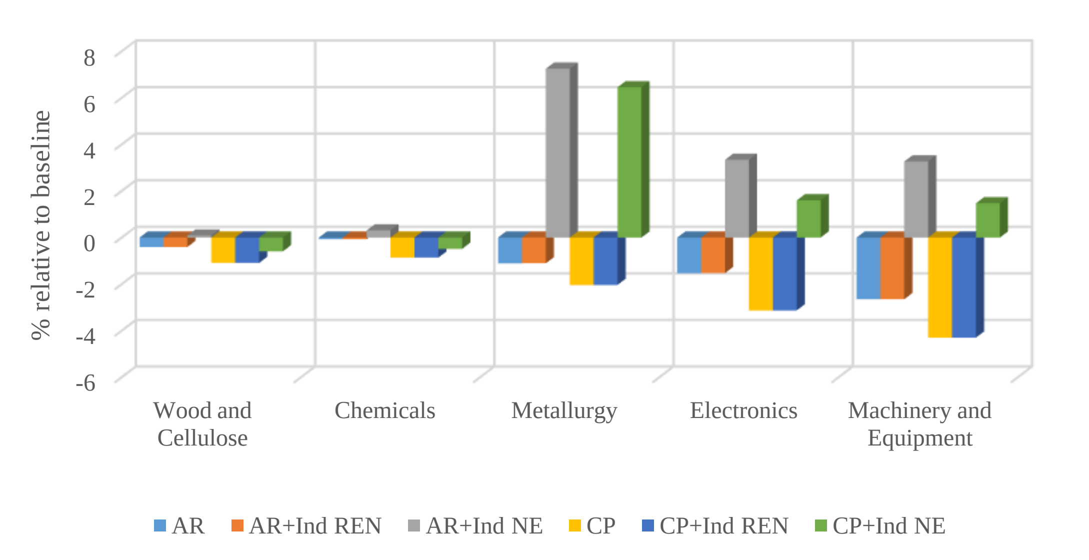


Figure 7.1 National total output of industrial sectors per scenario – cumulative variation relative to baseline

The regional disaggregation of industrial output results shows that positive impacts occur in the NE region, while negative variations to the baseline are dwarfed regionally (Figure 7.2). Noticeably, the 1% tax incentive to Metallurgy, Electronics and Machinery and Equipment in the NE creates an output increase between 124.89% (Machinery and Equipment) and 190.28% (Metallurgy) relative to baseline in the CP +Ind NE scenario.

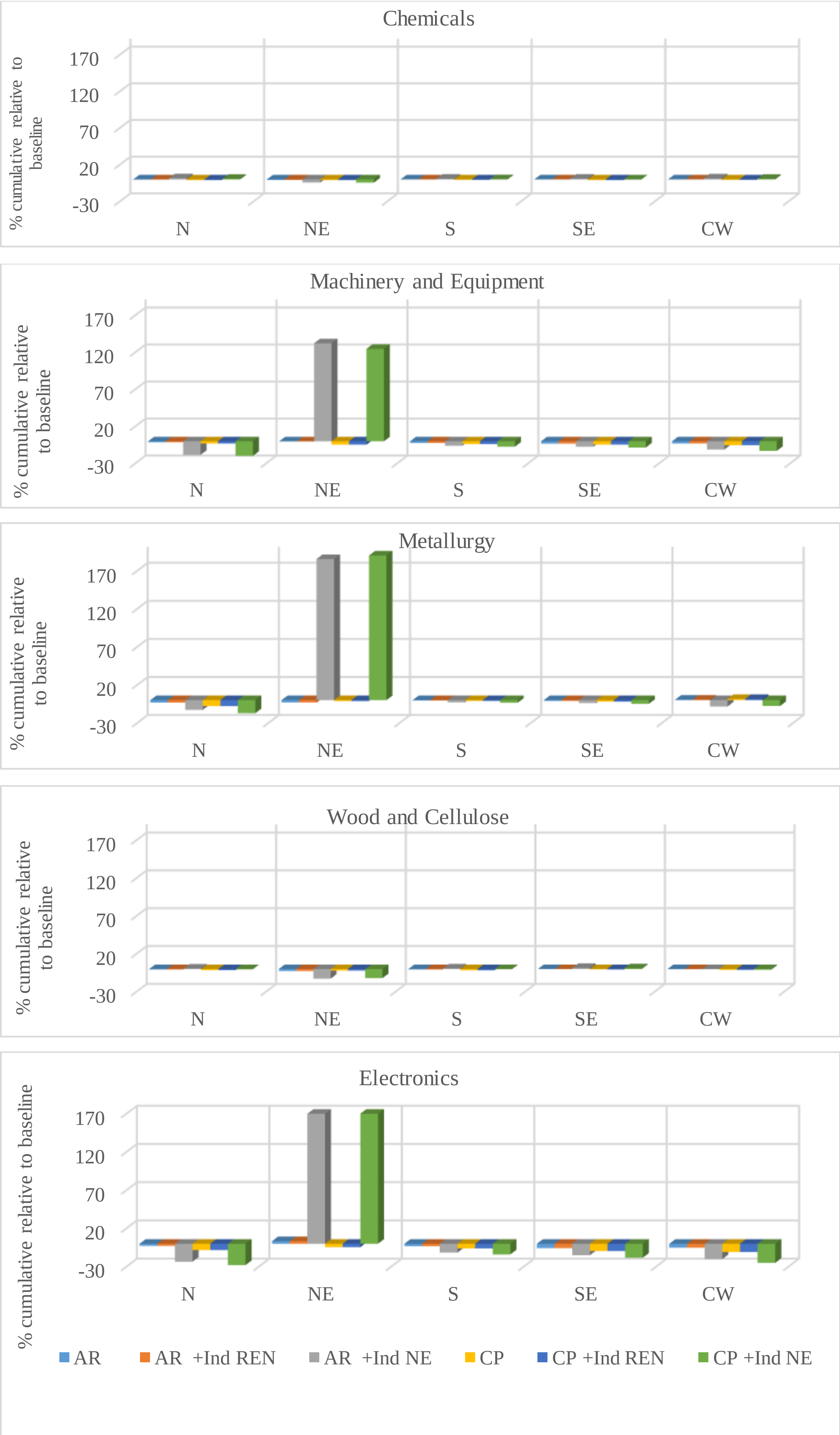


Figure 7.2 Regional total output of industrial sectors per scenario – cumulative variation relative to baseline

Meaningful negative impacts are usually compensatory impacts to gains in other sectors or regions. The North region, for example, would experience decreases in the output of industrial segments incentivised in the NE. In the North, Metallurgy output is 12.69% lower than the baseline, Machinery and Equipment output 18.37%, and Electronics output 23.49% lower than the baseline in 2050 in the AR capacity expansion trajectory with regional industrial incentives in the NE (N AR +Ind NE). In the CP scenarios, the North region has a decrease of 27.90% in Electronics output, 19.68% in Machinery and Equipment output and 17.18% in Metallurgy relative to the baseline in 2050 when there is an industrial incentive in the NE (N CP +Ind NE).

The CW region has similar variations to the North in these sectors and scenarios, showing mild counterbalance effects of incentivising industrial segments in the NE. However, it is important to notice that absolute economic impacts of reducing output in these regions is not so relevant, because, as explained in Chapter 3, these regional economies are hardly industrialised.

Sectoral impacts experienced by the South and SE regions in the simulation of an industrial incentive in the NE are more meaningful in terms of national economic impacts. In the AR capacity expansion pathway (AR +Ind NE), Machinery and Equipment output growth is negatively impacted by 7.26% in the SE and 6.01% in the South, Metallurgy 3.83% in the SE and 2.00% in the South and Electronics 14.95% in the SE and 11.52% in the South relative to baseline in 2050. In the CP trajectory, Machinery and Equipment output is lower than the baseline 8.39% in the SE and 7.35% in the South, Metallurgy 4.89% in the SE and 3.35% in the South and Electronics 18.24% in the SE and 14.01% in the South cumulatively in 2050.

Lastly, sectors which were not incentivised suffer a reduction of output growth relative to the baseline in 2050 in the NE: in the AR capacity expansion trajectory (AR +Ind NE), Wood and Cellulose manufactured products output decreases by 12.70% and Chemicals by 4.05% in the NE relative to the baseline. In the CP trajectory (CP +Ind NE), Wood and Cellulose manufactured products output decreases relative to the baseline by 12.06% and Chemicals' output by 4.33%.

7.1.2 Industrial investment

Sectoral investment in in manufacturing industries are lower than the baseline, unless when we simulate an incentive to segments in the NE region, even in the national aggregation of results (Figure 7.3). Even the Wood and Cellulose and the Chemical products sectors would experience slight increases relative to the baseline when the incentive in the NE is combined with the AR capacity expansion trajectory (AR +Ind NE).

In the CP scenario without industrial incentives, negative impacts relative to the baseline reach 6.26% on Metallurgy investment, 8.25% on Electronics investment and -9.72% on Machinery and Equipment. As mentioned, national incentives to wind and solar component production have negligible effects in reducing the negative variation: 6.25%, 8.24 and 9.72% below the baseline respectively (changes to the third decimal place).

However, in the presence of the regional incentive to these three targeted sectors in the NE, impacts are positive. In the AR pathway with such policy, Metallurgy investment grows 7.25% above the baseline, Electronics investment 3.34% and Machinery and Equipment 3.27% above the baseline level in 2050.

The two industrial sectors which were not incentivised, manufacturing of wood and cellulose products and chemicals, also experience decreases relative to baseline growth in almost all scenarios. Again, the CP capacity expansion creates the most negative impacts: investment 4.53% below the baseline cumulatively in 2050 for Wood and Cellulose, and 4.04% below the baseline for Chemicals, in the absence of industrial policy. The only scenario in which these two sectors experience some positive impact is the AR with industrial incentives in the NE (AR +Ind NE) but still very near zero.

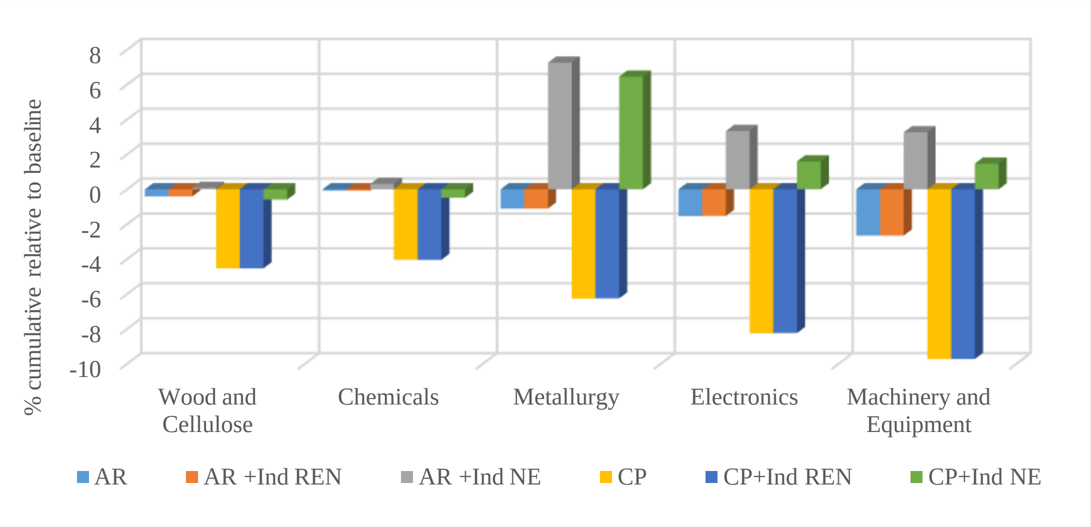


Figure 7.3 National real investment of industrial sectors per scenario – cumulative variation relative to baseline

Regional results show that renewable energy investment alone is not enough to increase substantially investment in increasing manufacturing productive capacity in the NE without additional incentives. The importance of using a dynamic-recursive CGE model in this kind of analysis is to account for the net impacts. That is, understand the multi-sectoral interactions to measure the final impacts, accounting for economy-wide feedback mechanisms.

From Figure 7.4, it is noticeable that net investment impacts on manufacturing sectors in the NE region are slightly negative in the absence of regional industrial incentive. However, impacts for the NE region are the highest among all variables analysed here when such incentive is in place: Metallurgy productive capacity growth would increase 366.99% above the baseline in the AR capacity expansion trajectory (AR +Ind NE) and 364.86% in the CP capacity expansion pathway (CP +Ind REN).

The other two incentivised sectors would also experience very high positive variations to the baseline: Machinery and Equipment productive capacity growth would be 264.24% larger than the baseline in the AR capacity expansion trajectory (AR +Ind NE) and 241.68% in the CP capacity expansion pathway (CP +Ind REN). Productive capacity in the Electronics segment would grow 298.53% above the baseline in the AR capacity expansion trajectory (AR +Ind NE) and 274.13% in the CP capacity expansion pathway (CP +Ind REN).

It is important to notice, though, that such very high growth rates reflect that in the model's base year, 2015, existing productive capacity of these sector were incipient. Hence, in order to produce enough goods to meet the new demand created by the incentive, the minimum production capacity is several times higher than otherwise.

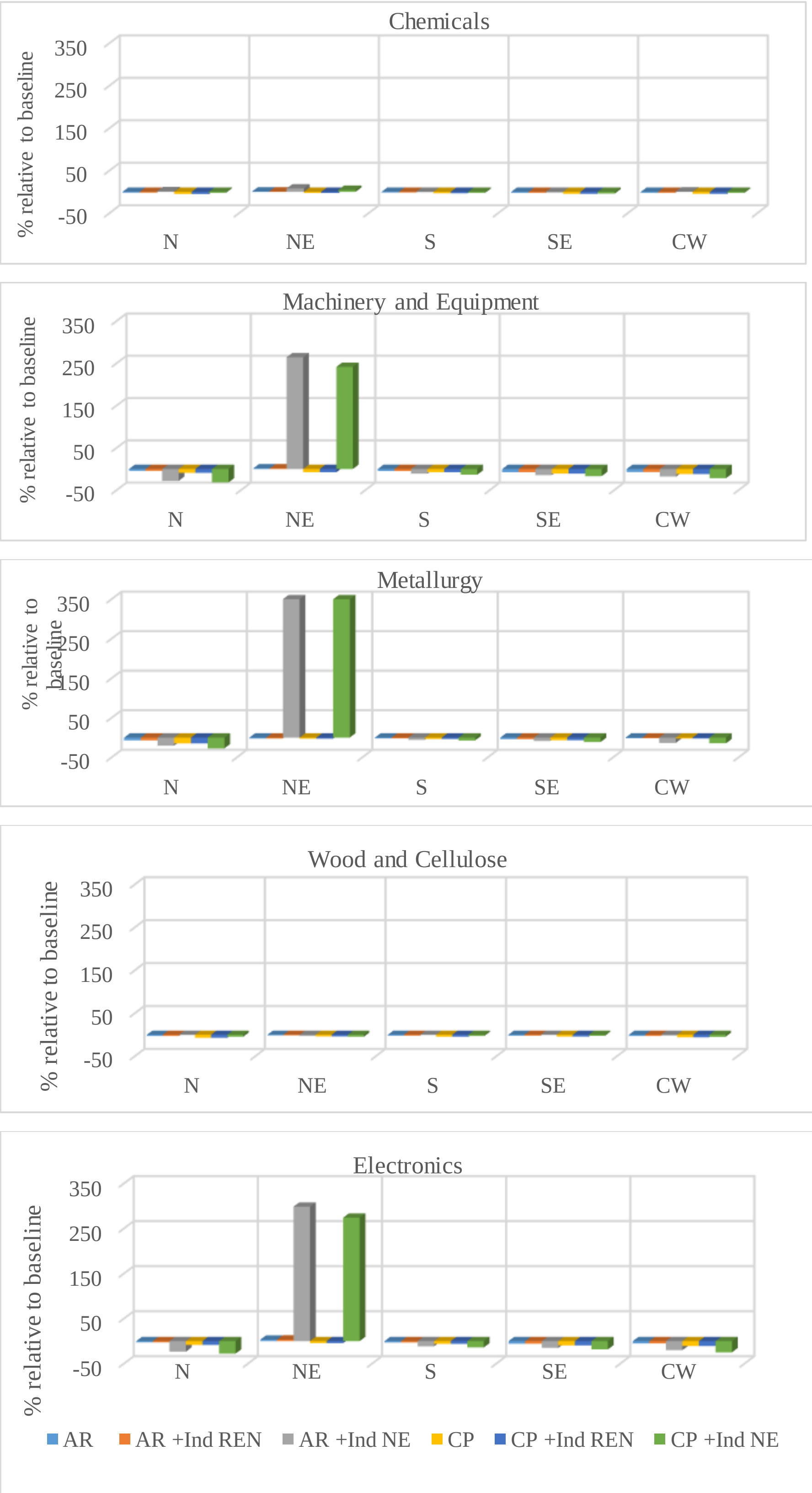


Figure 7.4 Regional real investment of industrial sectors per scenario – cumulative variation relative to baseline

As expected, there would be negative impacts on industrial segments in other regions, although in the case of investment, impacts on sectors not incentivised are negligible. Relevant negative impacts would occur over investment growth in the Electronics segment productive capacity in the South (11.52% in AR +Ind NE and 14.01% in the CP +Ind NE scenario) and SE region (14.95% and 18.24% below the baseline respectively). Similar negative impacts would be observed for Machinery and equipment investment growth: in the South, 10.88% in AR +Ind NE and 13.40% below the baseline in the CP +Ind NE scenario. In the SE region, negative impacts over investment growth would be 14.31% and 16.98% below the baseline respectively. This partly explains why in the national level, investment in these two sectors is not as larger than the baseline in 2050 as in Metallurgy.

7.1.3 Industrial aggregate employment

Job creation in manufacturing segments is also seen by many experts (including those who participated in this research expert elicitation) as a very important part of regional socioeconomic effects of electricity capacity expansion investment. Figure 7.5 shows employment growth deviation to the baseline cumulatively until 2050 at the national level. Clearly, the largest national impacts on employment would result from incentivising the Metallurgy sector in the NE, in which impacts would 8.70% and 8.66% above the baseline for the AR and the CP capacity expansion pathways respectively.

Impacts on the Electronics and Machinery and Equipment sectors are positive, but to a lower level: in the Electronics sector, employment growth would be 3.14% larger than the baseline level in 2050 in the AR capacity expansion case with industrial incentive in the NE (AR +Ind NE) and 1.74% in the similar case following the CP electricity capacity expansion (CP +Ind NE).

The largest losses relative to baseline in the national level are observed in the Machinery and Equipment sector in the CP capacity expansion scenario without industrial incentive (3.78% lower than baseline in 2050), and with the national incentive targeted only to wind and solar component manufacturing (also 3.78% lower than the baseline). Non-incentivised sectors, at the national level, experience negligible effects.

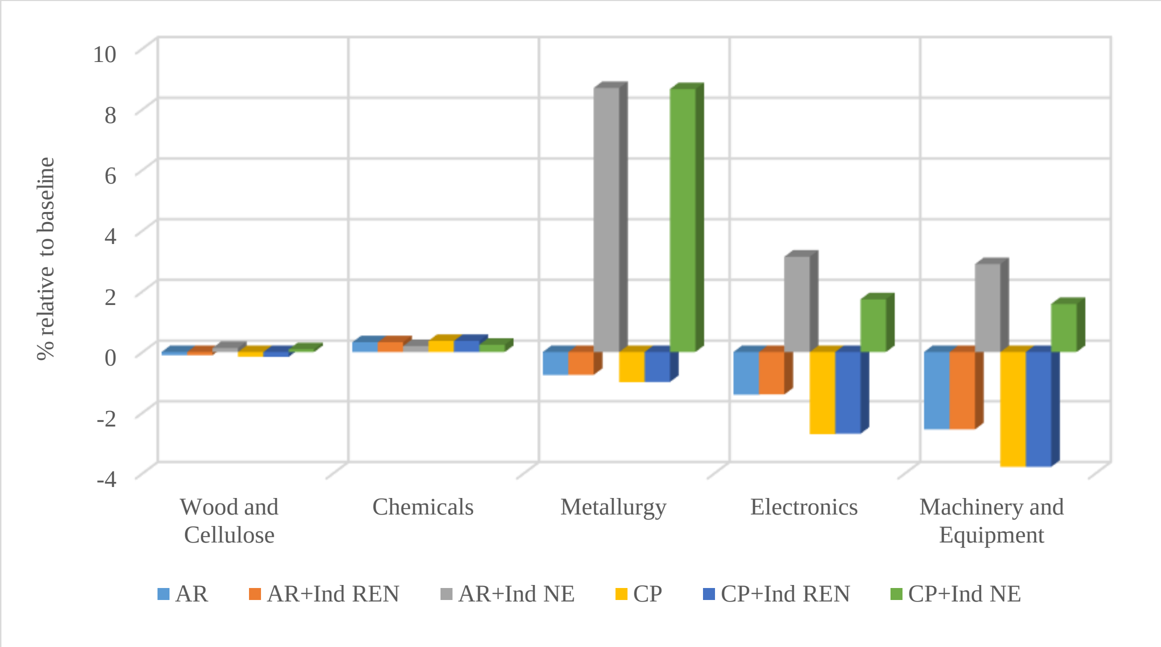


Figure 7.5 National employment of industrial sectors per scenario – cumulative variation relative to baseline

At the regional level, as expected, national results translate into very high positive employment growth impacts for the NE (Figure 7.6). This occurs particularly in the Metallurgy sector, in the AR scenario combined with regional industrial policy (AR +Ind NE). In this case, cumulative employment growth in this scenario in the NE is 180.30% larger than the baseline until 2050. In the CP capacity expansion pathway with the same incentive (CP +Ind NE), employment growth in the Metallurgy sector would not be as high, but still much higher than the baseline, at 122.22%.

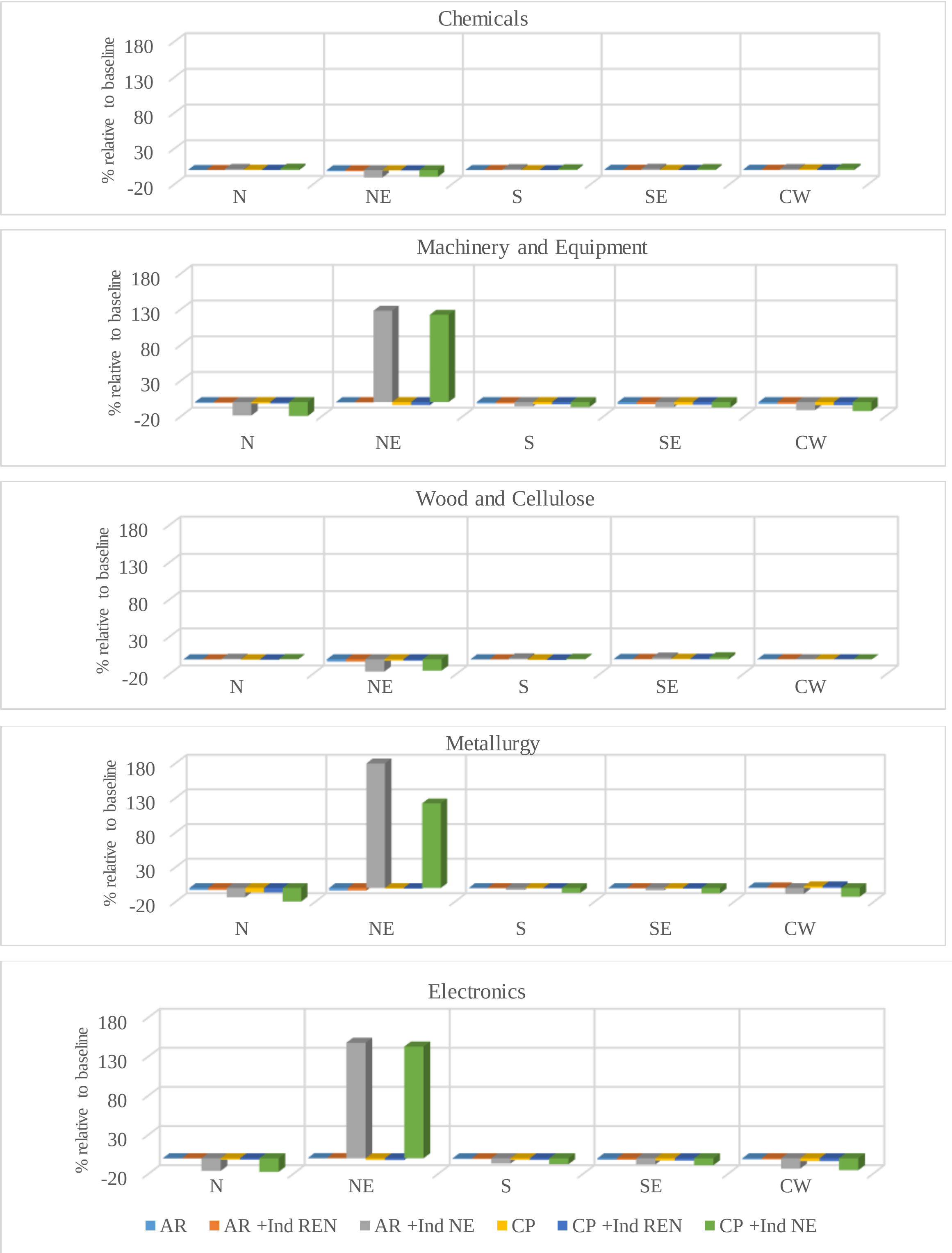


Figure 7.6 Regional employment of industrial sectors per scenario – cumulative variation relative to baseline

The other two incentivised sectors in the NE region, Electronics and Machinery and Equipment, would also benefit from high employment growth in the scenarios including regional industrial policy. The Electronics sector would experience an impact of 147.46% above the baseline in the AR capacity expansion pathway with the regional incentive (AR +Ind NE), and 142.84% in the CP capacity expansion with the same incentive (CP +Ind NE). The Machinery and Equipment sector, in turn, would experience an impact of 127.93% above the baseline in the AR capacity expansion pathway with the regional incentive (AR +Ind NE), and 122.22% in the CP capacity expansion with this same industrial policy (CP +Ind NE).

Negative impacts counterbalance to some extent such increase in the NE in the presence of a regional industrial incentive. At last, negative impacts on the non-incentivised industrial segments in the NE reduces the regional positive impacts overall: employment growth would be between 9.50% and 10.43% less than baseline levels in the Chemicals manufacturing sector and between 15.17% and 16.47% lower than the baseline in 2050 in the Wood ad Cellulose products sector.

The North region would face negative impacts relative to the baseline between 13% and 19% in sectors that are incentivised in the NE, in such scenarios. The North region, as aforementioned, is also a region that raises concerns in terms of socioeconomic development. However, such sectors are not relevant to the region's economy and therefore such impacts are small in absolute terms. The same is true for the CW region.

The South and SE region face reductions relative to the baseline between 6% and 7% in Metallurgy, Electronic and Machinery and Equipment, in the cases when they are, in fact, incentivised in the NE only (AR +Ind NE and CP +Ind NE). The exception is Metallurgy in the Alternative +Ind NE scenario, which impacts would be 2.64% below the baseline in 2050 for the South region and 3.31% for the SE region respectively. These negative impacts can represent more important employment losses than in the North and CW, since the SE has the largest share of national population and is the most industrialised region. Hence, a 6% to 8% negative impact in the SE could potentially cause political discontent.

7.1.4 Industrial exports

Exports are seen as a relevant indicator of macroeconomic impacts, as mentioned in Section 6.4. However, exports from manufacturing sectors are even more interesting due to their much higher added value than the goods Brazil traditionally exports: agricultural and livestock commodities.

Export variations of industrial sectors show insightful trends (Figure 7.7): the highest positive impacts observed are in Metallurgy, for scenarios in which this industrial segment is incentivised in the NE (13.09% above the baseline in the Alternative +Ind NE scenario and 10.52% above the baseline in the CP +Ind NE scenario). However, Metallurgy faces a negative impact on its exports in all other scenarios. This, counterintuitively, could be caused by a higher national demand for these goods, which reduces supply for the external demand, if the trade terms are constant.

However, when looking at the other two incentivised industrial segments, we see that they increase their exports in all cases, even if the highest rates occur when they are incentivised in the NE region (+ Ind NE cases).

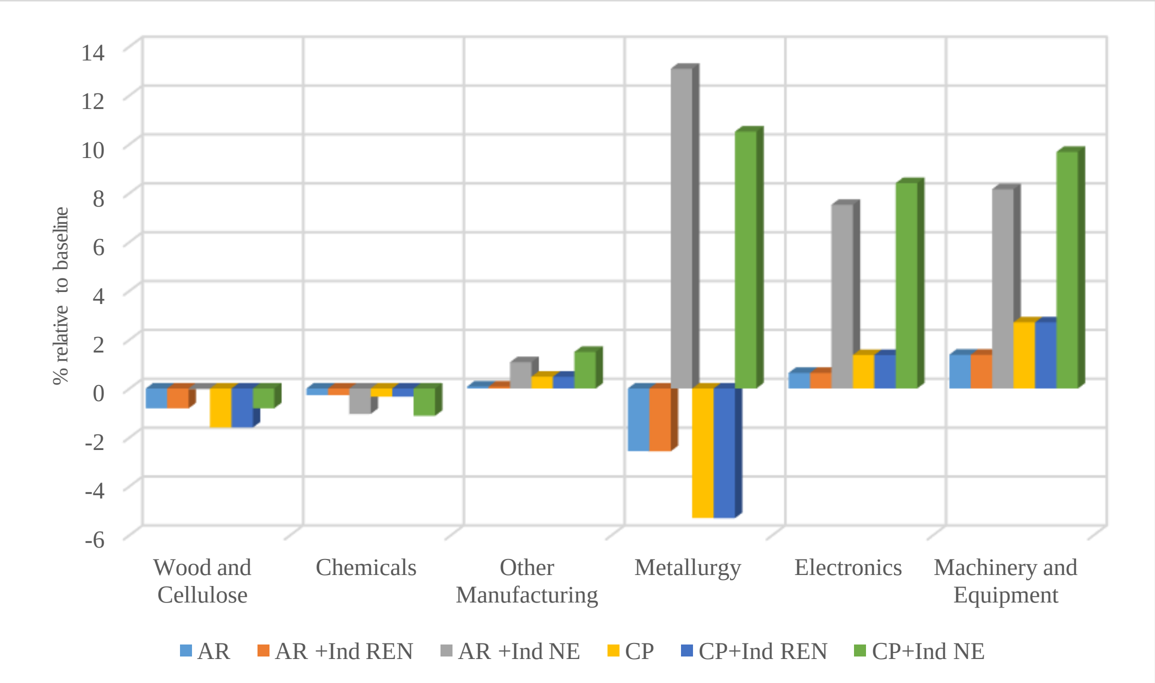


Figure 7.7 National export volumes of industrial sectors per scenario – cumulative variation relative to baseline

While total exports decrease in the NE in the presence of a regional industrial incentive (as seen in Section 6.4), the incentivised sectors' exports increase substantially. This shows the notable impact that a 1% tax incentive can have on attracting production of high added value goods to a region, at least in theoretical framework.

Figure 7.8 shows the increases in exports of the Metallurgy, Machinery and Equipment and Electronics sectors in the NE, increase relative to the baseline between 98.38% (Metallurgy in Alternative +Ind NE) and 195.73% (Machinery and Equipment in AR +Ind NE) until 2050. It is important to notice, though, that such high increase in percentage change occur due to the very small levels of production and particularly exports of high value-added goods from the NE in the start of the period.

Across industrial segments and scenarios, impacts are mostly negligible apart from those related to incentivised sectors in the NE, in the scenarios where the incentive is present. The South and SE region would not experience relevant losses in terms of high value-added goods exports.

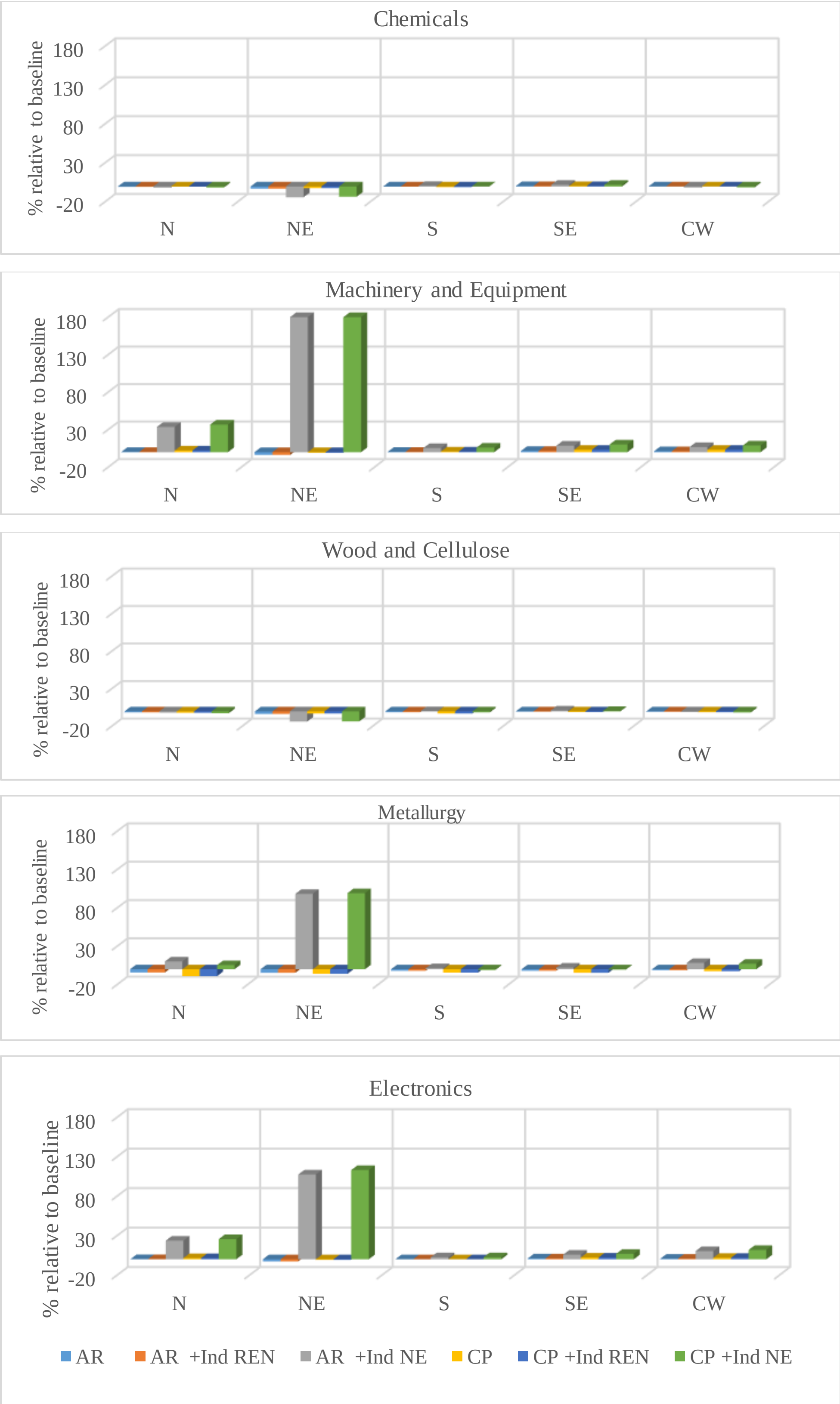


Figure 7.8 Regional export volumes of industrial sectors per scenario – cumulative variation relative to baseline

7.1.5 Industrial imports

Import reduction can reflect a few different phenomena: reduced economic activity and hence reduced demand, depreciation of terms of trade, or increased national output of good that would have been imported otherwise, if terms of trade remain constant.

In the national level (Figure 7.9), all industrial segments analysed would experience import reduction in all scenarios, except for mild increases in Wood and Cellulose products, Chemicals and Metallurgy in the AR scenario with industrial incentive in targeted sectors in the NE (AR +Ind NE).These could be caused by the relative reduction in the production of non-incentivised sectors, with demand increased by the higher economic activity level.

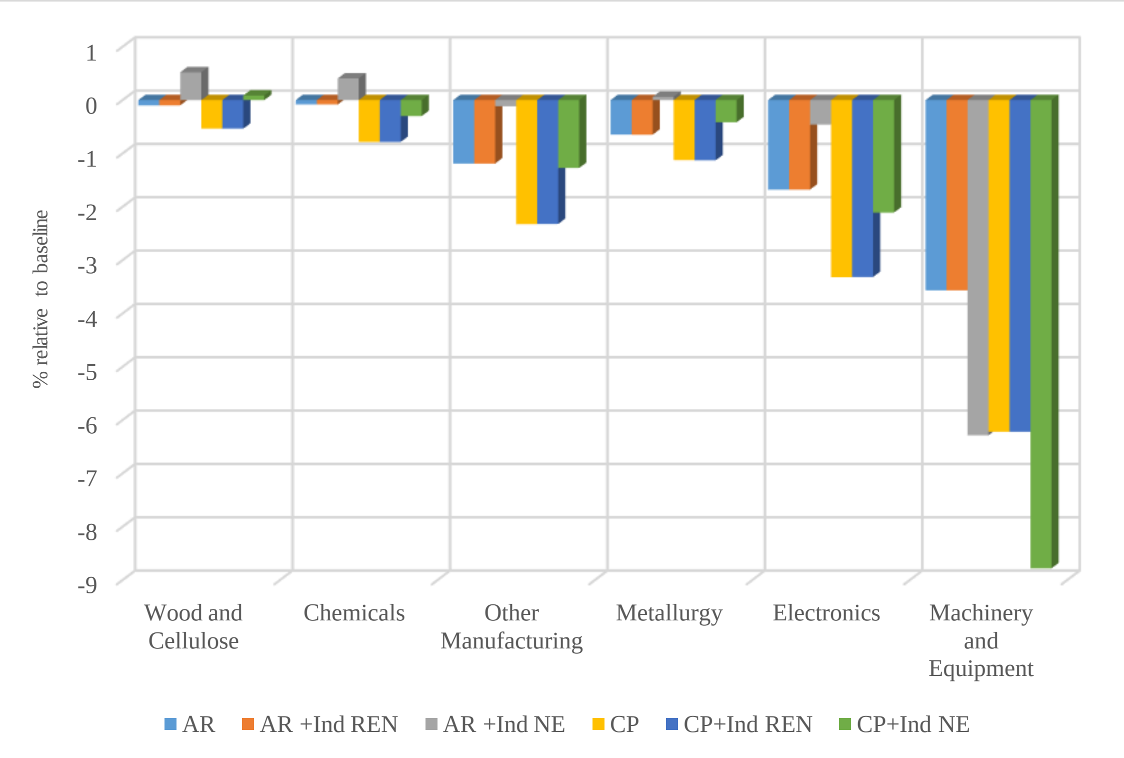


Figure 7.9 National import volumes of industrial sectors per scenario – cumulative variation relative to baseline

At the regional level, as expected, imports mostly decrease in the regions which economic activity decreases relative to the baseline (Figure 7.10): South, SE, North and CW. In the NE, when industrial segments are incentivised, imports tend to increase following the increase in economic activity. Depending on the incentivised industrial segment, imports can increase or decrease in the presence of the incentive, depending on the interactions with the external sector.

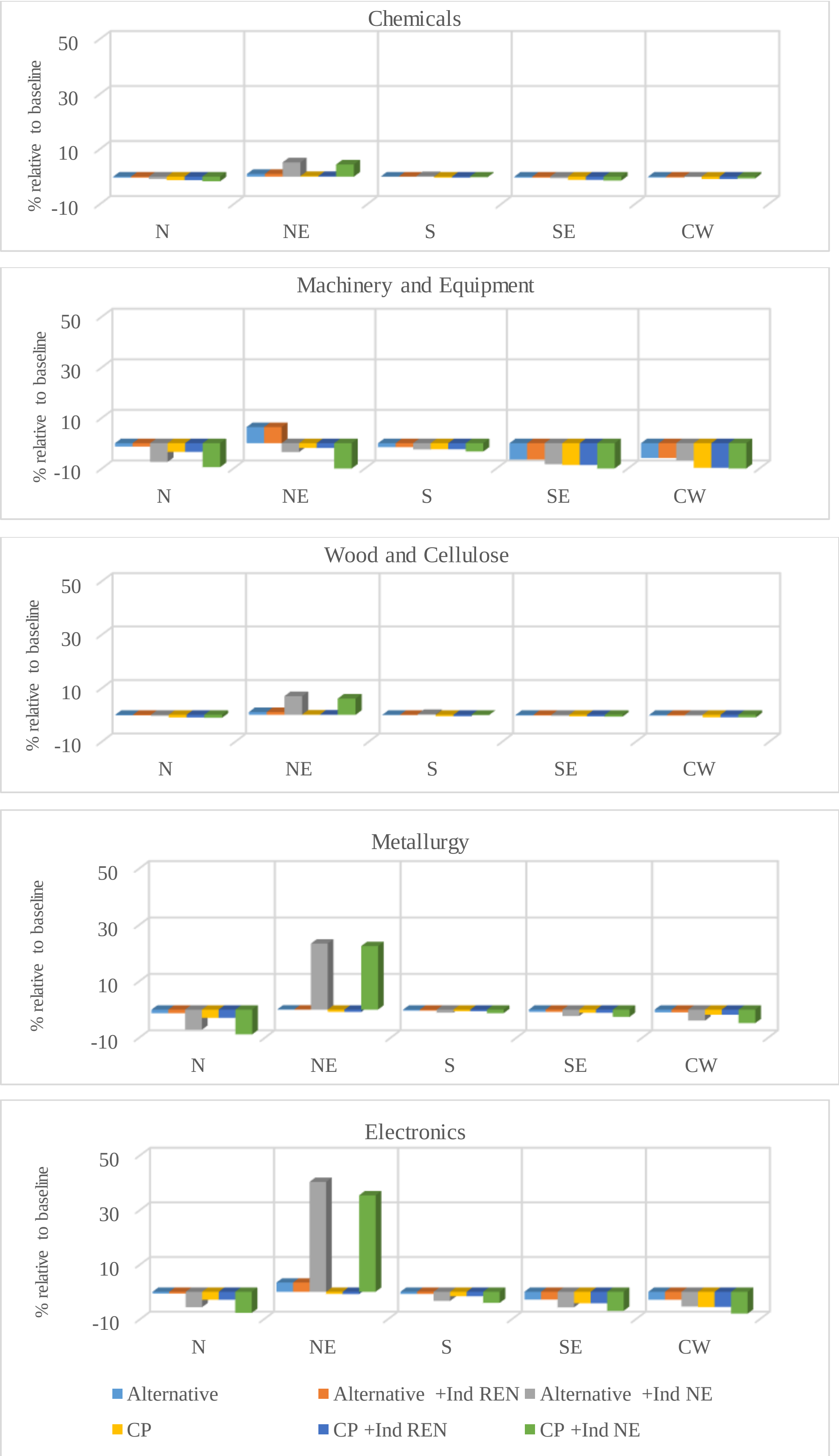


Figure 7.10 Regional import volumes of industrial sectors per scenario – cumulative variation relative to baseline

Machinery and equipment increase its imports in the AR capacity expansion not combined with industrial policy or combined with national incentives to wind and solar components only in 6.37% relative to the baseline until 2050 (both in Alternative +Ind NE and CP +Ind NE). However, Electronics would still import 40.23% above the baseline in the AR trajectory (AR +Ind NE) and 35.33% above the baseline in the CP pathway (CP +Ind NE). The Metallurgy sector imports would increase in the NE by 23.42% relative to the baseline in the AR trajectory (AR +Ind NE) and 22.52% in the CP pathway (CP +Ind NE) cumulatively in 2050.

7.2 Electricity sources Aggregate Employment

Most of the relevant variables in this research, which have been reported to the other sectors, are exogenous to the electricity sector, notably investment and electricity generation. Imports and exports of the electricity sector are not relevant since electricity is normally consumed domestically and no international integration has been considered. In contrast, impacts on the employment of electricity sources in each of the regions are an important result of the multi-regional CGE modelling simulations[22].

The employment impacts reported here are in percentage variations relative to the base year. Hence, regions which had very small employment levels of a given source in 2020, will experience larger percentage increases if the base year was close to zero. It is also important to note that the impacts reported here refer only to the employment in the power sector as such, also called direct impacts. The so-called indirect (along the supply chain) and induced (feedbacks between economic sectors) effects are those reported across the other sections of this chapter, and chapters 6 and 8 of this thesis.

National results show that the largest positive variations across scenarios are those of solar PV (Figure 7.11). However, this reflects the fact that in the base year, 2015, employment in this segment was very small (799 FTE in 2015). Clearly, the only two segments of the electricity sector in which employment increases are wind and solar

[22] In Section 7.2, values reported are relative to base year, not relative to the baseline, for visualisation purposes. Since some regions had near zero installed capacity of some sources in the base year, percentage changes in these cases are outliers and therefore alter the scale of graphs. Therefore, the baseline is reported as a scenario in the figure.

PV. In the AR trajectory, wind employment increases between 62% and 65% between 2020 and 2050.

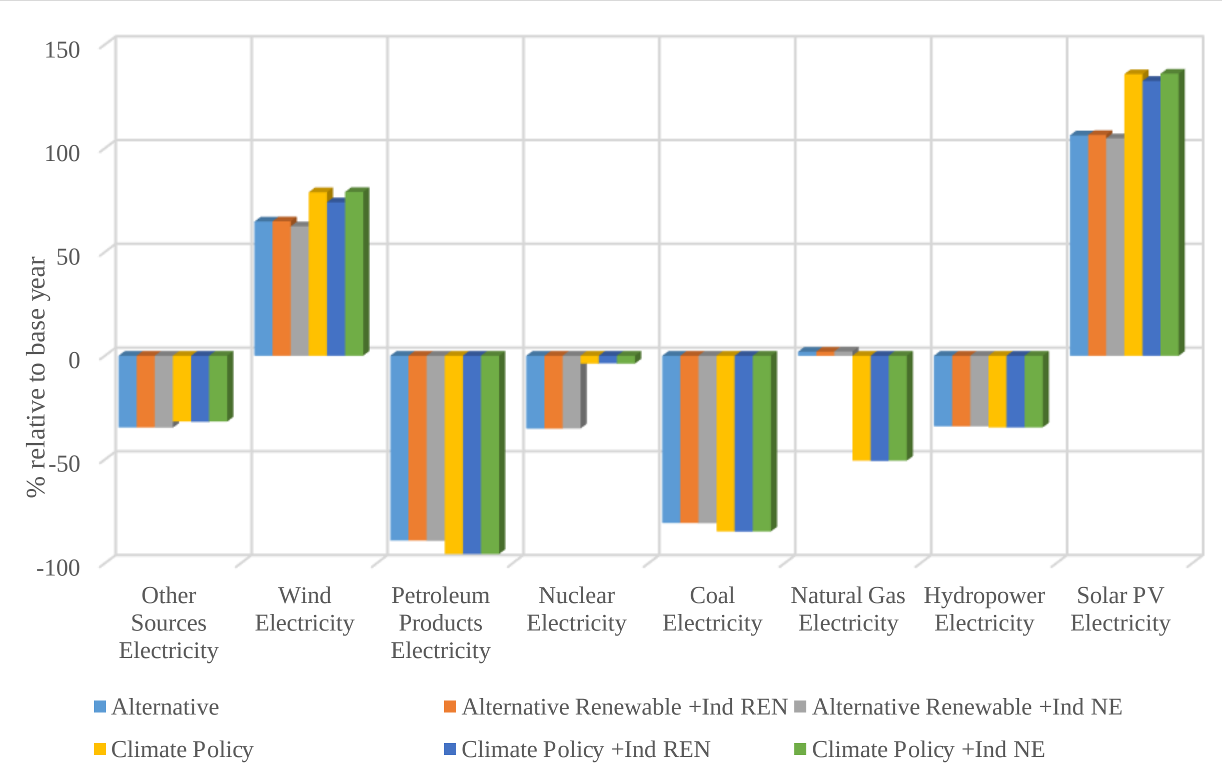


Figure 7.11 National employment of electricity sources per scenario – cumulative variation relative to base year

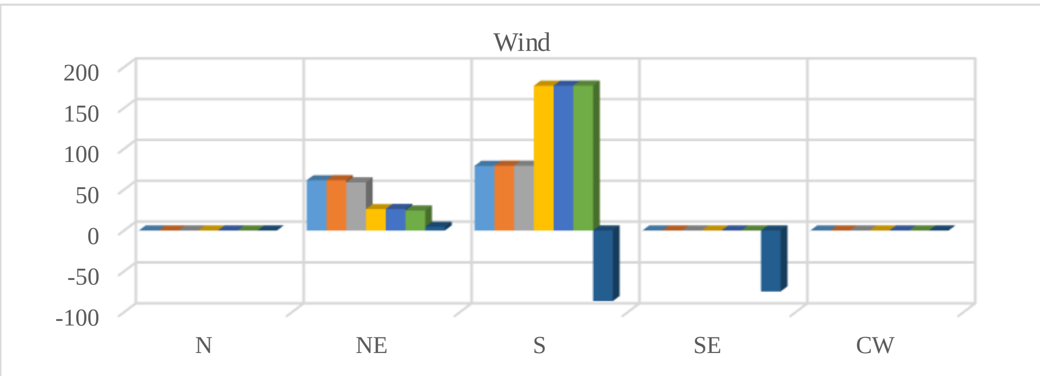
However, the regional distribution of electricity capacity expansion for each of the sources in each of the capacity expansion pathways also impacts employment creation. The South and the SE regions benefit from wind and solar power installation in the CP Pathway, while the NE benefits the most from the AR Pathway (Figure 7.12).

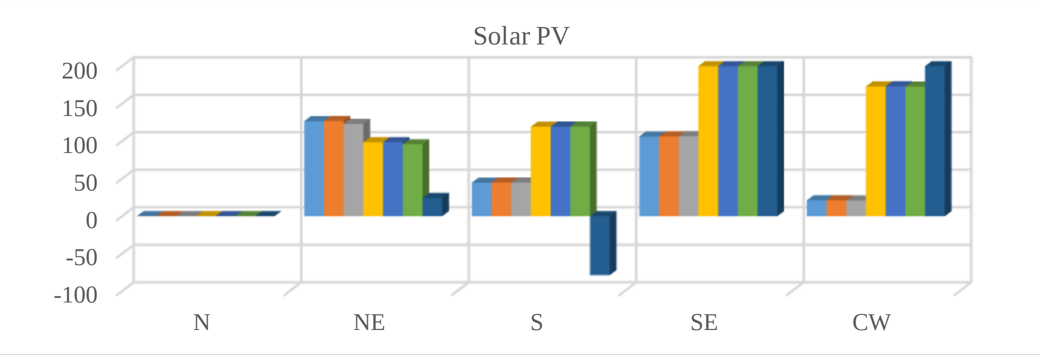
This happens because, in the CP capacity expansion trajectory, 50% of solar PV capacity is installed in the SE, 28% in the NE, 10% in the SE and 5% in the CW and North respectively. In this trajectory, 52% of the wind power capacity is installed in the NE, 29% is installed in the South and 16% in the SE. In the AR trajectory, in contrast, the NE receives 81% of wind power installed capacity and 42% of solar PV installed capacity. Since the NE already concentrated the majority of wind and solar installed capacity in the base year (as shown in Section 2.3), in relative terms, aggregate employment increases are higher in the South and SE regions because they start form a much smaller number of employed workers.

The difference between the regional distribution of installed capacity across scenarios is clearly reflected in the employment impacts. Although percentage variations in the NE are not the largest between regions, when looking at the different scenarios, the largest employment growth in the NE is in wind power in the AR scenario with the national industrial incentive (AR +Ind REN), with a 61.65% increase (a 57.16% growth relative to the baseline). Solar PV in the NE also increases the most in the AR trajectory scenarios (123% to 127%, or 119% to 123% higher than in the baseline) given the predominance of solar PV installed capacity in the NE in this trajectory.

For wind power installed capacity, the largest relative impacts occur in the South region, in the CP electricity capacity expansion pathway (177% or 263% above the baseline, in which none of the wind power capacity is installed in the South region). For solar PV, the largest increases are in the CP trajectory in the SE (243%). Markedly, the increase in the baseline capacity expansion trajectory in the SE is even larger, given that 77% of solar PV is installed in the SE in this trajectory, and 13% in the NE. It is interesting to notice that none of the electricity capacity expansion pathways considers significant wind or solar PV deployment in the North region, due to its forest cover.

Employment in the hydropower sector is lower than the base year across all scenarios and regions, due to the stagnation of hydropower installed capacity and its decrease in share of total. Cumulative decreases in hydropower aggregate employment vary from 17% below the base year in the baseline in the CW to a 46.8% decrease in the AR scenarios in the SE.




Solar PV
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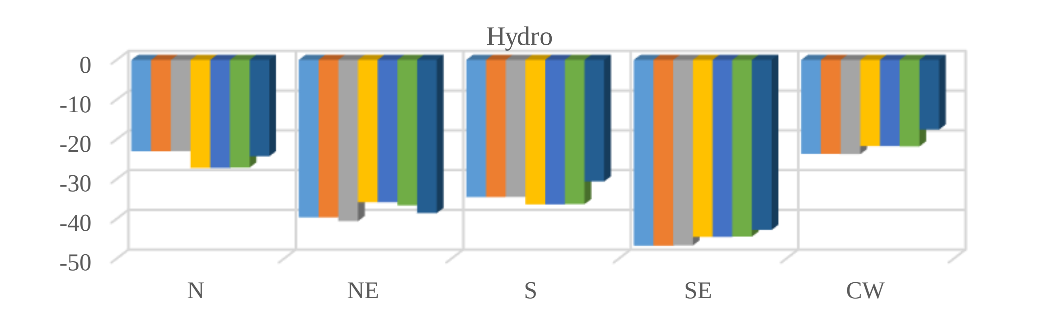
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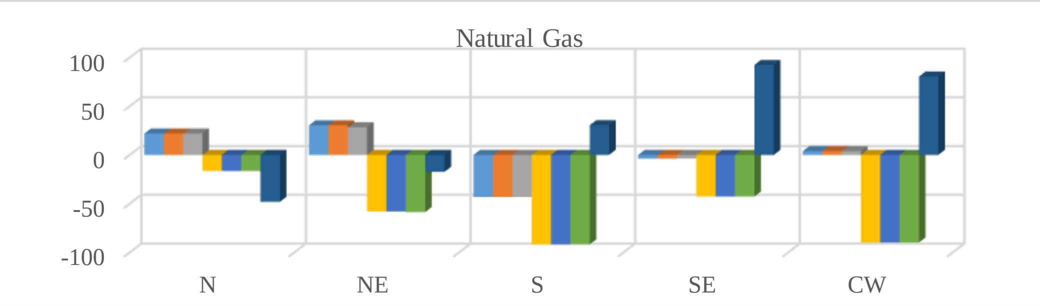
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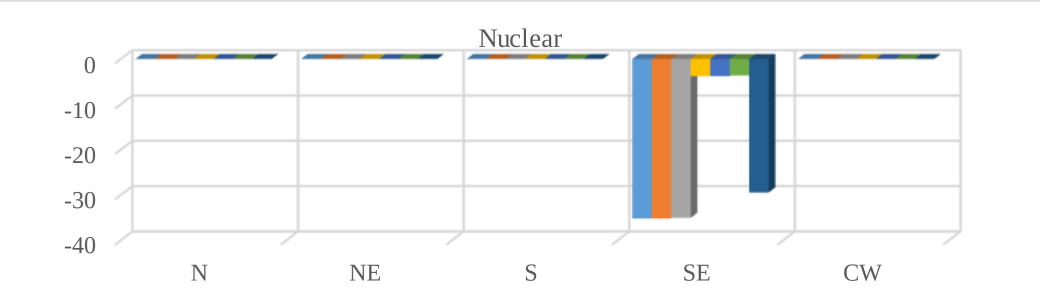
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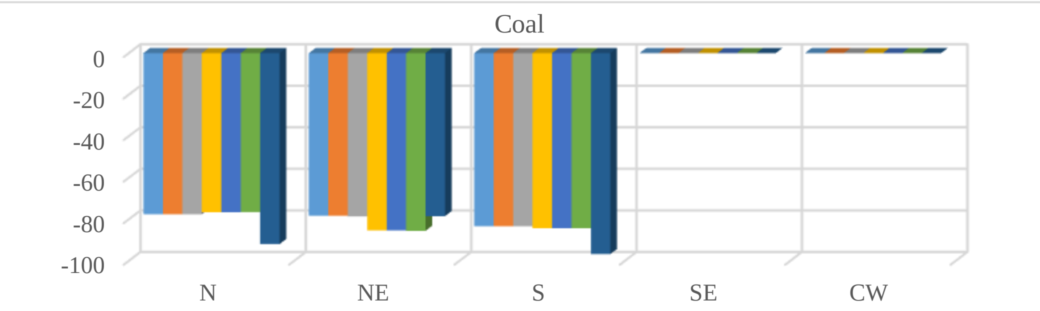
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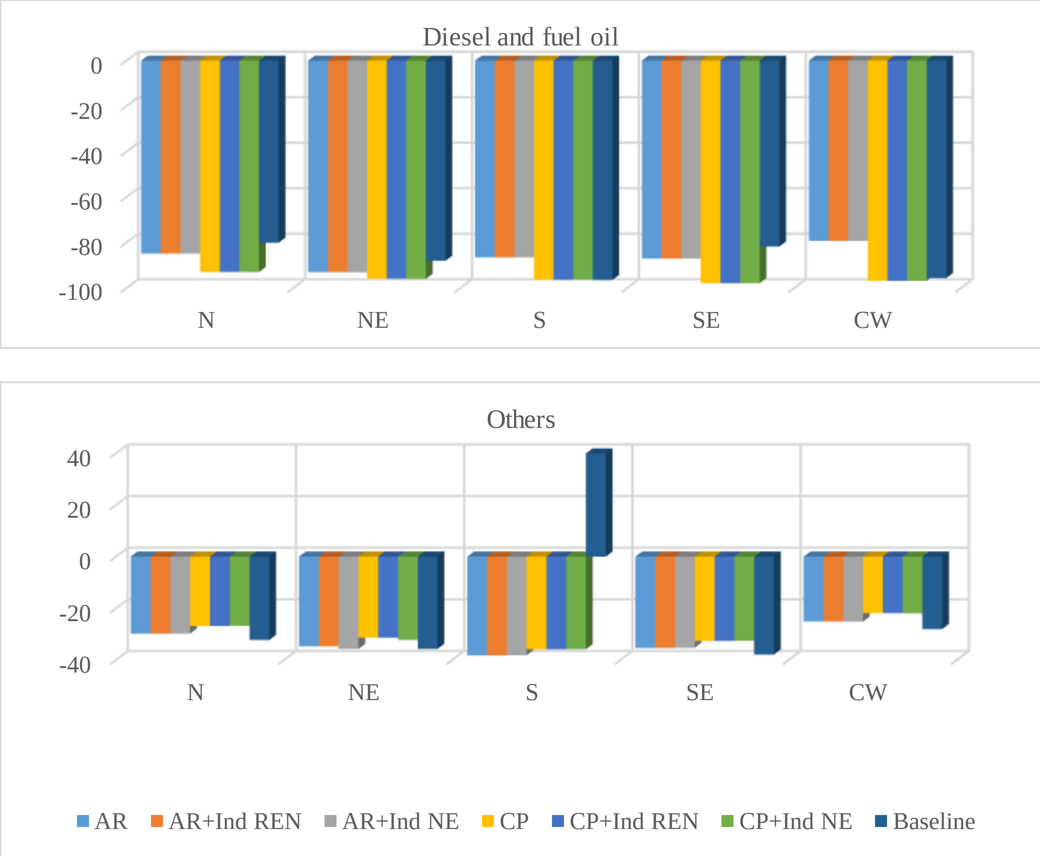

Figure 7.12 Regional employment of electricity sources per scenario – cumulative variation relative to base year

Aggregate employment in natural gas plants also follows capacity expansion trends, in which it decreases in almost all cases, apart from the baseline, and the AR scenario in the North and NE regions. This happens because the AR trajectory has an increase in natural gas installed capacity as a back-up for intermittent renewables, notably solar PV and wind power. In this trajectory, natural gas employment in the North region increases 21.9% from 2020 to 2050, which is 70% above the baseline in the same period. In the NE region, natural gas employment increases 30.4% cumulatively until 2050, which is 47.8% above the baseline.

Nuclear power employment decreases in all cases, and this process occurs in the SE region only because the only nuclear power plant in Brazil is located in Angra dos Reis, in the state of Rio the Janeiro. The AR capacity expansion trajectory does not consider any nuclear capacity expansion, hence the largest decrease in employment, at 35.17% lower in 2050 than in 2020, 6% lower than in the baseline.

Employment in the coal segment decreases between 80% and 100% in all scenarios in the three regions with exiting coal power plants operational in the base year, namely: North, NE and South. Diesel and fuel oil employment, similarly, decreased between 80% and 100% across all scenarios and regions.

7.2.1 Absolute employment variation in electricity sources

This section presents absolute metrics for full-time equivalent (FTE) jobs in direct employment in electricity sources (Figure 7.13), additionally to percentages changes relative to the counterfactual scenario presented in the previous section. It is visible that despite changes in the electricity mix, in 2050, hydropower would still be by far the source of electricity employing the most workers, despite a decrease of around 35% in hydropower jobs in all scenarios (from 27,068 FTE in 2015 to around 17,700 FTE in 2050). Hydropower accounted for 49% of direct electricity generation jobs in 2015 and in 2050, it would account for about 40% to 43% of total in AR and CP scenarios respectively.

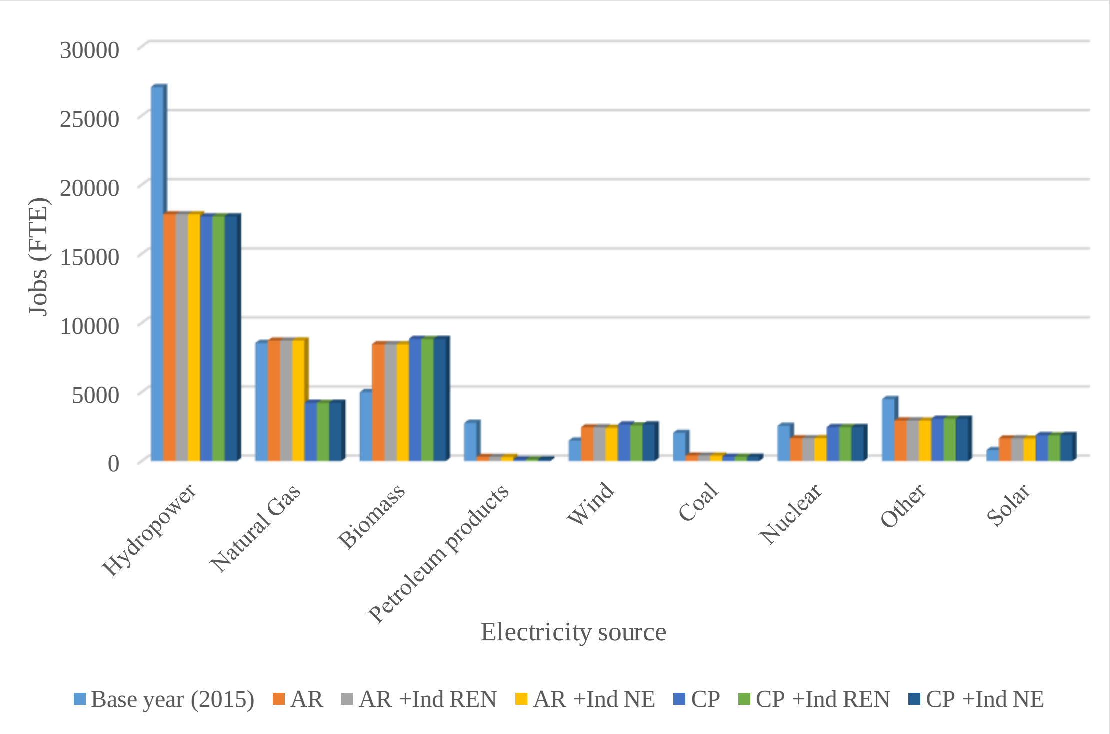

Figure 7.13 Total national employment of electricity sources in the base year of calibration (2015) and in 2050 per scenario (FTE)

Direct employment in natural gas slightly increases from the base year level in the AR trajectory scenarios given the maintenance of its installed capacity as a back-up to the variable renewables in the system. The CP scenarios, in contrast, do not have the same results given the characteristics of the electricity sector representation in the model that does not account for the same level of system operation detail as the modelling suite from which the AR energy-system scenario was generated.

Biomass employment remains stable across scenarios, which reflects the stability of installed capacity across time seen in Chapter 5. Notably, across scenarios, employment in petroleum products generation nears zero, given that it is virtually phased out. The same is true for the direct employment in the coal electricity generation sector.

Clearly, the main winners of the process are wind and solar electricity generation segments. Wind direct absolute employment nearly doubles, from around 1,400 in 2015 to around 2,600 FTE in 2050 across AR and CP scenarios. Solar direct absolute employment more than doubles, from 799 in 2015 to nearly 1,900 FTE in 2050 in the AR scenarios, and 1.650 FTE in 2050 in the CP scenarios.

7.3 Expert elicitation insights on Industrial and sectoral impacts of electricity capacity expansion scenarios

Industrial policy simulation results are to a great extent backed by the experiences and impressions reported in the expert elicitation process. Both electricity generation capacity expansion and industrial productive capacity expansion create new capital stock, which can ultimately translate into structural economic changes and development if accompanied by underlying strategies. All experts consulted raised the point that developing national and even regional supply chains of renewable power plant technologies is critical to potentializing socioeconomic benefits of renewable energy investment spending. One expert in particular said about the NE region, quoted (from Portuguese):

> "*Local socioeconomic impacts of large electricity projects are small due to the absence of a local supply chain*." (DFI2)

While another expert said, quoted (from Portuguese):

> *"Regional development will be a product of decentralised supply chains."* (DFI3)

It is important to highlight that the experts mentioned industrial policy spontaneously, since they were not asked about industrial policy and therefore this does not reflect a bias of the question. Questions asked only included whether multi-objective policy can be informed by the socioeconomic simulation results shown (see the questions asked in the expert elicitation process in Section 4.7.2).

7.3.1 Industrial strategies background in Brazil

Import substitution has been used as a development strategy in Latin America since the 1960s in an attempt to reproduce technological development strategies of advanced economies (Tavares, 2000). The aim was not to reduce total import volume, but rather reduce imports of high value-added goods, producing them nationally. Following such strategy, the BNDES local content policy for capital goods came into force in the 1960s (BNDES, 2019). Since, the bank has traditionally used subsidised finance conditionalities related to local content of power plants and oil and gas exploration. Industrial policy has therefore remained a component of the strategies to try to improve competitiveness and promote technological innovation in Brazil (Hochstetler and Montero, 2013).

According to an expert (DFI4), in 2012, BNDES started testing local content policies for non-hydro renewable energy sources focusing on specific components and processes. Between 2012 and 2015, several new industrial segments developed in Brazil as a result, as discussed in Section 3.2. Manufacturers started producing new components or adapted a similar production process. The rule BNDES imposed for wind power supply chain initially related only to the tower, not to other components. However, the BNDES realised empirically that if components are imported ready, not even assemblance is done nationally, there is no engineering development in Brazil. Whereas an industrial process that is done nationally creates a development opportunity. This is a perception the BNDES has had with tens of technologies they have funded, according to an expert consulted (DFI4).

However, strict local content policies not only in Brazil, but also in other developing and emerging economies such as India and South Africa showed signs of failure to meet its objectives (Hochstetler, 2020; Johnson, 2016; Morris et al., 2021; Probst et al., 2020). Hence, in 2018 the BNDES changed its policy from a nationalisation index policy, based on local content requirements, to an accreditation index instead. This means that suppliers of certain power plant components must be accredited to BNDES. Over 90% of products funded by BNDES must sign up to the supply chain accreditation policy, according to a participant of the expert elicitation (DFI3). The supplier accreditation policy covers suppliers for all parts of the wind tower: blades, nacelle, cube and even aerogenerator, etc.

7.3.2 Sub-national industrial strategies

In the case of the regional incentive in the NE, it makes sense to subsidise whole sectors rather than only specific components because it can create synergies in local industry. One expert consulted (DFI4) reported a case which happened in the state of Alagoas, when a producer of glass fibre was convinced by wind energy firms to adapt their production from boat components to start also producing wind farm components using the same material. This case illustrates the opportunities to seize regional capabilities to source power plant components locally and help retain the socioeconomic benefits of the new electricity sources.

Wind plant components' logistics have forced wind blade and tower manufacturers to move to the NE region, as explored in Section 3.2. Using Brazil's road transportation infrastructure to transport blades was prohibitive, according to two of the experts consulted (ELS4, DFI2).

One of them pointed out that both BNB and BNDES finance conditionalities attracted manufacturers to the NE region, even though conditionalities related to national suppliers, not regional. Wind component manufacturers first installed their factories in the SE, near their supply chain where metallurgy and electronics and other machinery and equipment sectors are. However, around five year later, logistic difficulties forced them to move to the NE states.

From 2017, the BNB started financing solar and wind power projects using the constitutional development fund for the NE. Initially, the BNB used the BNDES framework to promote industrial development. But then, it stopped using it, creating some inconsistency that hinders the process of boosting regional industrial development, according to an expert (DFI4). This is because the lack of clarity of rules to follow, or the existence of different rules and frameworks hinders business models and strategies planned to comply with such conditionalities.

7.3.3 Future dynamics of renewable power plant supply chains

Arguably, while the NE wind generation potential is not depleted, there is no reason to deploy wind farms supply chain industries in the South or SE. Experts indicated that they are not economically attractive, and wind turbine manufacturers have moved to the NE already (DFI2, DFI4, ELS3,ELS4). However, if Brazil explores offshore wind technology, which is not currently the case, the existing infrastructure for offshore oil and gas could be used to generate offshore wind near the load. This point was raised by three of the experts (ELS3, ELS4, DFI1). Recommissioning of offshore platforms is therefore seen as means to avoid further exploiting oil and gas reserves, which is necessary to meet the Paris Agreement temperature targets (Solano-Rodríguez et al., 2021).

If offshore platforms are indeed recommissioned, it would make sense to install a wind supply chain in the SE and South. Offshore wind exploitation could potentially cause a relocation of plant component manufacturers to the SE, or new manufacturing plants installation in the SE, once more due to the prohibitive logistics of using Brazil's road transportation infrastructure to transport blades, as mentioned in the previous section (7.3.2).

The main winner of the wind development process among Brazilian companies, mentioned by four of the experts (GOV1, DFI1, DFI4, ELS4), seems to be WEG Motors, a corporation from Santa Catarina, a South region state. WEG was already relevant in the motor production segment before the wind power boom, supplying several firms and sectors, including different electricity generation technologies, globally. WEG produces most components of wind turbines, and has recently launched a 7MW and 172 meters rotor diameter, which will be the largest in operation in the Brazilian market (WEG, 2022).

WEG, however, is the only company which maintained all of its factories in the South, incurring logistic costs of transporting its equipment to NE states. The concentration of motors production in the South region has been considered in the calibration of the multi-regional CGE model, in the step of regionalising the production of each of the industrial goods in the national database. Hence, this explains in part the gains that the

South region experiences in the modelling simulations even in the AR scenarios, in which almost all wind farms are installed in the NE region.

Arguably, having developed a supply chain to meet its nearly exponentially increasing demand for wind turbines, Brazil could also become an exporter of wind power plant equipment. This argument was backed by four of the experts consulted (ELS1, ELS4, ELS7, DFI2) and the BNDES also identified a potential to export particularly to the so-called Southern Cone[23] as a motivation to finance wind power equipment manufacturers (Seiceira et al., 2013).

LM Wind Power and Vestas facilities, based in the NE state of Pernambuco, produce blades for the Brazilian market, but according to an expert consulted (ELS4), they could also be exported from the NE ports. Hence, the NE could gain relevance as an exporter of high added-value goods by exporting wind power plant components.

However, this is not reflected in the modelling results of this research, because this is still far from the reality of the structure of Brazilian economy, and therefore not represented in the model's database. This is a model limitation that can be overcome in the future, if this process does start and exports of wind components start showing in national trade statistics.

7.3.3.1 Solar PV Supply Chain

Developing a supply chain for solar PV, however, is a significantly different challenge from wind. Efforts for solar PV supply chain development in Brazil started when this market had already been dominated by cheap panels produced in China, and to a lesser extent Vietnam and Malaysia (SEBRAE, 2017; Valor Econômico, 2022a). Hence, over 95% of panels installed in Brazil are sourced from China according to an expert (GOV1), and to an assessment of *Valor Econômico* newspapers from May 2022 (Valor Econômico, 2022a), according to which the remaining 5% are assembled in Brazil using imported silicon cells. Thus, BNDES recently decided to withdraw its local content policy for solar PV, as indicated by an expert consulted (DFI4).

PV cells, which correspond to 40% to 50% of total costs, require high upfront investment and a very large-scale demand to be financially attractive. Therefore, competition with imports from China tends to undermine investment (Grottera, 2022;

[23] The Southern Cone covers areas of South America, mostly south of the Tropic of Capricorn. Traditionally, it covers Argentina, Chile and Uruguay.

SEBRAE, 2017). The case of Chile is seen by two of the experts (GOV1, ELS4) as a role model, and yet national suppliers for solar PV account for solely 17% of goods and services demanded by projects in Chile (Saget et al., 2020).

According to an expert consulted (DFI4), quoted (translated from Portuguese):

> *"The main bottleneck to increase solar PV seems to be its supply chain. Brazil currently imports 99% of solar plant components. Brazil lost the timing in trying to create a supply chain for solar PV. The same is happening with batteries, while China dominates both supply chains. Chinese companies doing lobbying in Brazil to sell their solar panels, inverters. etc."*

7.3.3.2 Green hydrogen and the role of the state of Ceará

Green hydrogen is seen by seven of the experts[24] as key to deal with intermittency in the long run, with impacts on the trade balance, since it could increase exports. The state of Ceará has already attracted interest from companies from Europe and Australia according to an expert (DFI2), who expects USD 90 billion investment in hydrogen in the next years. Ceará is particularly strategic due to Porto de Pecém, a port from which exports leave Brazil, and which has already formed a partnership with the Dutch government to export green hydrogen produced in the NE (Complexo do Pecém, 2022). This would have a direct impact on the need to build new transmission lines to export the electricity generated in the NE to other regions, by transporting hydrogen instead. Besides, hydrogen can be exported to other countries while electricity cannot.

Noticeably, the NE state of Ceará is seen the main example of regional development pushed by energy investment spending. Four of the experts mentioned this particular state, as an example that received wind power plants, industrial segments of their supply chain, industrial federations, and expectations to create jobs (GOV1, DFI2, ELS4, ELS5).

7.4 Discussion

Overall, the main aim of enacting industrial policy associated with renewable energy deployment in EMDEs is to seize such investment spending to meet socioeconomic goals through multi-objective policymaking and multi-level governance of these

[24] ELS1, ELS2, ELS3, ELS6, DF1, DFI2, DFI3

policy objectives. Renewable energy technology deployment strategies can also become more politically acceptable if linked to socioeconomic development particularly in EMDEs.

Simulations results show that incentives to targeted manufacturing segments create economy-wide benefits when compared to capacity expansion scenarios in the absence of such policies. Socioeconomic impacts are slightly more positive when capacity expansion shocks are combined with a national incentive to manufacturing segments producing components of wind and solar power plants both in the AR and in the CP scenarios. However, a regional incentive to Metallurgy, Machinery and Equipment and Electronics in the NE region creates more significantly positive impacts not only at the regional level, but also at the national level.

Positive results found are pushed by the stimulus to manufacturing sectors seen in the previous sections of Chapter 7. Positive impacts on output and investment in industrial segments in the NE resulting from such stimulus were outstanding. This occurs due to the very low output and investment levels in the NE currently (and in the model's base year). So, a 1% incentive translates into a strong driver with positive feedback effects in the rest of the economy.

The electricity mix of the baseline increases the relative economic impact in the NE, given that in the baseline, it is 29% natural gas in 2050 (as presented in Section 5.1). Natural gas plants use industrial components mostly produced in the SE region. Hence, not only the baseline channels more investment spending to the SE region because most additional capacity is installed there, but also boosts demand for manufactured goods in the same region through these power plants' supply chains.

7.4.1 Compensatory mechanisms between industrial segments

An important compensating factor happens in scenarios where electricity capacity expansion is combined with industrial policy in the NE. That is, the output and investment of manufacturing segments of wood products and chemicals, that were not incentivised, decrease in the NE and increase in the SE. This shows that industrial sectors that were not incentivised in the NE become even more attracted to the SE than what is already the case.

In the absence of the regional industrial incentive in the NE, the NE uses more imported industrial goods in the policy scenarios (both AR and CP) than in the baseline. However, in the presence of industrial policy in the NE, the region imports more of the non-incentivised industrial commodities, showing more compensatory effects.

7.4.2 Solar PV industrial policy and trade frictions

The development of a solar PV supply chain is a significant challenge concerning renewables supply chain development indicated by experts consulted. Efforts to create a national supply chain for solar PV included not only the BNDES supplier accreditation rules to access finance, but also tax incentives that did not tackle directly the solar PV technology, but rather important components such as semiconductors that are relevant to several technologies across sectors (Hochstetler, 2020). The federal government created in 2007 the programme for semiconductor industry development support (PADIS, acronym in Portuguese). In 2015, semiconductors for solar PV modules were included in the PADIS as part of a strategy that aimed at having PV components being produced in Brazil until 2020.

However, later in 2015, Japan challenged the PADIS programme at the World Trade Organization (WTO) under the General Agreement on Tariffs and Trade (GATT). In early 2019, the WTO ruled that Brazil had violated trade rules. Later in 2019, the Brazilian government revised the programme rule by reinstating industrialised product taxes to semiconductors but reducing income tax over companies' revenues instead. This was accepted as compliant by the WTO. The PADIS was initially planned to last until 2022, but in January 2022 the Senate approved its prorogation until 2026 (Valor Econômico, 2022b). However, as mentioned above, the PADIS has not been successful in propelling solar PV module production in Brazil due to the dominance China technology gained in the market.

Disputes at the WTO are a threat to industrial incentives, particularly if they aim to incentivise a national supply chain as suggested by participants of the expert elicitation. However, incentives to a particular region which is underdeveloped when compared to the rest of the country, under a constitutional mandate to incentivise, seem less likely to trigger disputes under the WTO.

The WTO has not created to date any specific rule on green subsidies or carbon taxes (Bacchus, 2022). However, the literature has indicated that WTO rules should be revised to provide more policy space for sustainable development and clean energy subsidies (Charnovitz, 2014; Shadikhodjaev, 2015). For example, in a dispute against the India Solar Cells, the WTO programme rejected the argument that the subsidy to solar PV cells and modules was critical for energy security. However, this argument has been widely used as a primary justification for fossil fuel subsidies (Lydgate and Anthony, 2020).

This means that the risk of green subsidies facing WTO disputes when trying to incentivise a renewable energy supply chain is not a closed matter. Further research, discussions and international negotiations are needed and under way towards revising trade frictions that could act as barriers to the energy transition. This is the case for example of the idea of a climate club raised by the German G7 in 2022 (G7, 2022). It aims to implement a Carbon Border Adjustment Mechanism (CBAM) penalising imported goods produced outside of the club with a laxer emission standard.

Arguably, WTO subsidy rules have not distinguished renewable energy subsidies from fossil fuel subsidies, and there has never been any formal complaint about the latter. This reveals an asymmetry between the energy sources that needs to reformed if we are to pursue a net zero energy transition (Lydgate and Anthony, 2020).

7.4.5 Industrial Policy trade-offs and Foreign Direct Investment (FDI)

Clearly, regional trade-offs and logistic constraints linked to the size of the Brazilian territory cause regional trade-offs, related to those discussed in Section 6.7.2.3. For example, the South region, which wind power generation potential is exploited particularly in the CP capacity expansion trajectory, could face limitations to developing a wind power supply chain. Distances between the South and NE region can reach over 2,000 miles. Hence, the fact that the wind power supply chain is now concentrated in the NE can potentially limit the feasibility of exploring the wind power generation potential in the South due to logistic limitations and transport costs.

Markedly, most companies currently producing and assembling wind farm components in Brazil are subsidiaries of companies from advanced economies. These companies undertake Foreign Direct Investment (FDI) in Brazil by creating new business in Brazil which ownership they control from their headquarters. Iberdrola, Gamesa and Acciona from Spain, GE from the United States, Vestas and LM Wind Power from Denmark, Enercon from Germany and IRAETA from China are the main examples of companies manufacturing wind turbine components which have invested in Brazil through FDI.

The disadvantage of FDI is that these companies still send back large shares of their profits to their headquarters. However, most of the job posts they create are filled locally or nationally (skilled workers coming from the SE to the NE for example). Arguably, FDI allows for technological transfer and human capital development through employee training and tax revenue in the host country. But importantly, they also demand national goods along their own supply chain, such as steel and metallurgy products. According to a participant of the expert elicitation (DFI4), technical transfer from Spain due to FDI of Iberdrola, Gamesa and Acciona was successful in Brazil, and translated into technical productivity gains.

Although most companies manufacturing and assembling wind turbines are subsidiaries of Global North holdings, Brazilian companies also emerged, or started new production lines specifically to supply wind farms. Aeris is a Brazilian wind blade manufacturer headquartered in the state of Ceará which had in 2017 double the production capacity of both the Danish LM Wind Power and the Spanish Enercon (see Table 3.1 in Section 3.2). Torrebras is a Brazilian wind tower manufacturer based in the state of Bahia.

7.5 Chapter 7 conclusions

Chapter 7 presented the results of the simulation of two industrial incentive options to three industrial sectors of the CGE model: Metallurgy, Electronics and Machinery and Equipment, that are relevant to the supply chains of wind and solar power plants. The two industrial incentives simulated were (i) a 1% national incentive to nationally produced goods produced by these three sectors specifically demanded by the wind and solar PV electricity generation sectors and (ii) a 1% incentive to the three segments in the NE region only. The results of these simulations provide a response to the underlying research question (ii) of this thesis (Section 1.1).

Results suggest that industrial incentives would create economy-wide benefits when compared to capacity expansion scenarios in the absence of such policies.

Socioeconomic impacts became slightly more positive with the addition of the national incentive shock to manufacturing segments producing components of wind and solar power plants both in the AR and in the CP scenarios. However, a regional incentive in the NE region to Metallurgy, Machinery and Equipment and Electronics has created more significantly positive impacts not only at the regional level, but also at the national level.

The next chapter explores the effects of renewable energy policy and its combination with industrial policy on the work force and households to understand these policies' distributional impacts. Workers and households are disaggregated into ten groups respectively, a feature that allows for a close analysis of the impacts on lower wage and lower income bands. This, in turn, determines the extent to which such policies create or not benefits to the layers of society that carry most of the burden of a country's underdevelopment. As shown in Section 3.2, the NE region is where most of the Brazilian population under the poverty threshold resides, and therefore the analysis focuses on this region in particular.

8. DISTRIBUTIONAL IMPACTS OF ELECTRICITY CAPACITY EXPANSION SCENARIOS

Distributional impacts of the energy transition are an increasingly pressing issue in debates about climate and energy policy. Taking into account the 2030 Agenda for Sustainable Development by the United Nations Member States (United Nations, 2023), it is clear that climate and energy policies should factor in their distributional impacts to ensure equitable growth compatible with the Paris Agreement goals (Montenegro et al., 2021). Arguably, the energy transition should “leave no one behind” (Sarkki et al., 2022), and discussions around just transitions are already central to the climate debate. Most CGE modelling exercises of climate and energy policy do not explore distributive impacts due to the single representation of households by one representative agent. That is, they only have a single representative household and a single representative labour unit. They do not have households and labour disaggregated into income bands and wage levels.

Producing knowledge about the potential distributive impacts of renewable energy policy, and climate policy in general, is crucial. It allows governments to plan and implement complementary social and economic policies to support lower income households. As mentioned in Section 3.3, this is particularly relevant for EMDEs such as Brazil, where in 2022 nearly 63 million people live under the poverty threshold - USD5.5 per day per family in power purchase parity (Neri, 2022; World Bank, 2022).

The TERM-BR E15 model has ten household groups represented per income band (HHInc), and ten labour grades per wage level, also called occupation bands (OCC). This chapter therefore presents the impacts of the six scenarios modelled on labour, income and households, responding to research question (iii) of this thesis (Section

1.1). Results presented in this chapter are the following: Section 8.1 comprises results for labour and its income: aggregate employment per occupation band (8.1.1), real wage variation for each of the ten wage levels (8.1.2), and inter-regional workforce migration per occupation band (8.1.3). Section 8.2 explores impacts on households by presenting the results for household consumption variation per household income band.

Then, Section 8.3 explores the insights raised in the expert elicitation relating to the impacts of long-term electricity capacity expansion scenarios on labour and households' income distribution. Thus, Section 8.3 develops the five themes presented in Section 4.7.3, showing the views of experts on how the distributional results obtained would be used in policy and decision-making and what are the bottlenecks to using them to inform these processes. Then, Section 8.4 provides a discussion of the combination of modelling results with the insights raised by experts consulted in the expert elicitation process. Lastly, Section 8.5 summarises the main findings of Chapter 8.

8.1 Labour and income

This section explores the impacts of the six scenarios simulated on labour and income (wages) indicators at the national and regional level.

8.1.1 Aggregate employment per wage band

At the national level, aggregate employment levels of the policy scenarios have near zero negative impacts relative to the baseline (Section 6.3, Figure 6.7). However, when looking at the disaggregation of results into the ten wage bands, the losses are clearly not equally distributed (Figure 8.1). The most negative impacts occur on the lowest wage band (OCC1) in scenarios with an industrial incentive to targeted industrial sectors in the NE region. In the AR capacity expansion scenario with a regional industrial incentive in the NE (AR +Ind NE), employment in the lowest band would be 1.38% lower than the baseline in 2050, while in the CP trajectory with the same incentive (CP +Ind NE), the negative impact would be 1.28%.

The second wage band is the second most impacted, with the most negative impacts in the same two scenarios, although near zero: 0.32% loss in the AR +Ind NE scenario and 0.29% loss in the CP +Ind NE. However, Figure 8.1 shows that the third, fourth and fifth wage bands (OCC 3, 4 and 5) are normally the least impacted, together with the highest wage group particularly in the AR electricity capacity expansion scenarios. This could indicate that a movement from the lowest two wage bands to the middle bands has made the impacts on them less negative. The highest wage group is also among the least impacted, but in this case, especially in the CP scenarios.

This means that middle wage jobs are the most stable across scenarios, together with the highest wage group, associated to very high skilled jobs. Impacts on the lowest wage band (OCC1) in the scenarios with a regional industrial incentive in the NE, however, draw attention. Given that, as seen on section 6.3, the aggregated results are near zero, OCC1 reductions suggest that in scenarios where the economy becomes less specialised in primary goods, the least skilled workers move to middle wage bands. Thus, employment losses in the middle wage bands were less negative, allowing the total national results to be less negative.

The compensation process happens because of equilibrium condition, explained in previous sections (3.3 and 6.3). The assumption of full employment makes the overall impacts on employment very close to zero. However, there are differences between income bands. Since a large share of the population is in OCC1, particularly in the NE region, and overall results are near zero, we can infer that that is a transfer from OOC1 to higher wage levels, which decrease less than they would have otherwise, and therefore allow overall results to remain near zero. These results suggest that scenarios with higher shares of non-hydro renewable electricity in the mix create a demand for higher-skilled labour. However, as will be seen in the expert elicitation insights (Section 8.3), additional policies may be needed in order to create this movement toward more skilled jobs.

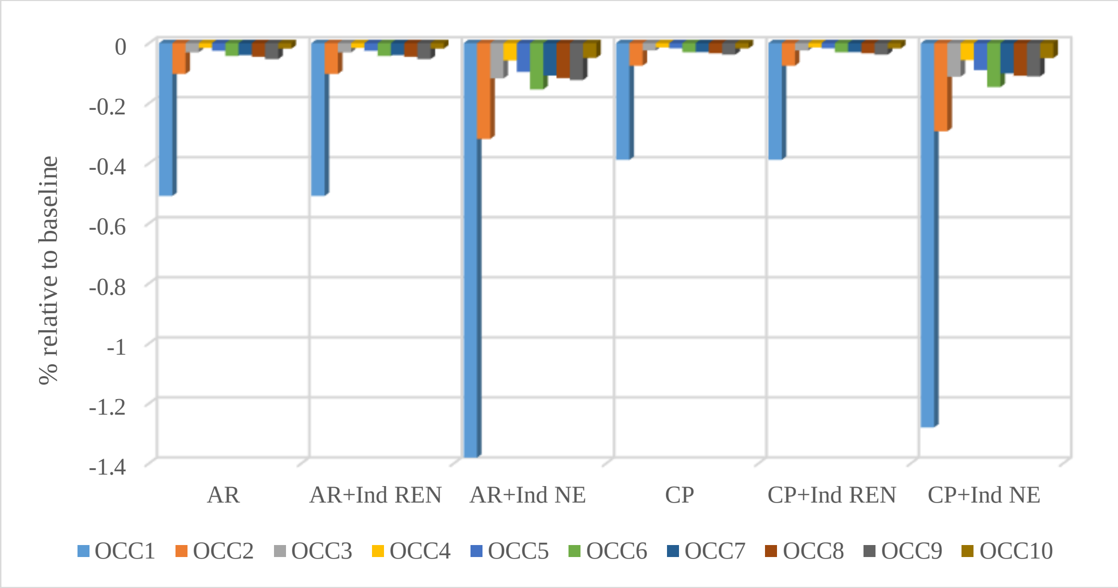

Figure 8.1 National employment per scenario per occupation wage level - cumulative variation relative to baseline

Figure 8.2 and Figure 8.3 show the regional employment impacts for the AR and the CP scenarios respectively. From both figures, it is visible that the NE region is the greatest winner in terms of job creation in the process of non-hydro renewable electricity capacity expansion.

Across all scenarios and wage levels, employment is positively impacted relative to the baseline in the NE region. The largest positive impact is on the sixth wage level (OCC6), in the presence of an industrial incentive in the NE: the OCC6 employment level is 1.28% above the baseline in the AR electricity capacity expansion pathway (AR +Ind NE) and 1.23% above the baseline in the CP case with the same incentive (CP +Ind NE) in 2050. In both cases, the second largest benefit is for the eighth wage level (OCC8): 0.97% above the baseline in the AR case, and 0.88% in the CP case. This suggests a trend of increasing the wage bands of the mid-skilled workers.

However, it is important to notice that the first wage band (OCC1) comes right after in both cases with 0.89% and 0.83% positive impacts respectively in the NE. Although small, this shows that in the NE region the trend would be the opposite of other regions, where the lowest wage level is negatively impacted the most. This could be an important indicator that the NE would still employ less skilled work than the other regions, even when its economic activity is boosted, continuing the existing trend: the

NE would still be the region concentrating low skill workers, even if it becomes more industrialised.

Noticeably, negative employment impacts observed on OCC1 in all the other regions in the scenarios with the regional industrial incentive in the NE in place are ten to 20 times the negative aggregated impacts shown in Section 6.3. This indicates a movement from OCC1 to higher wage levels. Otherwise, the aggregated loss would have been larger.

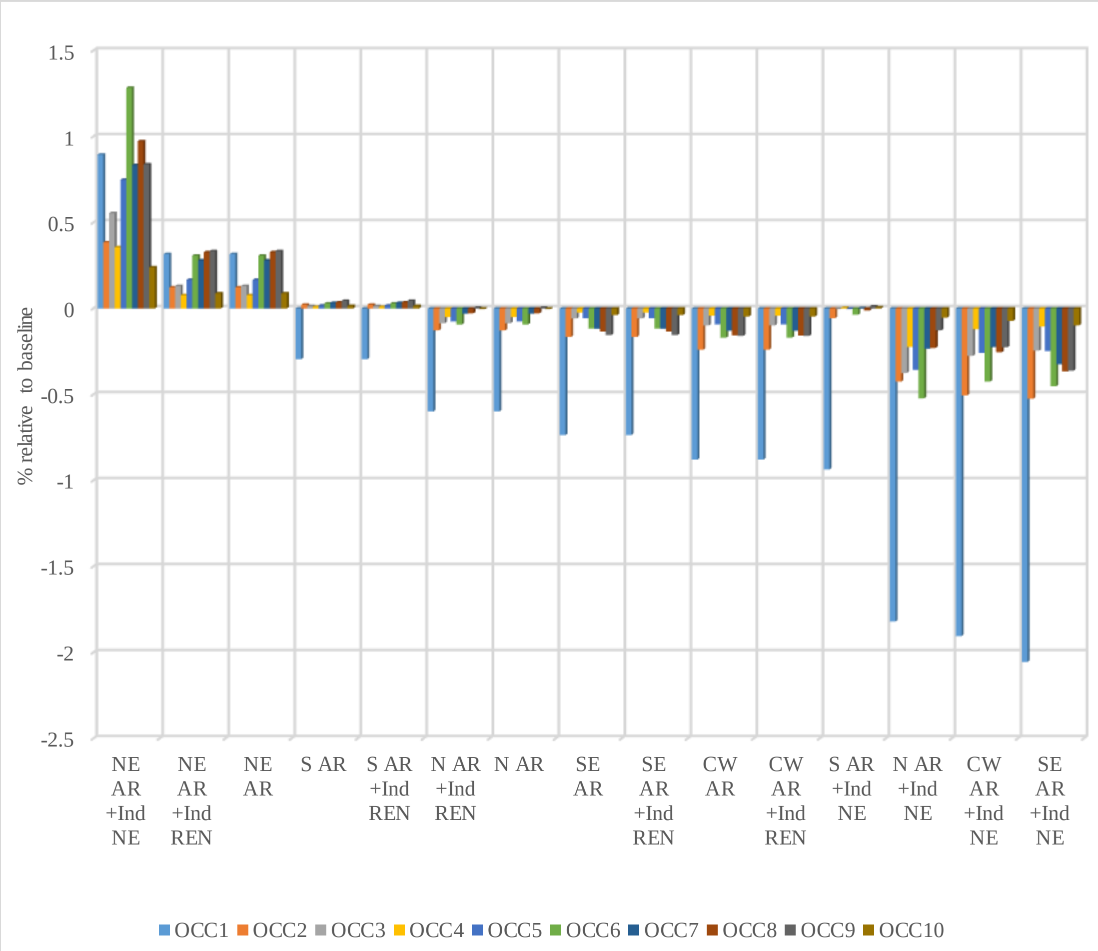

Figure 8.2 Regional employment in AR scenarios per occupation wage level - cumulative variation relative to baseline

Most regions experience negative employment impacts, counterbalanced by the NE. The exception to this process is the South region, to which the industrial incentive in the NE would not be particularly detrimental. The South region is the only one apart from the NE which impacts would be positive (near neutral) in scenarios without industrial incentives (AR and CP) and with national incentives to the solar and wind component manufacturing (+Ind REN). It is noticeable, though, that in the South region, across scenarios, the most positive impacts are concentrated in the highest wage levels.

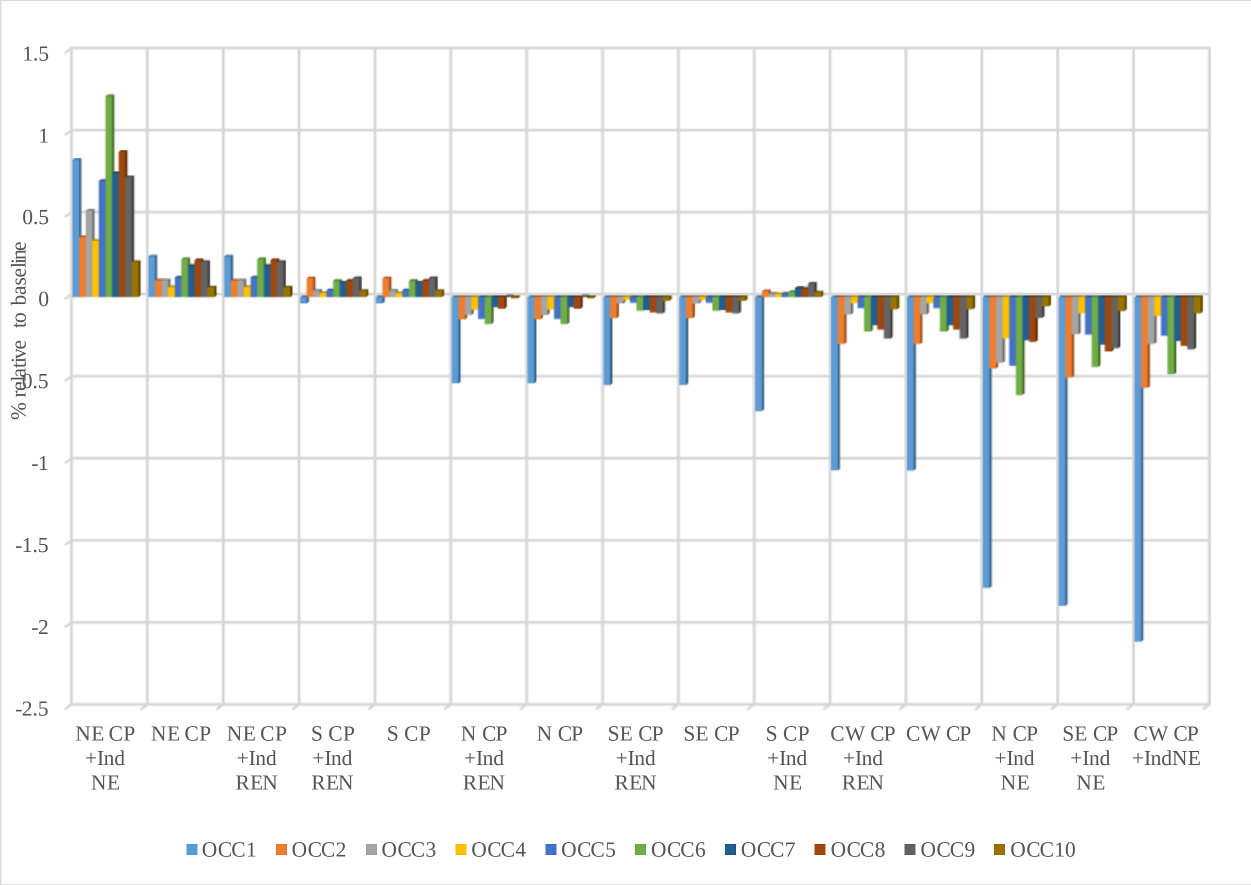

Figure 8.3 Regional employment in CP scenarios cumulative variation per occupation wage level – cumulative variation relative to baseline

The CW region, which economy is heavily based on agricultural commodities, is the most negatively impacted across scenarios. Impacts in the CW are particularly negative to the first wage level (OCC1), especially in the scenario where an industrial incentive in the NE is simulated: growth is 2.05% below the baseline in the AR trajectory and 2.10% lower than the baseline in the CP capacity expansion pathway. Like in the CW region, with the exception of the fourth wage band (OCC4), the impacts are less negative the higher the wage band, suggesting that unemployment would be deeper the lower the wage level in these regions.

8.1.2 Real wage per wage band

Real wage impacts are wage variations having discounted the loss in purchase power due to the inflation effect. Impacts disaggregated per wage level provide useful insights. As shown in Section 6.3, scenarios with industrial incentive in the NE have the most positive results in both electricity capacity expansion trajectories: AR (AR +Ind NE) and CP (CP +Ind NE). But noticeably, the most benefitted, or least negatively impacted, wage level across scenarios is the first one (OCC1).

On the national level (Figure 8.4) the increase in real wage of OCC1 suggests that the reduction in its number of jobs means that there is a movement of workers from this wage level to higher levels in the long-term. This is positive in terms of socioeconomic development. That is, less people are employed in the lowest wage band because they can move to jobs in higher bands. Employment in these higher wage bands, in turn, increased, or decreased less than average relatively to the baseline. This process is also consistent with the near zero employment impacts in the long run (the full-employment long-term assumption of the Walrasian theory): people who are not employed anymore in each wage band are normally employed in another wage band instead of unemployed.

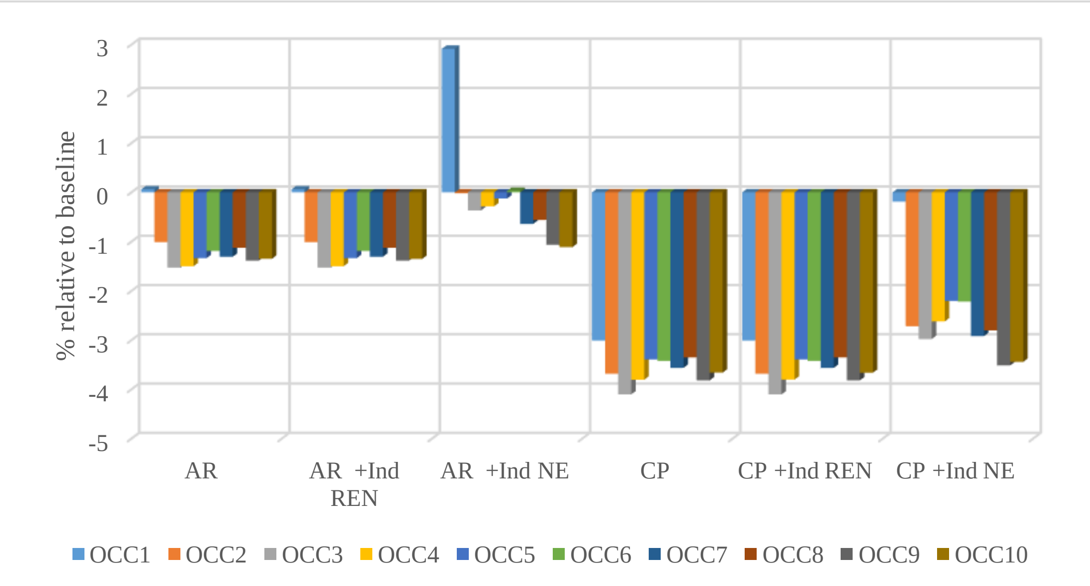

Figure 8.4 National real wage per scenario per occupation wage level - cumulative variation relative to baseline

Figure 8.5 and Figure 8.6 show the regional real wage impacts in AR capacity expansion pathways and CP capacity expansion pathways respectively. In the NE region, real wage impacts would be positive across all wage levels in simulations with the regional industrial incentive (AR +Ind NE and CP +Ind NE).

The NE region would have the lowest demand surplus for the lowest skilled work all cases, reflected in the fact the real wage of OCC1 has the lowest positive impact: 5.01% real wage growth increase relative to the baseline until 2050 in the AR capacity expansion scenario with the regional industrial incentive and 1.27% in the CP capacity expansion trajectory with the same incentive in 2050.

Indeed, the largest real wage gains were in the middle wage bands: 15.46% in OCC4 (AR +Ind NE) and 11.32% (CP +Ind NE) above the baseline until 2050. OCC4 is followed in both scenarios by OCC5, with 13.53% (AR +Ind NE) and 9.76% (CP +Ind NE), OCC7, with 12.88% (AR +Ind NE) and 9.08% (CP +Ind NE) and OCC3 with 12.72% (AR +Ind NE) and 8.40% (CP +Ind NE) above the baseline in 2050.

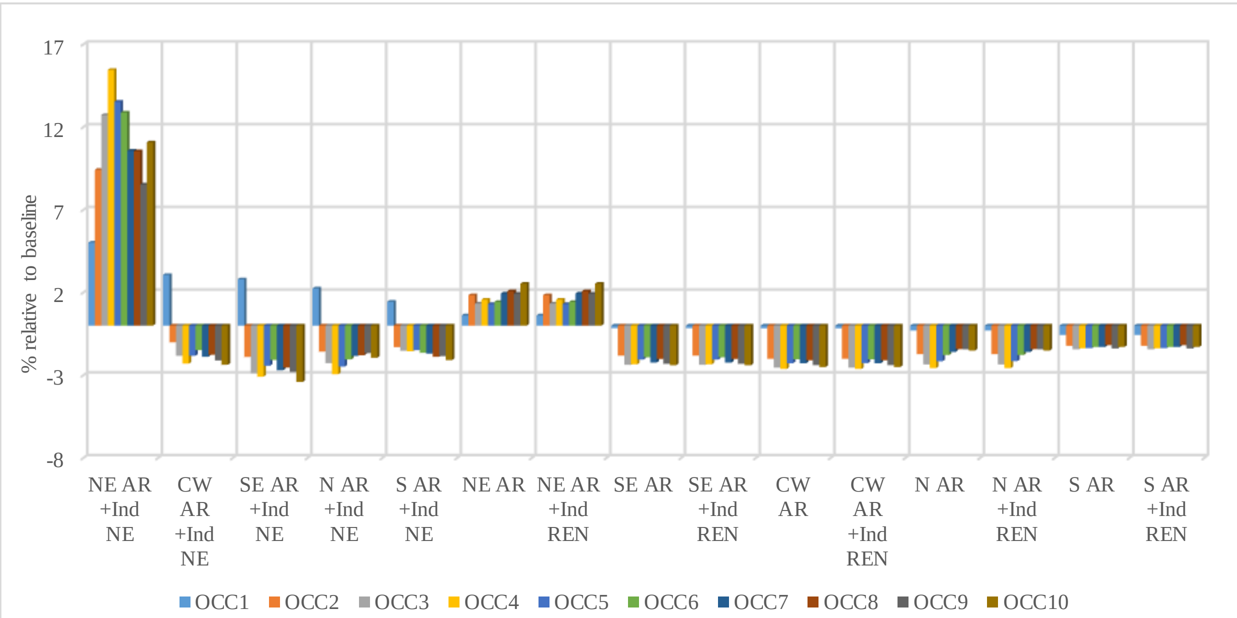

Figure 8.5 Regional real wage growth in AR scenarios per occupation wage level - cumulative variation relative to baseline in 2050

In the NE region, in all scenarios, OCC1 has the lowest real wage growth of all wage levels. In all other regions, in contrast, OCC1 has the highest positive, or lowest negative impacts depending on the case. Negative impacts across the other wage levels range between 3.00% and 1.20% below the baseline in the AR scenarios, and 6.09% to 3.35% lower than the baseline in CP scenarios. OCC1 impacts, in contrast, range between 0.57% below the baseline and 2.80% above the baseline in the AR scenarios and between 3.83% and 0.66% below the baseline in CP scenarios in 2050.

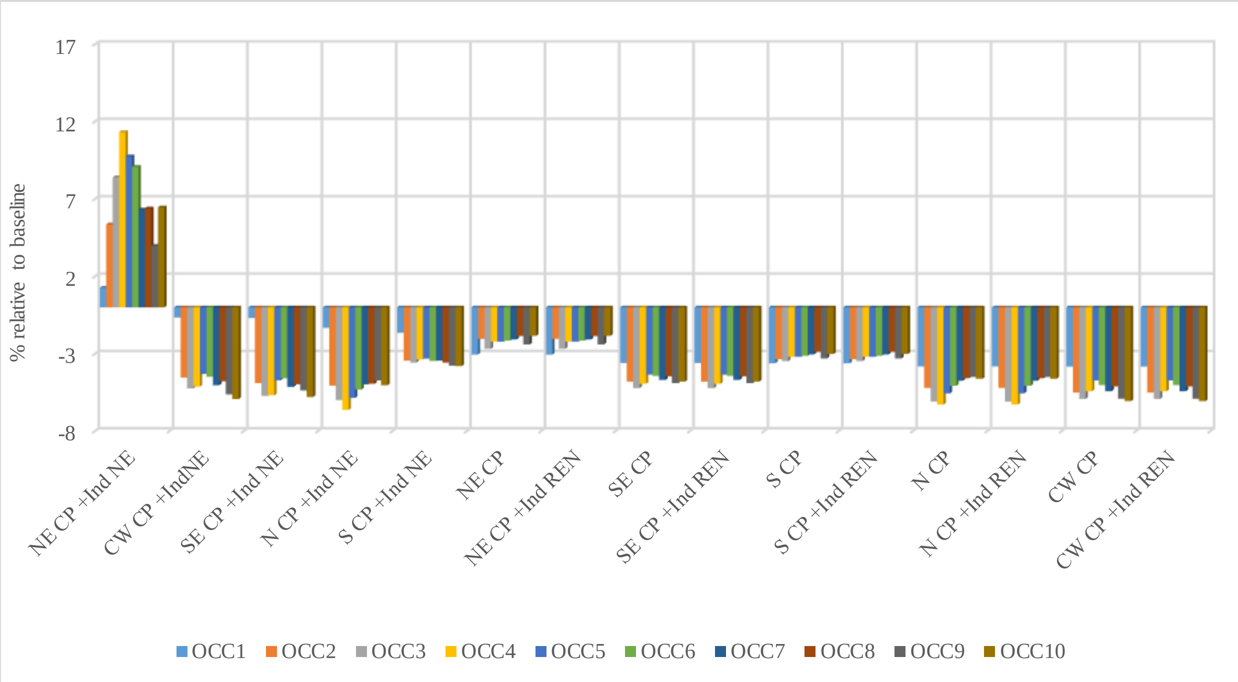

Figure 8.6 Regional real wage growth in CP scenarios by occupation wage level - cumulative variation relative to baseline in 2050

8.1.3 Migration: inter-regional workforce movements

Inter-regional migration movements show an important inversion to historical trends. In the simulations of the policy scenarios, since the NE is the only region where real wage grows above the baseline, it attracts workforce, while historically NE workers seek better opportunities in the SE region. Net impacts on inter-regional migration flows are shown in Figure 8.7 for AR capacity expansion scenarios and Figure 8.8 for CP scenarios. Negative flows mean workforce migration outflows are larger than inflows, while and positive migration flows means migration inflows are larger than outflows.

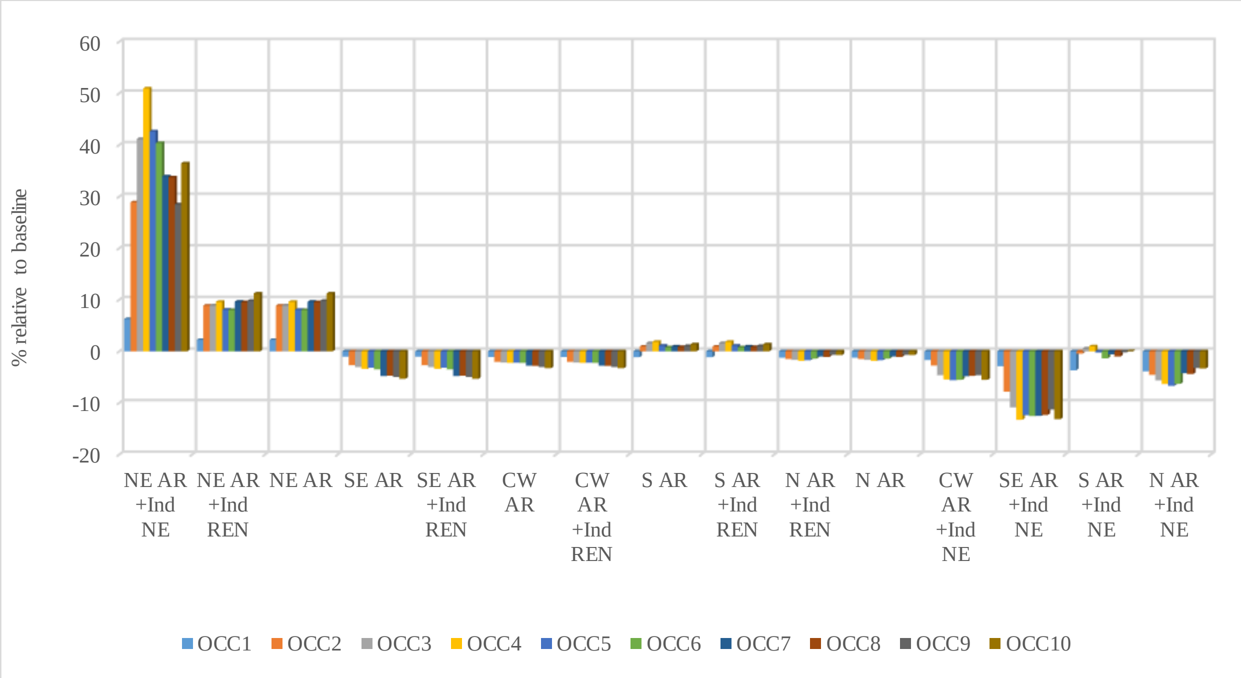

Figure 8.7 Migration inflows by destination region in AR scenarios by occupation wage level - cumulative variation relative to baseline

Migration flows follow real wage variations in each of the regions. This means that regions where real wage grows more than the baseline will attract workforce and regions where real wage decreases will experience migration outflows considering some level of mobility of the workforce. From both Figure 8.7 and Figure 8.8, it is visible that the NE and the South are the only regions receiving more migrants than those leaving from these two regions. This is directly related to regional real wage growth and ultimately to GDP growth observed in Chapter 6.

Most migration flows are concentrated in the middle wage bands, with a 50.94% increase in OCC4 migration inflows to the NE in the AR scenario with the regional industrial incentive (NE AR +Ind NE), and a 48.96% increase in OCC4 migration inflows to the NE in the CP scenario with such industrial policy (CP +Ind NE). In both capacity expansion pathways, OCC4 is followed by OCC3, OCC5 and OCC6, all around 40% positive variation relative to the baseline in 2050.

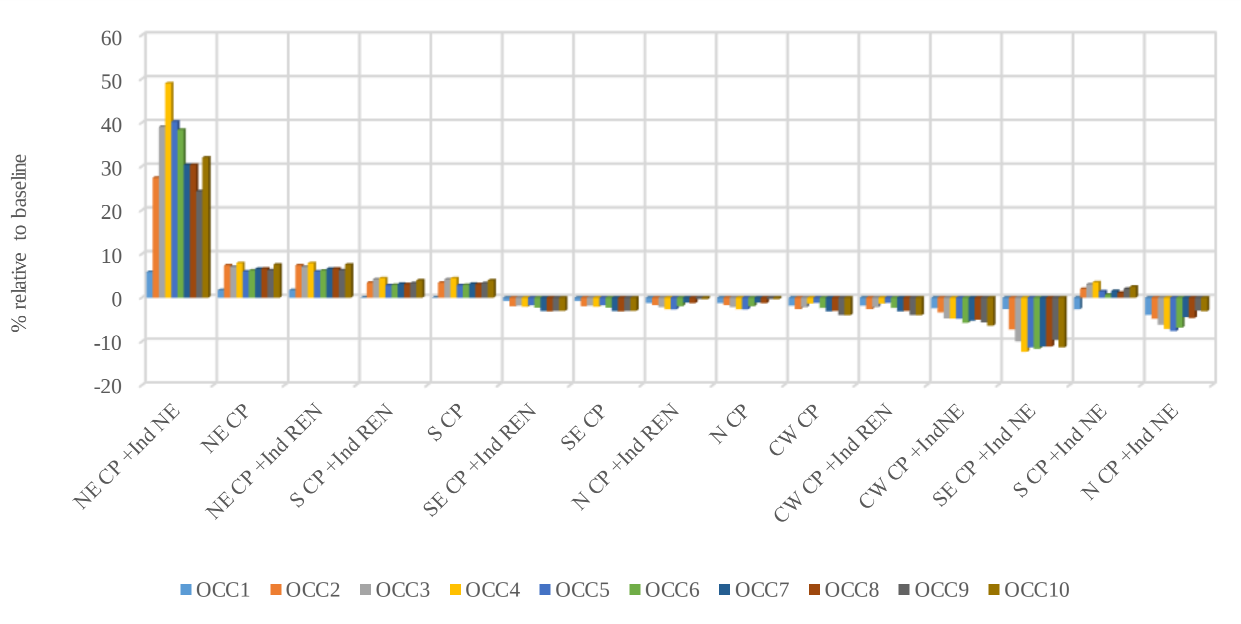

Figure 8.8 Migration inflows by destination region in CP scenarios by occupation wage level - cumulative variation relative to baseline

Apart from scenarios in which the regional industrial incentive in the NE is simulated, migration flows are fairly evenly distributed between the different occupation levels. The exception is normally the lowest wage level (OCC1), which labour supply and demand were mostly balanced within regions and therefore both inflows and outflows would experience little variations.

8.2 Household consumption

Household consumption levels are an important indicator of welfare, particularly when looking at lower income bands, to which the income elasticity of demand for normal goods is higher. This section analyses national and regional household consumption variation across the ten household income levels for the six scenarios simulated.

National impacts to household consumption are shown in Figure 8.9. Clearly, at the national level, the household groups to win the most, or lose the least, from investing in AR electricity would be the two lowest household income bands (HHInc1 and HHInc2). In all scenarios related to the AR capacity expansion pathway, as well as the CP scenario with the industrial incentive in the NE (CP +Ind NE), the two lowest income bands would benefit nationally.

In the AR scenario with the regional industrial policy in the NE, the lowest income band household (HHInc1) consumption growth would be 4.52% higher than the baseline, the second income band households (HHInc2) 2.88% higher, and, in this particular case, the third lower income band (HHInc3) would also benefit, with a consumption growth 1.13% higher than the baseline until 2050.

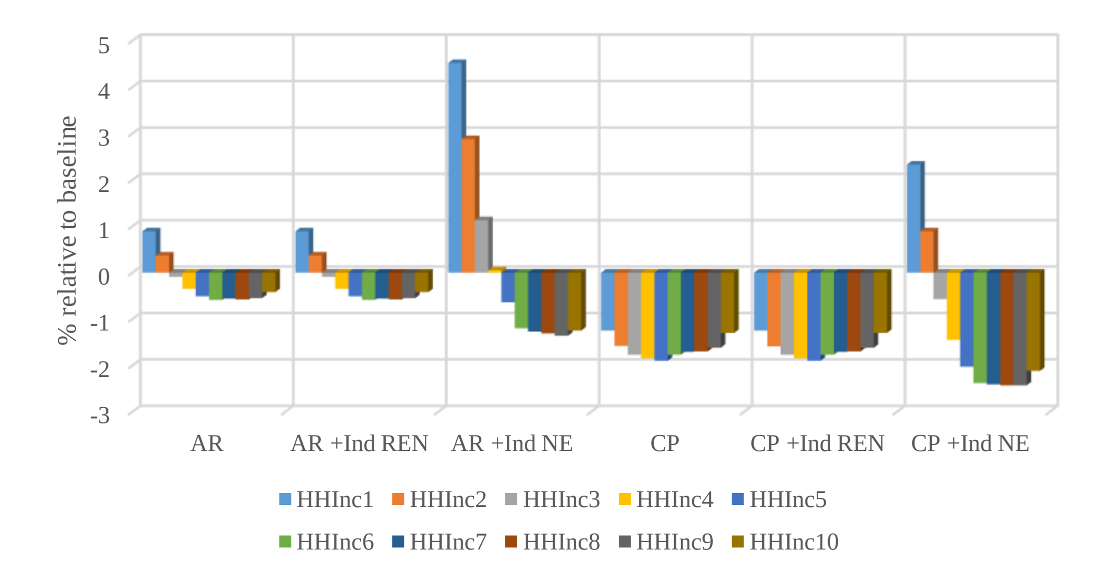

Figure 8.9 National household consumption growth per income level per scenario – cumulative relative to the baseline

When looking at regional impacts (Figure 8.10 and Figure 8.11), undoubtedly the household consumption winners in the process of AR energy investment are in the NE region. Also, household consumption gains are notably uniform across income bands in this region, particularly in the case of the AR electricity capacity expansion scenarios.

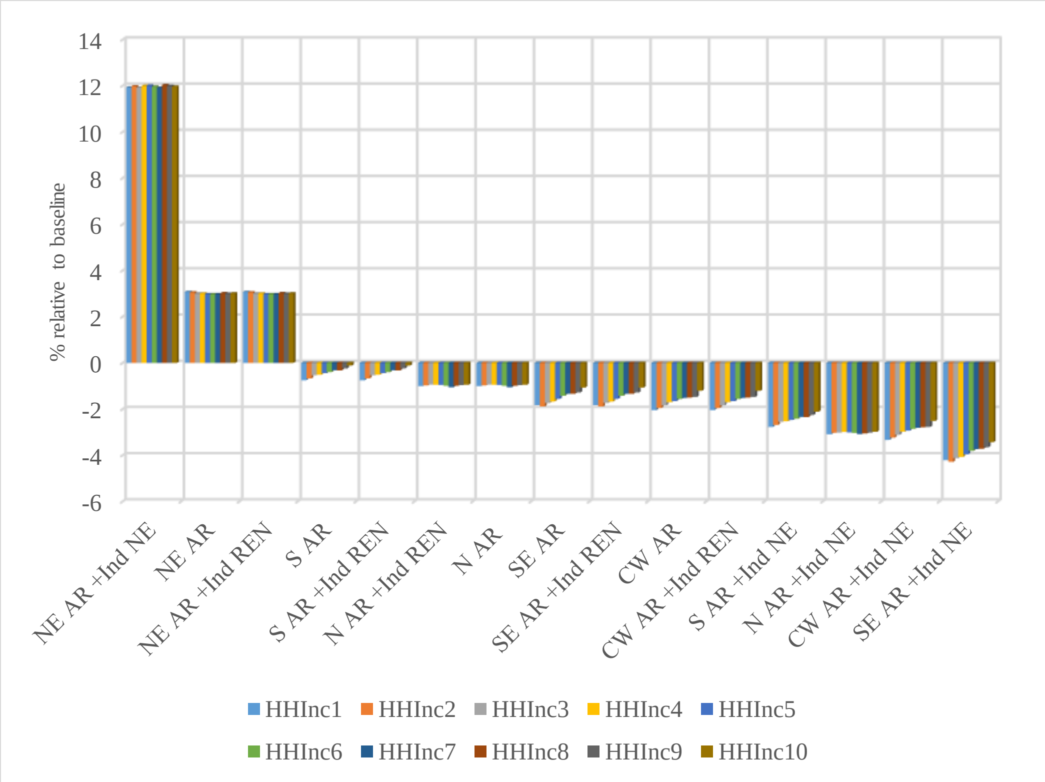

Figure 8.10 Regional household consumption growth in AR scenarios per household income band - cumulative variation relative to baseline

In the AR scenario with regional industrial incentive in the NE (NE AR +Ind NE), all household income groups would have an increase in consumption around 12%. In the AR scenarios without any industrial policy (NE AR) and with the national incentive to manufacturers of wind and solar energy components (NE AR Ind REN), all income groups household consumption would grow around 3% above the baseline until 2050.

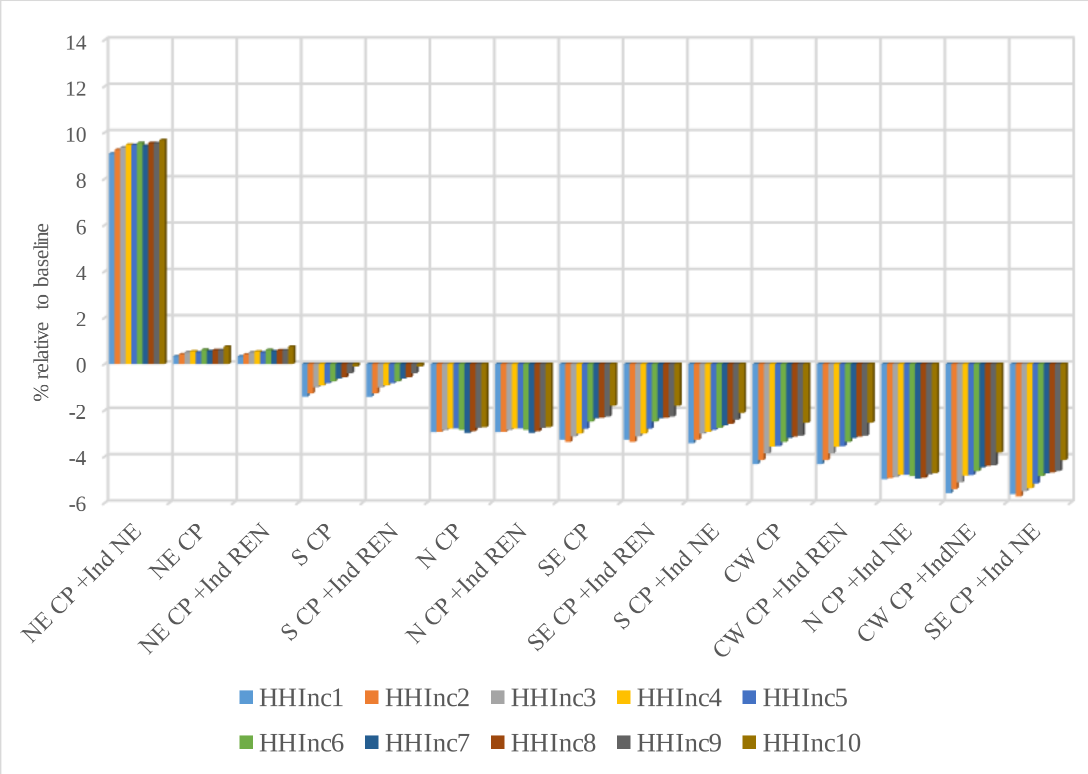

Figure 8.11 Regional household consumption growth in CP scenarios per household income band - cumulative variation relative to baseline

Most regions, though, show regressive impacts. That is, household consumption growth variations are more negative the lower the household income band. In the South region, in all scenarios, there is a near linear curve in which the most negative impacts on household consumption growth are to the lowest household income band (HHInc1), increasingly steadily until the least negative impacts occurring to the highest household income band (HHInc10). The same process is observable to the SE and CW. The North region is the exception in this process. Across scenarios, impacts in the North region are nearly constant across household income groups.

8.3 Expert elicitation insights on distributional impacts of electricity capacity expansion scenarios

Modelling results have shown clear economic benefits to the NE region from an investment spending that prioritises non-hydro renewable electricity as opposed to the baseline, in which natural gas and hydropower dominate the electricity mix. This means an improvement in the income distribution between Brazilian geoeconomic regions. However, improved income distribution between income bands within each region does not seem to be a natural tendency, since it does not happen in all regions. Clearly, more significant distributional benefits in the NE, both in terms of lower wage levels and household income levels, affect national results positively.

8.3.1 Income distribution within and between Brazilian regions

Most experts consulted[25], when shown modelling results, agreed that the baseline case of electricity capacity expansion will not be a driver of income distribution between the five Brazilian regions. Instead, they argued that pursing climate targets can be a driver for regional socioeconomic development particularly in the NE. The latter could happen not only by channelling non-hydro renewable energy investment to the NE region, but also by contributing to climate change mitigation and consequently avoiding the harsh climate impacts discussed in Section 2.4.2.

However, an overarching idea among participants of the expert elicitation is that any investment in the NE region is most welcome, but there must be accompanying public policies and strategies to promote income distribution. All experts agree that receiving any kind of infrastructure investment spending boosts regional economies. But this increase in economic activity is not a synonym of socioeconomic development, or does not necessarily enhance income distribution, most of them recognised.

They argued that the most important question is to which extent benefits really stay in the region, since, after installation, local population provide just a few maintenance services. Noticeably, modelling results suggest positive impacts throughout the period from 2020 until 2050. This happens because installation of new power plants does not cease until the end of the time horizon and the more non-hydro renewable installed capacity, the more the NE receives investment.

Notwithstanding, even if infrastructure investment does not by itself create socioeconomic development, it is still a necessary condition, even if not sufficient, according to experts[26]. Moreover, most infrastructure investment is traditionally concentrated in the SE. Hence, any scenario that reinforces this pattern, as is the case

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[25] ELS1, ELS2, ELS3, ELS4, ELS6, ELS7, DFI1, DFI2, DFI3, GOV1, AC1.

[26] DFI1, DFI3, GOV1, ELS3, ELS4, ELS7

of the baseline scenario modelled in this thesis, would only deepen regional inequalities according to the experts.

One expert (ELS3) raised the concern that other regions may not accept policies with the aim to distribute income between regions, rather than between income bands within a region. Losses to the SE, even if not absolute losses, but rather relative to a BAU case, may create political tensions, given that 42% of the population live in the SE. Although the NE is the second most populated region, with just over 27% of the Brazilian population (as seen in Chapter 3, Section 3.2).

8.3.2 Multi-objective policies and additional strategies to retain socioeconomic co-benefits in the NE

Most participants of the expert elicitation agreed that income distribution both between regions and between income bands can only be met by multi-objective energy policy with multi-level governance. But multi-objective energy policy is not yet a reality in Brazilian ministries, especially with regards to the energy system. Energy public policy is done very much in silos in Brazil, according to most experts. One of the experts from the electricity sector said:

> "*In Brazil, we do not have multi-objective policies but rather multiple overlapping policies sometimes for a single objective*." (ELS4)

Arguably, regional development strategies must include broader policies than only some temporary industrial incentive. It should tackle for example capacity building, in the long term to increase the skill level of workers across renewable power plant supply chains in the NE, where labour productivity is the lowest. An example of this in Brazil, raised by one of the experts (ELS7), is the National Service for Industrial Learning (SENAI). SENAI is a non-profit private education system linked to the National Industrial Confederation (CNI) and several industrial unions which provides professional education based on demands from manufacturing segments. But promoting socioeconomic development as such needs further political alignment, organised civil society, stronger capacity building programmes that are consistently maintained for at least 30 years, according to two of the experts consulted (GOV1, ELS7).

One expert raised the concern that policymaking can only deliver multiple-objective policies if the different interested parties can reach consensus (ELS3). If policy options are not the optimal in the power-system mathematical models, they must still be seen as near optimal to the electricity system to be implemented, given the political strength and power of influence of this sector. Electricity sector officials may question multisectoral climate policies for example because they may not be the cost-minimising choice. However, most experts consulted seem to agree that it is a major problem for the country that the electricity sector sees itself as exogenous to all processes. It is widely agreed that the operation and planning of the electricity sector is currently rather isolated from other sectors and policies, and that it is inefficient for the country's development that it operates as such.

8.3.3 Electricity sector position as exogenous to the economic system

Experts who serve in the electricity sector operations as such[27] tend to see regional development as a much more natural co-benefit of electricity capacity expansion than academics and regional development experts[28]. Electricity sector officials and executives see positive economic indicators as closer to a synonym of development and identify less need for coordinated, multi-objective policy including energy policy, regional development, industrial and environmental policies, for example.

When asked about regional development and multi-objective policies, some of the experts serving electricity system organisations were vague in their responses. They argued that there is no doubt that the investment in new electricity generation capacity creates regional socioeconomic development (ELS1, ELS2, ELS6). Some added that, in their view, any electricity generation source has positive and negative externalities. They do not see the regional development aspect, or objective, of policies as a role of the electricity sector. Instead, they attribute the responsibility to actors such as national and regional governments, municipalities, agencies and other public actors such as the development banks. They do not indicate, however, the willingness to collaborate closely with these jurisdictions and institutions in order to promote regional development.

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[27] ELS1, ELS2, ELS3, ELS5, ELS6

[28] DFI1, DFI2, DF3, DF4, GOV1, AC1, ELS7.

The dispute for water endorses the need for better coordination and integration between the multiple policy objectives. As highlighted in Section 3.2, access to resources can be determinant to the economic activities that a region develops, but also directly related to the socioeconomic conditions of their populations. Hence, policymaking clearly needs to consider national electricity provision, access to vital resources such as water and socioeconomic development through quality job creation that promotes income distribution. There is therefore a strong case for a national view rather than a sectoral view, as was put by an expert elicitation participant (ELS4). This means a strong call for different ministries to cooperate, but most importantly, for the Ministry of Mines and Energy (MME), which is seen as isolated, to cooperate with other ministries.

BNDES finance conditionalities are seen as the most successful strategies in bringing the electricity sector planning closer to other development objectives, notably industrial development. Arguably, industrial development is a driver of socioeconomic development, as seen across previous chapters. But even when industrial development is achieved, income distribution depends on further policies to ensure that electricity capacity expansion policies do not have a regressive effect, and ideally that they improve income distribution.

One expert (DFI2) stressed that energy companies have implemented local social programmes in municipalities in the NE where they have installed wind farms and invested in capacity building. This was the case, for example, of the energy company Renova Energia in municipalities in the state of Bahia, where they performed training programmes and formed a partnership with the city hall of the municipality of Caetité to employ local workers (Prefeitura Municipal de Caetité, 2021). However, the expert (DFI2) argued that companies' social programmes have too little impact. Local governments need more fiscal space to spend in structural programmes to retain benefits of renewable electricity investment.

As discussed in Section 6.7.2, expert elicitation participants also raised the concern that electricity generation tax income does not translate into programmes to the community (DFI2, DF3, GOV1, ELS4). Tax revenue could promote public education to the children and therefore social mobility in the long run, capacity building to current workers and local infrastructure. They argue that if tax collection were done by local governments, they could canalise electricity tax income to the right regional objectives. However, federal tax collection channels this tax income to the national treasury and its spending has no commitment to where tax income was generated.

There is a clear potential for solar PV in the NE semiarid (as indicated in Section 2.4.1), where capacity factor is particularly high, which the same expert (GOV1) believes could develop the urban fabric in the semiarid. Small towns lacking infrastructure are still to be planned. So, they have the opportunity to become smart cities with the income that would come to states and municipalities depending on the tax structure. But it is critical that a supply chain is developed in the region including services, that should not be provided by firms based in other regions with qualified labour force that just visits the region on a temporary basis. So, the conclusion is there is great potential for regional development through this investment inflow, but it depends on planning and accompanying policies (GOV1).

One expert pointed out that the Brazilian energy planning agency EPE conducts socioenvironmental impact assessments for its decennial energy plan (ELS5), mostly influenced by the controversies around large hydropower projects, highlighted in Chapter 2. However, these studies are not systematically produced ahead of project implementation, and it does not necessarily influence decision-making at the ministry level. Additionally, another expert consulted (ELS1) raised that the MME does not consider such studies in its policy making.

8.3.4 Further bottlenecks for income distribution

Land ownership and land lease were raised by five of the experts as a pressure point that hinders income distribution particularly related to wind farms in the NE (AC1, DFI1, DFI2, GOV1, ELS4). They argued that wind farms land lease contributes to income concentration since the existing owners of large properties are the ones who lease their land to wind farm, and therefore land lease income is concentrated. Besides, competition for the use of land for power plants, different demands for land lease, increase regional land prices in the NE, which land prices are and have always been lower than in the rest of Brazil.

One of the experts (GOV1) argued that the main bottleneck for further onshore wind expansion is land disputes. This is because energy companies buy large portions of land with a huge wind generation potential, but they do not use all of the land, so this may saturate the wind market without having exploited all of the electricity generation potential.

Distributed generation can potentially contribute to solve the land lease problem. Two experts (GOV1, ELS4) indicated that large wind power projects, besides concentrating income through land lease, create few jobs, most of them high skilled engineering jobs whose workers come from the SE and South temporarily. They receive the highest salaries of the industry, but they create demand in the region where they are based. Distributed generation, in contrast, arguably creates a larger number of stable jobs in the middle wage bands with installation divided into a larger number of smaller projects than centralised generation.

8.4 Discussion

Modelling results suggest job creation and improvements in income distribution and wage levels associated with higher shares of non-hydro renewable energy in the NE region mostly, and more mildly in the South region. Strategies underlined by the experts consulted in the expert elicitation can enhance results observed in the simulations, in which case non-hydro renewable investment can create more quality jobs, generate more income, and promote more income distribution.

These strategies start from the cooperation between the various ministries in the policymaking process though a multi-sectoral group to ensure multi-objective policy formulation. This includes: (i) energy planning, through the Ministry of Mines and Energy; (ii) the ministry of environment, to align electricity capacity expansion with climate targets; (iii) the Ministry of Integration and Regional Development, which should consider renewable electricity investment as a driver for regional development; (iv) the Ministry of Finance, the Ministry of Development, Industry, Trade and Services and the Ministry of Planning, to rethink local fiscal space and to promote targeted industrial development and potential industrial exports; (v) the Ministry of Education, to create the right skills in regional workforce. This group should also include all the respective administrative units in municipality and state governments.

This multi-sectoral policy group should consider (i) creating the right capacity building in the short term and an education plan for the long term for local workers to fill the new job posts created; (ii) revising tax collection to allow local governments to implement strategies; (iii) fostering distributed generation to reduce income concentration and competition for land use; (iv) accounting for water scarcity and its impacts over the population's socioeconomic conditions when conducting energy planning and considering further hydropower generation.

The competition for the use of water is a clear example of the isolation of the electricity sector planning that impacts directly the socioeconomic conditions of the population, notably in the NE (Caiado Couto et al., 2021; Carvalho, 2020). The main water basin of the NE, the São Francisco River basin, has been the subject of intense disputes between electricity generation, household water provision, agriculture and livestock, and environmental concerns. Around 91% of the NE hydropower generation capacity resides in dams of this basin. It is also the main water body supplying water to households in the NE. However, agriculture irrigation is the main water use in this basin due to the semiarid conditions of the region.

Arguably, the electricity sector seems to dominate the basin management and planning hindering other economic activities and the achievement of minimum living standards in NE households (Carvalho, 2020). Besides, it is important to notice that given the integrated nature of the SIN, electricity generated in the São Francisco River basin is mostly exported to supply the load in other regions, particularly the SE. Hence, hydropower generation in the San Francisco River basin does not necessarily provide electricity to the NE but is part of the dispute for the scarce water resources of the NE region.

Therefore, the main conclusion is that non-hydro renewable energy policy in the electricity sector can create energy security while contributing to improving socioeconomic conditions and living standards in the NE region. However, multi-objective policies must be planned and implemented via coordinated efforts of several departments and levels of government.

8.5 Chapter 8 conclusions

Chapter 8 presented the results of the CGE modelling simulations of electricity capacity expansion scenarios for labour, income and households, responding directly to the research question (iii) of this thesis, presented in Section 1.1. This chapter explored the hypothesis of improvements in income distribution between and within Brazilian regions from the current conditions, which were revised and discussed in Chapter 3.

Modelling results have indicated that scenarios with higher shares of non-hydro renewable electricity in the mix create a demand for higher-skilled labour nationally. However, as discussed in the expert elicitation insights (Section 8.3 and the chapter discussion (Section 8.4), multi-objective policies are necessary to create a migration from lower skills toward higher skilled jobs.

It is visible from the results present in Chapter 8 that the NE region is the greatest winner in terms of job creation of the process of renewable electricity capacity expansion. Across all scenarios and wage levels, employment increased relative to the baseline in the NE region. This shows that a renewable pathway is not only feasible but would create more jobs in Brazil's poorest region than a less-renewable pathway. However, most regions apart from the NE experience negative employment impacts in the policy scenarios, counterbalanced by the NE, indicating the regional trade-offs discussed by participants of the expert elicitation in Section 8.3.1.

Modelling results for inter-regional migration movements have indicated a relevant inversion to previous migration flows in Brazil. In the policy scenarios, the NE is the only region where real wage grows above the baseline and therefore the NE region it attracts workforce. Historically, however, the NE workers have migrated in search for better opportunities in the SE region, where wage levels are higher. The NE region is also the clear winner in terms of household consumption in policy scenarios. Household consumption gains are equal across income bands in this region, particularly in the case of the AR electricity capacity expansion scenarios. Chapters 6-8 have presented the results of the modelling work and expert elicitation, answering questions (i), (ii), and (iii). The final chapter pulls these results together, and draws conclusions from the research, identifying further research needs and policy recommendations.

9. CONCLUSIONS

9.1 Restatement of the research problem

The economy-wide impacts of the energy transition are still unknown. The fear that the transition will cause an economic downturn can create strong political resistance against climate action. Besides, the literature widely recognises that the transition should not have regressive impacts (Grubb et al., 2022). That is, the energy transition should not destroy jobs or negatively impact lower-income workers and households more than the wealthier ones.

Brazil has a specific challenge related to the energy transition in the electricity sector, which is intrinsically related to climate change's physical impacts and natural resource availability (Chapter 2). Brazil's electricity generation has historically had a low emission profile, given its dependency on hydropower caused by abundant water bodies. However, changes to rainfall regimes are increasingly hindering hydropower generation. Moreover, most of the remaining hydropower potential is unlikely to be explored due to the socioenvironmental impacts prohibited by laws to protect indigenous communities and the environment, particularly in the Amazon. Due to these two factors, the electricity system has heavily resorted to thermal power generation in the last ten years.

Hence, the future of the renewable profile of the Brazilian electricity mix is threatened, contradicting its climate commitments. However, the Lula da Silva administration, who came into power on 1st January 2023, has shown determination to meet Brazil's climate targets in the energy sector by creating the Energy Transition Secretary under the Ministry of Mines and Energy on the 2nd of January 2023 (MME, 2023).

Brazil has a clear opportunity to meet its increasing demand for electricity with non-hydro renewable sources, notably wind and solar power. Brazil's wind and solar electricity generation potentials are concentrated in its least developed geoeconomic region: the Northeast (NE). The latter has the country's poorest socioeconomic indicators. Economic activities beyond subsistence agriculture failed to develop there, partly due to its semiarid climate with annual harsh and prolonged droughts.

Therefore, Northeast Brazil is a textbook case for understanding the socioeconomic impacts of investing in solar and wind power plants (as seen in Chapter 3). However, the existing literature assessed only the job and income creation of the specific power plant projects. The economy-wide net impacts of the long-term process, comparing counterfactual scenarios, is the research gap this thesis has filled.

Arguably, EMDEs like Brazil will only benefit from the energy transition to create socioeconomic development in the long term if they develop the industries of the supply chains for such technologies. This argument also applies to regions within a continental country such as Brazil. While Brazil's South and Southeast regions have industrialised, the Northeast, where most investments in wind and solar power happen, has never substantially attracted segments producing high-value-added goods and services before. Hence, socioeconomic development in the Northeast region that reduces regional inequalities in Brazil goes beyond economic growth as such. It should include developing new economic activities, education and capacity building that increase skilled labour to supply the new demand created by renewable electricity investment spending.

By combining multi-regional CGE modelling (Chapter 4, Sections 4.1 to 4.6) with energy-system models’ scenarios (Chapter 5) and the expert elicitation (Section 4.7), this thesis has shown that renewable pathways are not only feasible but also economically and socially beneficial, particularly to Brazil’s least developed region, the Northeast. The thesis assessed the multi-regional socioeconomic impacts of electricity capacity expansion scenarios in Brazil, considering different levels of each electricity source in the mix until 2050.

The analysis developed a multi-regional recursive-dynamic CGE model for Brazil with the following disaggregated electricity sources: wind, solar, hydropower, natural gas, coal, nuclear, biomass, petroleum products and others, as well as the transmission and distribution sector. Then, a soft link was done with three different energy system models (Chapter 5), which produced the three scenarios for electricity capacity expansion from 2020 to 2050 for each of the five geoeconomic Brazilian regions. The analysis then included scenarios of two options of industrial policy accompanying the investment spending of electricity capacity expansion: (i) a 1% federal tax reduction to the national production of solar and wind power plant equipment in the most relevant industrial segments to these two supply chains; and (ii) to these same industrial segments in the Northeast region.

The expert elicitation (detailed in Section 4.7) which consulted 13 senior experts acting in aspects relevant to the Brazilian electricity sector and development complemented the modelling simulations. The expert elicitation explored the implications of modelling results to policy making and thus additional aspects not included in the scope of the modelling. The expert elicitation results were used to discuss the possibility of developing the Northeast region of Brazil through solar and wind power investment spending in the region and long-term electricity generation in Brazil.

9.2 Main findings

The main finding from modelling simulations is that the more wind and solar in the electricity mix, the more socioeconomic benefits occur in Brazil's least developed region, the NE. Therefore, both Alternative Renewable (AR) energy policy and the multi-sectoral Climate Policy (CP) in Brazil would create positive macroeconomic, sectoral and distributional impacts on the NE region. However, mild negative impacts on other regions partly compensate, mainly in the most developed SE, revealing a regional trade-off. Therefore, the analysis performed in this thesis found the winners and losers of long-term renewable electricity generation policies.

This thesis modelled the macroeconomic, sectoral and distributional impacts of electricity capacity expansion in the five geoeconomic Brazilian regions (South, SE, North, NE and CW) in seven scenarios in total, namely:

1. Baseline
2. Alternative Renewable electricity capacity expansion scenario (AR)
3. Climate Policy electricity capacity expansion scenario (CP)
4. Alternative Renewable electricity capacity expansion scenario with a national wind and solar supply-chain industrial policy (AR +Ind REN)
5. Climate Policy electricity capacity expansion scenario with a national wind and solar supply-chain industrial policy (CP +Ind REN)
6. Alternative Renewable electricity capacity expansion scenario with an industrial policy to targeted segments in the NE region (AR +Ind NE)

7. Climate Policy electricity capacity expansion scenario with an industrial policy to targeted segments in the NE region (CP +Ind NE)

This thesis has used an expert elicitation to test the results of the multi-regional electricity-sector-tailored CGE modelling analysis against real-world conditions. The main finding from the expert elicitation process is that modelling results indicating positive outcomes to the NE region can and should be used to encourage long-term renewable energy policy in Brazil. However, a multi-level and multi-objective policy must be in place through the coordination of various government departments and agencies to improve the well-being and increase the economic standard of living of the region's population.

The results were grouped into the responses to each of the three research questions of the thesis stated in Section 1.1: Chapter 6 answers research question (i), Chapter 7 answers research question (ii) and Chapter 8 research question (iii). The following subsections explore the main findings organised according to the three result chapters: Section 9.2.1 explores the macroeconomic impacts from Chapter 6; Section 9.2.2 the industrial and sectoral impacts from Chapter 7 and Section 9.2.3 the distributional impacts from Chapter 8.

9.2.1 Macroeconomic impacts

The impacts of long-term renewable electricity generation policies on the national and regional macroeconomic aggregates presented in Chapter 6 respond to this thesis's research question (i), stated in Section 1.1. This research question was answered by finding that higher investment in solar and wind power capacity expansion has a slightly negative long-term impact on national real GDP compared to a baseline scenario in which natural gas and large hydropower are the basis of the electricity mix. National cumulative GDP growth in the policy scenarios from 2020 to 2050 was 2.2% lower than the baseline in the most negative impact case of the CP scenario with industrial policy in the NE (CP +Ind NE).

Overall, scenarios associated with the CP electricity capacity expansion trajectory have resulted in the most negative deviations from the baseline, while the AR pathway yields the most positive outcomes. Regional GDP results reflect this process: the most significant gain was in the NE for the AR capacity expansion scenario associated with an industrial incentive to the regional industrial segments relevant to power plants supply chains (NE AR +Ind NE).

Real investment variation results show a similar tendency to the real GDP at the national level. Most policy scenarios result in a slightly lower than the baseline real investment level. The exceptions are the CP scenario with no industrial policy and the CP capacity expansion trajectory associated with the national industrial incentive for solar and wind supply chains (CP +Ind REN). They presented the most negative results across scenarios: 4.72% lower than the baseline in 2050. The largest positive impact on real investment across all scenarios and geographical levels is the AR trajectory with regional industrial policy in the NE (NE AR +Ind NE scenario) at 21.14% real investment gain to the NE region until 2050.

At the national level, aggregate employment is the closest to the baseline results across variables analysed, given the theoretical nature of the CGE model. The largest variation observed is 0.11% lower than the baseline in the AR and CP capacity expansion trajectories combined with regional industrial policy in the NE (AR +Ind NE and CP +Ind NE).

At the regional level, scenarios following the AR electricity capacity expansion show more positive results for aggregate employment than those of the CP trajectory, combined or not with industrial incentives. Again, the NE benefits the most, particularly in the AR scenario, with a regional industrial incentive (NE AR +Ind NE). It is the only result presenting a variation over 0.5% both for national and regional results, including positive and negative variations. In this scenario, the NE yield a 0.56% cumulative gain in employment creation, despite the national loss of this scenario being the largest.

It is important to notice, however, that renewable energy policy will need accompanying strategies to ensure sustained improvements to the socioeconomic conditions of the NE region. The expert elicitation has shown that exploring what development means to the different groups involved is essential. Together, policymakers and civil society need to determine whether their aim is purely to increase capital stock and GDP growth, the growth of the set of macroeconomic aggregates analysed here, or variations in other indicators of sustained improvement in the living standards of communities.

Although long-term renewable energy policies will probably increase the NE region's GDP, we cannot expect the economic profile and structure of the NE region to change until 2050 purely by receiving renewable electricity investment. In order to bring about new economic activities with higher value-added, sustained job creation and capacity building for high-skilled jobs, experts highlighted the need for industrial strategies that would promote manufacturing sectors. The following subsection explores the impacts on these sectors.

9.2.2 Industrial and sectoral impacts

The impacts of electricity capacity expansion scenarios on industrial sectors presented in Chapter 7 respond to this thesis's research question (ii), stated in Section 1.1. This question was answered by presenting and discussing the results of the modelling simulations of scenarios for the main manufacturing sectors of power plants' supply chain, as well as the endogenous employment impacts on each of the electricity sources.

On the national level, it is visible that manufactured goods production is negatively impacted relatively to the baseline by the AR and the CP capacity expansion pathways unless there is a targeted regional industrial incentive in the NE. On the other hand, the national incentive specific to wind and solar components (Ind REN) does not cause a notable reduction in negative impacts. This is because the industrial incentive to the selected sectors in the NE (Ind NE) has a much larger impact on industrial output than the national incentive to solar and wind components (Ind REN).

Associating electricity capacity expansion scenarios with industrial policy creates more positive socioeconomic impacts in Brazil. National industrial incentives to targeted manufacturing sectors producing components of wind and solar plants create very small socioeconomic benefits across variables analysed. Notwithstanding, regional industrial policy to propel the relevant manufacturing sectors in the NE yields larger national socioeconomic benefits than the previous industrial policy option. Socioeconomic benefits and long-term structural changes observed in the NE economy create only mild negative consequences for other regions.

Sectors targeted (Metallurgy, Electronics and Machinery and Equipment) clearly benefit from the NE regional industrial policy even at the national level. In the CP scenario without industrial incentives, impacts relative to the baseline reach 6.26%

below the baseline on Metallurgy output, 8.25% on Electronics output and 9.72% on Machinery and Equipment. In contrast, national incentives to wind and solar component production showed negligible effects in reducing the negative variation. However, the regional incentive to these three targeted sectors in the NE causes positive impacts in simulations performed here. In the AR pathway with such a policy, Metallurgy output grows by 7.25% above the baseline, Electronics output by 3.34% and Machinery and Equipment by 3.27% above the baseline level in 2050.

Nationally, the results of direct employment impacts in electricity generation sources have shown that the largest positive variations across scenarios are those of solar PV. However, this reflects that in the base year, 2015, employment in this segment was very small (799 FTE in 2015). Wind and solar PV were the only two segments of the electricity sector in which employment increases. Wind employment would increase from 62% to 65% in the AR trajectory between 2020 and 2050.

9.2.3 Distributional impacts

The impacts of electricity capacity expansion scenarios on industrial sectors presented in Chapter 8 respond to this thesis's research question (iii), stated in Section 1.1. The answer to this research question consists of modelling results for labour and households; each disaggregated into ten income levels.

Modelling results suggest that including more wind and solar power in the electricity mix improves income distribution in the NE region while worsening in the SE and South regions. The NE region gains in job creation and real wage levels, especially in the middle-wage bands (OCC 4-7). This process increases migration from the SE to the NE, which is the inverse of historical processes.

At the national level, aggregate employment is slightly lower than the baseline, with near zero negative impacts. However, the most negative impacts occur on the lowest wage band (OCC1) in scenarios with an industrial incentive to target industrial sectors in the NE region. In the AR capacity expansion scenario with a regional industrial incentive in the NE (AR +Ind NE), employment in the lowest band would be 1.38% lower than the baseline in 2050, while in the CP trajectory with the same incentive (CP +Ind NE), the negative impact would be 1.28%.

At the national level, the real wage increase of OCC1 suggests that the reduction in its number of jobs means a movement of workers from this wage level to higher levels in the long-term. This is positive in terms of socioeconomic development. That is, fewer people are employed in the lowest wage band because they can move to jobs in higher bands. In turn, employment in these higher wage bands increased or decreased less than average relatively to the baseline.

The NE and the South are the only regions receiving more migrants than those leaving, meaning they have net positive migration flows. This is directly related to regional real wage growth and ultimately to regional GDP growth observed in Chapter 6. The middle-wage bands concentrate most inter-regional migration flows, with a 50.94% increase in OCC4 migration inflows to the NE in the AR scenario with the regional industrial incentive (NE AR +Ind NE) and a 48.96% increase in OCC4 migration inflows to the NE in the CP scenario with such industrial policy (CP +Ind NE). In both capacity expansion pathways, OCC4 is followed by OCC3, OCC5 and OCC6, with around 40% positive variation relative to the baseline in 2050.

Most participants of the expert elicitation, when shown modelling results, agreed that pursing climate targets can be a driver for regional income distribution particularly in the NE. The latter could happen not only by channelling non-hydro renewable energy investment to the NE region, but also by contributing to climate change mitigation and consequently avoiding the climate impacts that affect the poorest the most.

Experts argued that income distribution both between regions and between income bands can only be achieved by multi-objective policy implemented with multi-level governance. But multi-objective energy policy is not yet a reality in Brazilian ministries, especially with regards to the energy system, which is isolated and positions itself as exogenous to the economic system. The next section will explore the policy recommendations to overcome the challenges outlined.

9.3 Policy recommendations

As discussed in Chapter 8, modelling results show job creation and improvements in income distribution and wage levels associated with higher shares of non-hydro renewable energy in the NE region, mostly and more mildly in the South region. However, strategies underlined by the experts consulted can improve results observed in the simulations, in which alternative renewable energy investment can create more quality jobs, generate more income, and promote more income distribution.

The strategies involve primarily the cooperation between several governmental sectoral departments and ministries through a multisectoral group to ensure multi-objective policy formulation. The following groups should be included in a task force (i) energy planning officials through the Ministry of Mines and Energy; (ii) the Ministry of Environment to align electricity capacity expansion with climate targets; (iii) the Ministry of Integration and Regional Development, to include renewable electricity investment as a driver for regional development; (iv) the Ministry of Finance and the Ministry of Development. Industry, Trade and Services and the Ministry of Planning, to rethink local fiscal space and to promote targeted industrial development and potential industrial exports; (v) the Ministry of Education, to create capacity building and foster the right skills in the regional workforce. This task force should as well include all the administrative units in the local levels, municipality and state governments.

This multisectoral policy group should consider (i) creating the right capacity building in the short term and an education plan for the long term for local workers to fill the new job posts created; (ii) revising tax collection to allow local governments to implement strategies; (iii) fostering distributed generation to reduce income concentration and competition for land use; (iv) accounting for water scarcity and its impacts over the population's socioeconomic conditions when conducting energy planning and considering further hydropower generation.

9.4 Contributions to existing knowledge

This thesis has been the first effort in the literature to quantify the socioeconomic impacts of long-term scenarios for electricity capacity expansion in Brazil by modelling the impacts of long-term electricity investment through a macroeconomic model. Previous literature had assessed, mainly through Input-Output multipliers, job creation, income and output generation of specific renewable energy projects in Brazil. However, this has been the first research to assess net economy-wide impacts for the whole country of increasing the share of non-hydro renewable capacity expansion in the long term.

This research is one of the few to conduct the assessment above for a developing economy, and it is only the second of the BRICS countries to have this type of analysis after China. This allowed for a comparison of results with the latter. Additionally, very few CGE models are multi-regional within a country, and even fewer in applications to electricity generation sources, disaggregating this sector into sources. Finally, most CGE models have a single representative household, a limitation of other studies that prevents them from analysing distributive impacts. This thesis addressed the limitation by modelling ten income-levels of households and ten wage levels for the workforce. This enabled the analysis of the socioeconomic impacts of the transition, which is important not only to provide evidence to governments for such transitions, but also to ensure that ‘no-one is left behind’ (as introduced in Chapter 8).

Although CGE models have been widely used to estimate the socioeconomic impacts of policies, the data challenge of calibrating a multi-regional model within a country is significant. This is due to the lack of trade data between sub-national regions for almost all countries in the world. Moreover, the disaggregation of the electricity sector of a macroeconomic model into sources is a substantial data-related challenge, given the absence of consistent energy-economic data, particularly in EMDEs, as is the case of Brazil.

This thesis has overcome the challenges and calibrated a multi-region country CGE model with the electricity sector disaggregated into nine sources and transmission and distribution. It then applied this model to long-term electricity capacity expansion scenarios. Obtaining the most up-to-date energy-system modelling scenarios was a crucial achievement. This research applied scenarios for the Brazilian electricity sector capacity expansion until 2050 from the three existing models for the country, which belong to three different institutions. This required evoking the Brazilian public institutions' obligation to provide information in order to obtain the detailed results of the EPE scenario for the baseline of this thesis. It also required networking efforts to obtain the private scenarios from the Cenergia laboratory and, mostly, from PSR Consulting.

These scenarios formed the basis of modelling efforts that fulfilled this thesis's three underlying research questions. First, an estimation of the macroeconomic, industrial, sectoral and distributional impacts of such electricity capacity expansion scenarios, combined or not with two industrial strategy options.

Moreover, the thesis performed a multi-method approach by complementing the modelling with the expert elicitation. The latter allowed this research to take a step beyond most modelling analyses by discussing modelling results with decision-makers and policymakers. These experts explored how modelling results from this research can inform decision-making in the electricity sector and multi-objective policymaking in Brazil at the national and sub-national levels.

This analysis is particularly relevant for Brazil as it moves into a decisive and extremely important stage of policy making and agenda setting with the newly inaugurated Lula da Silva presidency with new government departments being created across ministries to tackle the climate crisis and promote a green economy. Not only the Ministry of Mines and Energy created the Energy Transition Secretary, but also the Ministry of Development, Industry, Trade and Services has created a new Green Economy Secretary (EPBR, 2023), and a Climate Action Authority is planned to be created by March 2023 (Brazilian Presidency, 2023). Therefore, the multi-sectoral, multi-region analysis performed here can inform policymaking across these government departments.

9.5 Limitations and future work

Several complementing ideas emerged from the analysis performed in this thesis for future work to explore. First, there are important limitations to the energy system models that produced the long-term electricity capacity expansion trajectories used here in reflecting structural changes in the future with the emergence of new technologies. This is the case of the use of storage, mostly through batteries and hydrogen. For this reason, none of the scenarios had a trajectory that led to a 100% renewable electricity mix in 2050. The AR scenario, obtained by the most detailed electricity system modelling framework available, still has a relevant share of natural gas in 2050 to allow for firm power in the system.

Hence, an important next step is to work with the energy system modellers to overcome the challenges of increasing the share of non-hydro renewables in scenarios to reach 100% or close to 100%. Moreover, the multi-regional CGE model does not have a representation of energy storage. As storage becomes more economically viable and gains scale as a solution, including storage as a sector of the CGE model will be critical to analysing the socioeconomic impacts of investment spending in this sector.

Second, differentiating onshore and offshore wind as sectors of the CGE model will be an important future effort once offshore wind starts to be installed in the country. Participants of the expert elicitation also suggested that if Brazil starts exploiting the offshore wind potential, the regional distribution of wind farms will shift because the SE already has offshore infrastructure for oil and gas that could be recommissioned. This process would also possibly cause an industrial relocation back to the SE to supply the offshore wind farms. This would not be desirable if multi-objective policy aims to promote socioeconomic development in the NE, and therefore assessing the impacts of this hypothetic process would be interesting.

Third, it is known that labour productivity in the NE is lower due to the aspects of its development gap relative to the other regions, which was discussed in Chapter 3. The region's specialisation in the least technology-intensive economic activities, including agricultural crops and the consequent lowest education levels (as shown in Section 3.2), have caused labour in the NE to be the least skilled relative to other regions. This limits the capacity of the NE to supply higher-skill workers to meet power plant demand. However, labour productivity was not shocked in the modelling simulations presented here. Future studies can explore the impacts of labour productivity increases in the NE as an effect of education policies in parallel with renewable energy investment.

Fourth, although modelling results do not show any significant increase in total land use in any region, the expansion of sugar cane production to new frontiers to supply biomass electricity generation could increase the need for irrigation and compete with other water uses. However, this is not the focus of this research since no energy-system scenario considers substantive increase in biomass generations and the model does not account for water use, and therefore it was not possible to assess the economic trade-off involving water uses. However, this gap cannot be adequately overcome in the case of Brazil. Not only due to a data gap but mostly because most water use is not priced currently.

This means there are major challenges in including water as a factor of production with actual monetary values in a model, and the TERM-BR E15 model's database is entirely in monetary units. Therefore, a hybrid model with physical water units is needed to analyse the issue in depth.

Finally, treating parametric and structural uncertainties that are inherent to modelling (discussed in Section 5.7) is an important continuation of the work of this thesis. A combination of various uncertain factors such as the availability of resources and socio-economic dynamics over time are relevant to the robustness of both to the energy-system modelling and the macroeconomic CGE modelling results. The first next step to address uncertainty would be a sensitivity analysis of the elasticities of substitution between the sources of electricity in the CGE model.

9.6 Thesis conclusions

Brazil has a privileged position in terms of opportunities for climate-consistent development. Its electricity mix has been considered one of the cleanest in the world, given its high share of hydropower. Nevertheless, the dependence on hydropower has recently revealed a high exposure to climate risks, which has conducted Brazil to the opposite pathway of the Paris Agreement by increasingly resorting to thermal power. This thesis has explored the economic effects and the potentialities to promote regional socioeconomic development through investing in long-term renewable electricity capacity expansion in Brazil nationally, and in its five official geoeconomic regions.

Maintaining the renewable profile of Brazil's electricity mix, if combined with social, economic and environmental policies, could put the country in a leading position as a low-carbon economy, which has not been the focus in recent years. Challenges to doing so include integrating the electricity sector and its planning with broader regional and national planning. This is necessary to couple electricity capacity expansion and generation with other development goals and strategies, such as regional equality and income distribution. Currently, the electricity sector is isolated and considers itself exogenous to the economic system.

The multi-region economic analysis performed in this thesis suggests that the more wind and solar in the energy mix, the most benefit to the NE, Brazil's least developed region. Long-term renewable electricity generation policies have a negligible national GDP impact in the long run compared to a baseline scenario in which the electricity mix is heavily based on large hydropower and natural gas. Finally, including more wind and solar improves income distribution in the NE region but indicates a trade-off as it worsens income distribution in the South region.

REFERENCES

ABDI, 2017. Atualização do Mapeamento da Cadeia Produtiva da Indústria Eólica no Brasil. Brasília, Brazil.

ABSOLAR, 2016. Potencial técnico de energia solar no país pode chegar a 30 mil GW [WWW Document]. URL https://www.absolar.org.br/noticia/potencial-tecnico-de-energia-solar-no-pais-pode-chegar-a-30-mil-gw/ (accessed 9.7.22).

ABSOLAR, 2022. Evolução da Fonte Solar Fotovoltaica no Brasil [WWW Document]. Assoc. Bras. Energ. Sol. Fotovoltaica. URL https://www.absolar.org.br/mercado/infografico/ (accessed 10.24.22).

Aguiar, A.A.P.D., Rajão, R., Almeida, C., Bezerra, F.G.S., 2020. Who is burning and deforesting the Brazilian Amazon. E-letter submitted on September 10 2020, as a reply to et al "Smoke pollution's impacts in Amazonia." Science 369.6504 (2020), Science.

Aklin, M., Urpelainen, J., 2013. Political competition, path dependence, and the strategy of sustainable energy transitions. Am. J. Pol. Sci. 57, 643–658.

Anderson, K., Jewell, J., 2019. Climate Policy Models Debated. Nature 573, 348–349.

ANEEL, 2008. Atlas de energia elétrica do Brasil. Brasília.

ANEEL, 2018. Agência Nacional de Energia Elétrica - Potencial Eólico Brasileiro [WWW Document]. URL http://www2.aneel.gov.br/aplicacoes/atlas/energia_eolica/6_3.htm

ANEEL, 2022a. Sobre Bandeiras Tarifárias — Agência Nacional de Energia Elétrica [WWW Document]. URL https://www.gov.br/aneel/pt-br/assuntos/tarifas/bandeiras-tarifarias (accessed 2.1.23).

ANEEL, 2022b. Sistema de Informações de Geração da ANEEL - SIGA [WWW Document]. Matriz por Origem Combust. URL https://antigo.aneel.gov.br/siga (accessed 4.8.21).

ANP, 2015. Evolução dos preços de GLP (R$/botijão de 13 kg).

Arias, M.E., Farinosi, F., Lee, E., Livino, A., Briscoe, J., Moorcroft, P.R., 2020. Impacts of climate change and deforestation on hydropower planning in the Brazilian Amazon. Nat. Sustain. 3, 430–436.

ASA, 2021. SEMIÁRIDO - ASA Brasil - Articulação no Semiárido Brasileiro [WWW Document]. Articul. do Semiárido Bras. URL https://www.asabrasil.org.br/semiarido (accessed 6.25.21).

Athayde, S., Mathews, M., Bohlman, S., Brasil, W., Doria, C.R., Dutka-Gianelli, J., Fearnside, P.M., Loiselle, B., Marques, E.E., Melis, T.S., Millikan, B., Moretto, E.M., Oliver-Smith, A., Rossete, A., Vacca, R., Kaplan, D., 2019. Mapping research on hydropower and sustainability in the Brazilian Amazon: advances, gaps in knowledge and future directions. Curr. Opin. Environ. Sustain. 37, 50–69.

Azevedo, A.A., Rajão, R., Costa, M.A., Stabile, M.C.C., Macedo, M.N., dos Reis, T.N.P., Alencar, A., Soares-Filho, B.S., Pacheco, R., 2017. Limits of Brazil's Forest Code as a means to end illegal deforestation. Proc. Natl. Acad. Sci. 114, 7653–7658.

Azuela, G.E., Barroso, L., Khanna, A., Wang, X., Wu, Y., Cunha, G., 2014. Performance of Renewable Energy Auctions. Policy Res. Work. Pap.

Babatunde, K.A., Begum, R.A., Said, F.F., 2017. Application of computable general equilibrium (CGE) to climate change mitigation policy: A systematic review. Renew. Sustain. Energy Rev. 78, 61–71.

Bacchus, J., 2022. Trade Links: New Rules for a New World. Cambridge University Press, Cambridge.

Barlow, J., Berenguer, E., Carmenta, R., França, F., 2020. Clarifying Amazonia's burning crisis. Glob. Chang. Biol. 26, 319–321.

Batini, N., Di Serio, M., Fragetta, M., Melina, G., Waldron, A., 2022. Building back better: How big are green spending multipliers? Ecol. Econ. 193.

BCB, 2018. Boletim Regional do Banco Central do Brasil.

Bezerra, F.D., Santos, L.S. dos, 2017. Potencialidades da Energia Eólica no Nordeste. Cad. Setorial ETENE 2–20.

Bloomberg, 2018. World's Best Breezes Lead to Cheapest Wind Power in Brazil [WWW Document]. URL https://about.bnef.com/blog/worlds-best-breezes-lead-to-cheapest-wind-power-in-brazil/ (accessed 2.15.22).

BNB, 2021. FNE - Banco do Nordeste [WWW Document]. URL https://www.bnb.gov.br/fne (accessed 9.18.21).

BNDES, 2019. O impacto da Política de Conteúdo Local do BNDES sobre o setor de bens de capital brasileiro.

BNDES, 2022. Parques Eólicos [WWW Document]. URL https://www.bndes.gov.br/wps/portal/site/home/financiamento/produto/leiloes-infraestrutura/parques-eolicos-2013 (accessed 2.15.22).

BNDESPAR, 2018. Sistema BNDES - Participações Acionárias - Setembro/2018 [WWW Document]. URL https://www.bndes.gov.br/wps/portal/site/home/transparencia/consulta-operacoes-bndes/carteira-acionaria

Boccanfuso, D.E., Estache, A., Savard, L., 2011. The intra-country distributional impact of policies to fight climate change: A survey. J. Dev. Stud. 47, 97–117.

Böhringer, C., Keller, A., van der Werf, E., 2013. Are green hopes too rosy? Employment and welfare impacts of renewable energy promotion. Energy Econ. 36, 277–285.

Brando, P.M., Paolucci, L., Ummenhofer, C.C., Ordway, E.M., Hartmann, H., Cattau, M.E., Rattis, L., Medjibe, V., Coe, M.T., Balch, J., 2019. Droughts, Wildfires, and Forest Carbon Cycling: A Pantropical Synthesis. Annu. Rev. Earth Planet. Sci. 47, 555–581.

BRASIL, 1988. Constituição da República Federativa do Brasil de 1988.

Brasil Escola, 2018. Divisão Regional Brasileira. Portal Brasil Escola.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3, 77–101.

Brazilian Presidency, 2011. Base Legislação da Presidência da República - Lei nº 12.527 de 18 de novembro de 2011 [WWW Document]. URL https://legislacao.presidencia.gov.br/atos/?tipo=LEI&numero=12527&ano=201

1&ato=dc1UTUU1UMVpWT65a (accessed 6.11.22).

Brazilian Presidency, 2023. Marina Silva anuncia a criação da Autoridade Nacional de Segurança Climática [WWW Document]. URL https://www.gov.br/pt-br/noticias/meio-ambiente-e-clima/2023/01/marina-silva-anuncia-a-criacao-da-autoridade-nacional-de-seguranca-climatica (accessed 2.6.23).

Burniaux, J.-M., Truong, T.P., 2002. GTAP-E: an energy-environmental version of the GTAP model. GTAP Tech. Pap. 1–61.

Byers, E., Gidden, M., Leclere, D., Balkovic, J., Burek, P., Ebi, K., Greve, P., Grey, D., Havlik, P., Hillers, A., Johnson, N., Kahil, T., Krey, V., Langan, S., Nakicenovic, N., Novak, R., Obersteiner, M., Pachauri, S., Palazzo, A., Parkinson, S., Rao, N.D., Rogelj, J., Satoh, Y., Wada, Y., Willaarts, B., Riahi, K., 2018. Global exposure and vulnerability to multi-sector development and climate change hotspots. Environ. Res. Lett. 13.

Caiado Couto, L., Campos, L.C., da Fonseca-Zang, W., Zang, J., Bleischwitz, R., 2021. Water, waste, energy and food nexus in Brazil: Identifying a resource interlinkage research agenda through a systematic review. Renew. Sustain. Energy Rev. 138, 110554.

Calzadilla, A., Parrado, R., 2017a. Extending Macroeconomic Modelling into the Resource Nexus 220–235.

Calzadilla, A., Parrado, R., 2017b. Extending Macro- Economic Modelling Into 220–235.

Cambridge Econometrics, 2022. E3ME: Our Global Macro-econometric Model | Cambridge Econometrics [WWW Document]. URL http://www.camecon.com/how/e3me-model/ (accessed 9.3.22).

Cameron, L., Van Der Zwaan, B., 2015. Employment factors for wind and solar energy technologies: A literature review. Renew. Sustain. Energy Rev. 45, 160–172.

Cano, W., 1997. Concentração e desconcentração econômica regional do Brasil 1970/95. Econ. e Soc. 6, 101–141.

Cano, W., 2010. A Criação da Sudene Furtado: a Questão Regional e a Agricultura Itinerante no Brasil. Cad. do Desenvolv. 5, 23–51.

Cappelli, F., Costantini, V., Consoli, D., 2021. The trap of climate change-induced "natural" disasters and inequality. Glob. Environ. Chang. 70, 102329.

Caron, J., Cohen, S.M., Brown, M., Reilly, J.M., 2018. Exploring the Impacts of A National US CO2 Tax and Revenue Recycling Options with a Coupled Electricity-Economy Model 9, 1–40.

Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2017. Comparative analysis of direct employment generated by renewable and non-renewable power plants. Energy 139, 542–554.

Carvalho, P.L.V.B., 2020. A Normative-Institutional Approach to the Water-Energy Nexus: A case Analysis of Brazil. University College London.

Carvalho, T.S., Domingues, E.P., Horridge, J.M., 2017. Controlling deforestation in the Brazilian Amazon: Regional economic impacts and land-use change. Land use policy 64, 327–341.

Castellanos, E.J., Lemos, M.F., Astigarraga, L., Chacón, N., Cuvi, N., Huggel, C., Miranda, L., Vale, M.M., Ometto, J.P., Peri, P.L., Postigo, J.C., Ramajo, L., Roco, L., Rusticucci, M., Menezes, J.A., Borges, P., Bueno, J., Cuesta, F., Drenkhan, F., Guerra, A., Guinder, V., Hagen, I., Hardoy, J., Hartinger, S., Herrera, G., Herzog, C., Jacob, B., Kasecker, T., Lampis, A., Lentino, I., Domingues, L.C.S.M., Marengo, J., Lapola, D.M., Moreno, A.R., Caldas, J. de N., Pacay, E., Pasten, R., Piaggio, M., Rezende, O., Rodriguez-Morales, A.J., Romanello, M., Ryan, S.J., Stewart-Ibarra, A., Valladares, M., 2022. Chapter 12: Central and South America. Clim. Chang. 2022 Impacts, Adapt. Vulnerability - Work. Gr. II Contrib. to Sixth Assess. Rep. Intergov. Panel Clim. Chang. 1–181.

Cavaliero, C.K.N., da Silva, E.P., 2005. Electricity generation: Regulatory mechanisms to incentive renewable alternative energy sources in Brazil. Energy Policy 33, 1745–1752.

CCEE, 2020. Resultados Consolidados de Leilões.

Cenergia, 2021. Who we are | Cenergia Lab [WWW Document]. URL http://www.cenergialab.coppe.ufrj.br/who-we-are (accessed 4.15.21).

CEPEL, C. de P. de E.E., 2017. Atlas do Potencial Eólico Brasileiro Simulações 2013 1º Edição. Rio de Janeiro.

CGU, 2022. Fala.BR - Plataforma Integrada de Ouvidoria e Acesso à Informação [WWW Document]. Control. Geral da Uniao. URL https://falabr.cgu.gov.br/Login/Identificacao.aspx?idFormulario=3&tipo=8&ReturnUrl=%2Fpublico%2FManifestacao%2FRegistrarManifestacao.aspx%3FidFormulario%3D3%26tipo%3D8%26origem%3Didp%26modo%3D (accessed 6.11.22).

Chapman, A.J., McLellan, B.C., Tezuka, T., 2018. Prioritizing mitigation efforts considering co-benefits, equity and energy justice: Fossil fuel to renewable energy transition pathways. Appl. Energy 219, 187–198.

Charnovitz, S., 2014. Green Subsidies and the WTO. SSRN Electron. J.

Chatri, F., Yahoo, M., Othman, J., 2018. The economic effects of renewable energy expansion in the electricity sector: A CGE analysis for Malaysia. Renew. Sustain. Energy Rev. 95, 203–216.

CHESF, 2018. Companhia Hidreletrica do Sao Francisco [WWW Document]. Sist. Geração. URL https://www.chesf.gov.br/SistemaChesf/Pages/SistemaGeracao/SistemasGeracao.aspx

Chunark, P., Limmeechokchai, B., Fujimori, S., Masui, T., 2017. Renewable energy achievements in CO2mitigation in Thailand's NDCs. Renew. Energy 114, 1294–1305.

CNI, 2018. CNI - Perfil da Indústria nos Estados [WWW Document]. Confed. Nac. da indústria. URL http://perfildaindustria.portaldaindustria.com.br/busca (accessed 11.14.18).

Complexo do Pecém, 2022. Hub de Hidrogênio Verde do Complexo do Pecém [WWW Document]. URL https://www.complexodopecem.com.br/hubh2v/ (accessed 9.22.22).

Cronin, J., Hughes, N., Tomei, J., Caiado Couto, L., Ali, M., Kizilcec, V., Adewole, A., Bisaga, I., Broad, O., Parikh, P., Eludoyin, E., Hofbauer, L., Machado, P.G., Butnar, I., Anandarajah, G., Webb, J., Lemaire, X., Watson, J., 2021. Embedding justice in the 1.5°C transition: A transdisciplinary research agenda. Renew. Sustain. Energy Transit. 1, 100001.

Da Silva, M.V.M., Da Silva Silveira, C., Da Costa, J.M.F., Martins, E.S.P.R., Vasconcelos, F.D.C., 2021. Projection of climate change and consumptive demands projections impacts on hydropower generation in the Sao Francisco river basin, Brazil. Water (Switzerland) 13.

Dai, H., Xie, X., Xie, Y., Liu, J., Masui, T., 2016. Green growth: The economic impacts of large-scale renewable energy development in China. Appl. Energy 162, 435–449.

Dai, H., Xie, Y., Liu, J., Masui, T., 2018. Aligning renewable energy targets with carbon emissions trading to achieve China's INDCs: A general equilibrium assessment. Renew. Sustain. Energy Rev. 82, 4121–4131.

de Faria, F.A.M., Davis, A., Severnini, E., Jaramillo, P., 2017. The local socio-economic impacts of large hydropower plant development in a developing country. Energy Econ. 67, 533–544.

de Faria, F.A.M., Jaramillo, P., 2017. The future of power generation in Brazil: An analysis of alternatives to Amazonian hydropower development. Energy Sustain. Dev. 41, 24–35.

de Jong, P., Tanajura, C.A.S., Sánchez, A.S., Dargaville, R., Kiperstok, A., Torres, E.A., 2018. Hydroelectric production from Brazil's São Francisco River could cease due to climate change and inter-annual variability. Sci. Total Environ. 634, 1540–1553.

DeCarolis, J., Daly, H., Dodds, P., Keppo, I., Li, F., McDowall, W., Pye, S., Strachan, N., Trutnevyte, E., Usher, W., Winning, M., Yeh, S., Zeyringer, M., 2017. Formalizing best practice for energy system optimization modelling. Appl. Energy 194, 184–198.

Diniz, T., 2019. Impactos econômicos e regionais dos investimentos em geração de energia elétrica no Brasil. Universidade de São Paulo.

Diniz, T., Gurgel, A., Tonry, S., 2019. International market mechanisms under the Paris Agreement : A cooperation between Brazil and Europe ☆. Energy Policy 129, 397–409.

Diniz, T.B., 2018. Expansão da Indústria de Geração Eólica no Brasil. Planej. E Políticas Públicas 234–255.

Diniz, T.B., Caiado Couto, L., 2021. Achieving a high share of non-hydro renewable integration in Brazil through wind power: regional growth and employment effects.

Dixon, P.B., Parmenter, B.R., Sutton, J., Vincent, D.P., 1982. ORANI: A Multisectoral Model of the Australian Economy. North-Holland Publ. Co., Amsterdam.

Doria, C.R. da C., Athayde, S., Marques, E.E., Lima, M.A.L., Dutka-Gianelli, J., Ruffino, M.L., Kaplan, D., Freitas, C.E.C., Isaac, V.N., 2018. The invisibility of fisheries in the process of hydropower development across the Amazon. Ambio 47, 453–465.

Dutra, R.M., Szklo, A.S., 2008. Incentive policies for promoting wind power production in Brazil: Scenarios for the Alternative Energy Sources Incentive Program (PROINFA) under the New Brazilian electric power sector regulation. Renew. Energy 33, 65–76.

ECEN, 2002. Brasil – Energia em 2002: Principais Indicadores [WWW Document]. URL https://ecen.com/eee39/brasil_energia_em_2002.htm (accessed 8.13.21).

Effendi, Y., Resosudarmo, B.P., 2021. Development of renewable electricity in ASEAN countries: socio-economic and environmental impacts. Asia-Pacific J. Reg. Sci.

EIA, 2022. Glossary - U.S. Energy Information Administration (EIA) [WWW Document]. US Energy Inf. Adm. URL https://www.eia.gov/tools/glossary/?id=electricity (accessed 9.6.22).

Eletrobras, 2021. Programa de Incentivo às Fontes Alternativas de Energia Elétrica - Proinfa [WWW Document]. Programa Incent. às Fontes Altern. Energ. Elétrica. URL https://eletrobras.com/pt/Paginas/Proinfa.aspx (accessed 6.1.21).

EPBR, 2023. MDIC terá secretaria de economia verde; e o clima na estrutura das pastas [WWW Document]. URL https://epbr.com.br/mdic-tera-secretaria-de-economia-verde-veja-quais-ministerios-incluiram-clima-na-estrutura/ (accessed 2.6.23).

EPE, 2013a. Anuário estatístico de energia elétrica 2012. Rio de Janeiro, Brazil.

EPE, 2013b. Balanço Energético Nacional 2013: Ano base 2012, Ministério de Minas e Energia, Brasília.

EPE, 2016. Balanço Energético Nacional. Rio de Janeiro, Brazil.

EPE, 2017. Balanço energético nacional.

EPE, 2018a. Considerações sobre a Expansão Hidrelétrica nos Estudos de Planejamento Energético de Longo Prazo, Documento de Apoio ao PNE 2050.

EPE, 2018b. Balanço Energético Nacional 2018: Relatório Síntese: ano base 2017 62.

EPE, 2018c. Anuário Estatístico de Energia Elétrica 2018 [WWW Document]. Empres. Pesqui. Energética. URL http://epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/anuario-estatistico-de-energia-eletrica (accessed 11.13.18).

EPE, 2020a. Plano Nacional de Energia 2050. Rio de Janeiro, Brazil.

EPE, 2020b. Plano Decenal de Expansao de Energia (PDE) 2030. Empresa de Pesquisa Energética, Ministério de Minas e Energia, Brasília-DF, Brazil.

EPE, 2020c. Plano Nacional de Energia 2050 - Energia Eólica. Rio de Janeiro, Brazil.

EPE, 2020d. Investimentos Para a Expansão do SIN Dezembro de 2020. Rio de Janeiro, Brazil.

EPE, 2021. Escassez hídrica e o fornecimento de energia elétrica no Brasil 1–4.

EPE, 2022. Balanço energético nacional 2022. Rio de Janeiro, Brazil.

EPL, 2018. Relatório Executivo do Plano Nacional de Logística - PNL 2025. EPL - Empres. Planej. Logístico S.A. 140.

Época Negócios, 2019. Fabricantes de turbinas eólicas iniciam uma guerra de gigantes no mercado brasileiro - Época Negócios | Empresa [WWW Document]. URL https://epocanegocios.globo.com/Empresa/noticia/2019/06/fabricantes-de-turbinas-eolicas-iniciam-uma-guerra-de-gigantes-no-mercado-brasileiro.html (accessed 2.15.22).

Fan, Y., Wu, J., Timilsina, G., Xia, Y., 2017. Understanding the Interactions between Emissions Trading Systems and Renewable Energy Standards Using a Multi-Regional CGE Model of China. Underst. Interact. between Emiss. Trading Syst. Renew. Energy Stand. Using a Multi-Regional CGE Model China.

Ferreira Filho, J.B. de S., 2011. The rise in global demand for ethanol and poverty in

Brazil. In: Lima, J.D., LaFleur, M., Pellandra, A. (Eds.), Trade, Poverty and Complementary Policies in Latin America. p. 273.

Ferreira Filho, J.B. de S., Horridge, M., 2011. Ethanol expansion and indirect land use change in Brazil. Land use policy 36, 595–604.

Ferreira Filho, J.B. de S., Horridge, M., 2014. Ethanol expansion and indirect land use change in Brazil. Land use policy 36, 595–604.

Ferreira Filho, J.B. de S., Horridge, M., 2017. Biome Composition in Deforestation Deterrence and GHG Emissions in Brazil Joaquim Bento de Souza Ferreira Filho Escola Superior de Agricultura " Luiz de Queiroz ", And.

Ferreira, J., Souza, D.E., Filho, F., Ribera, L., 2015. Deforestation Control and Agricultural Supply in Brazil.

Filho, J.B.S.F. de, Horridge, M.J., 2006. Economic integration, poverty and regional inequality in Brazil. Rev. Bras. Econ. 60, 363–387.

Fonseca, M.G., Alves, L.M., Aguiar, A.P.D., Arai, E., Anderson, L.O., Rosan, T.M., Shimabukuro, Y.E., de Aragão, L.E.O. e. C., 2019. Effects of climate and land-use change scenarios on fire probability during the 21st century in the Brazilian Amazon. Glob. Chang. Biol. 25, 2931–2946.

Fraundorfer, M., Rabitz, F., 2020. The Brazilian renewable energy policy framework: instrument design and coherence. Clim. Policy 20, 652–660.

G7, 2022. G7 Statement on Climate Club.

Garrett-Peltier, H., 2017. Green versus brown: Comparing the employment impacts of energy e ffi ciency , renewable energy , and fossil fuels using an input-output model. Econ. Model. 61, 439–447.

Gonçalves da Silva, J., 2010. Impactos econômicos de políticas de mitigação das mudanças climáticas na economia brasileira: um estudo a partir de um modelo de equilíbrio geral computável. Universidade de São Paulo.

Gonçalves Da Silva, J., de Souza Ferreira Filho, J.B., Horridge, M., 2014. Greenhouse gas mitigation by agriculture and livestock intensification in Brazil 1–22.

Gonçalves, S., Rodrigues, T.P., Chagas, A.L.S., 2020. The impact of wind power on the Brazilian labor market. Renew. Sustain. Energy Rev. 128, 109887.

Gray, P., Irwin, T., 2003. Exchange Rate Risk Allocating Exchange Rate Risk in Private Infrastructure Projects, Viewpoint: Public Policy for the Private Sector. Washington, DC: The World Bank.

Grottera, C., 2022. Reducing emissions from the energy sector for a more resilient and low-carbon post-pandemic recovery in Latin America and the Caribbean. Santiago.

Grubb, M., 2014. Planetary Economics: Energy, climate change and the three domains of sustainable development. Routledge.

Grubb, M., de Coninck, H., Sagar, A.D., 2015. From Lima to Paris, Part 2: Injecting Ambition. Clim. Policy 15, 413–416.

Grubb, M., Drummond, P., Mercure, J., Hepburn, C., Barbrook-johnson, P., Ferraz, J.C., Clark, A., Anadon, L.D., Farmer, D., Hinder, B.E.N., Ives, M., Jones, A., Jun, G.A.O., Kelkar, U., Lam, A., Mathur, R., Pasqualino, R., Penasco, C., Pollitt, H., Ramos, L., Roventini, A., Salas, P., Sharpe, S., Songli, Z.H.U., Vercoulen, P.I.M., Waghray, K., Xiliang, Z., 2021a. THE NEW ECONOMICS OF INNOVATION AND TRANSITION : EVALUATING OPPORTUNITIES AND RISKS AND SYSTEM TRANSITION (EEIST) CONSORTIUM.

Grubb, M., Okereke, C., Arima, J., Bosetti, V., Chen, Y., Edmonds, J., Gupta, S., Köberle, A., Kverndokk, S., Malik, A., Sulistiawati, L., 2022. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In: IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Grubb, M., Wieners, C., Yang, P., 2021b. Modeling myths: On DICE and dynamic realism in integrated assessment models of climate change mitigation. Wiley Interdiscip. Rev. Clim. Chang. 12, 1–26.

GTAP, 2021. Global Trade Analysis Project (GTAP) [WWW Document]. URL https://www.gtap.agecon.purdue.edu/ (accessed 4.14.21).

GWEC, 2011. Analysis of the regulatory framework for wind power generation in Brazil.

Haddad, E., Giuberti, A.C., 2014. Economic impacts of natural resources on regional economy: the case of the pre-salt oil discoveries in Espírito Santo, Brazil. Econ. Reg. 1, 111–124.

Hansen, U.E., Nygaard, I., Morris, M., Robbins, G., 2020. The effects of local content requirements in auction schemes for renewable energy in developing countries: A literature review. Renew. Sustain. Energy Rev. 127.

Harrison, J., Horridge, M., Jerie, M., Pearson, K., 2015. GEMPACK Manual.

Hazilla, M., Kopp, R.J., 1990. Social Cost of Environmental Quality Regulations : A General Equilibrium Analysis Author (s): Michael Hazilla and Raymond J . Kopp Source : Journal of Political Economy , Vol . 98 , No . 4 (Aug ., 1990), pp . 853-873 Published by : The University of C 98, 853–873.

Hertel, T.W., Tsigas, M.E., 1997. Structure of GTAP, Global Trade Analysis: Modeling and Applications.

Hochstetler, K., 2020. Political Economies of Energy Transition. Cambridge University Press, Cambridge.

Hochstetler, K., 2021. Climate institutions in Brazil: three decades of building and dismantling climate capacity. Env. Polit. 30, 49–70.

Hochstetler, K., Montero, A.P., 2013. The Renewed Developmental State: The National Development Bank and the Brazil Model. J. Dev. Stud. 49, 1484–1499.

Hochstetler, K., Viola, E., 2012. Brazil and the politics of climate change: Beyond the global commons. Env. Polit. 21, 753–771.

Hofbauer, L., McDowall, W., Pye, S., 2022. Challenges and opportunities for energy system modelling to foster multi-level governance of energy transitions. Renew. Sustain. Energy Rev. 161.

Hondo, H., Moriizumi, Y., 2017. Employment creation potential of renewable power generation technologies: A life cycle approach. Renew. Sustain. Energy Rev. 79, 128–136.

Horridge, J., Filho, J.F., 2003. Linking gtap to national models: Some highlights and a practical approach. 6th Annu. Conf. ….

Horridge, J.M., 2003. ORANI-G: A Generic Single-Country Computable General Equilibrium Model. Working Paper Centre of Policy Studies 3.

Horridge, M., 2012. The TERM Model and Its Database. Glob. Issues Water Policy 3, 13–35.

Horridge, M., Madden, J., Wittwer, G., 2003. Using a highly disaggregated multi-regional single-country model to analyse the impacts of the 2002-03 drought on Australia, Centre of Policy Studies/IMPACT Centre Working Papers.

Horridge, M., Madden, J., Wittwer, G., 2005. The impact of the 2002-2003 drought on Australia. J. Policy Model. 27, 285–308.

Horridge, M., Wittwer, G., 2008. SinoTERM, a multi-regional CGE model of China. China Econ. Rev. 19, 628–634.

Hughes, L., Urpelainen, J., 2015. Interests, institutions, and climate policy: Explaining the choice of policy instruments for the energy sector. Environ. Sci. Policy 54, 52–63.

Hunt, J.D., Nascimento, A., Caten, C.S. ten, Tomé, F.M.C., Schneider, P.S., Thomazoni, A.L.R., Castro, N.J. de, Brandão, R., Freitas, M.A.V. de, Martini, J.S.C., Ramos, D.S., Senne, R., 2022. Energy crisis in Brazil: Impact of hydropower reservoir level on the river flow. Energy 239.

IAMC, 2021. Model Documentation - BLUES - IAMC-Documentation [WWW Document]. URL https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_BLUES (accessed 4.15.21).

IAMC, 2022. Model Documentation - REMIND-MAgPIE [WWW Document]. URL https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_REMIND-MAgPIE (accessed 9.4.22).

IBGE, 2017. Sintese de Indicadores Sociais 2017 [WWW Document]. URL https://www.ibge.gov.br/estatisticas-novoportal/sociais/saude/9221-sintese-de-indicadores-sociais.html?=&t=downloads

IBGE, 2018a. Instituto Brasileiro de Geografia e Estatística [WWW Document]. Pesqui. Nac. Amostras por Domicílios. URL https://ww2.ibge.gov.br/home/estatistica/populacao/trabalhoerendimento/pnad2015/default.shtm

IBGE, 2018b. Pesquisa de Orçamentos Familiares, Instituto Brasileiro de Geografia e

Estatística [WWW Document]. URL https://sidra.ibge.gov.br/pesquisa/pof/tabelas

IBGE, 2018c. Características gerais dos domicílios e dos moradores 2017 1–8.

IBGE, 2019. Pesquisa Nacional por Amostra de Domicílios Contínua - PNADC [WWW Document]. URL https://ww2.ibge.gov.br/home/estatistica/pesquisas/pesquisa_resultados.php?id_pesquisa=149

IBGE, 2020. Desemprego | IBGE [WWW Document]. Inst. Bras. Geogr. e Estat. Pesqui. Nac. por Amostra Domicílios Contínua – PNAD Contínua. URL https://www.ibge.gov.br/explica/desemprego.php (accessed 3.1.21).

IBGE, 2021a. Portal de mapas do IBGE [WWW Document]. URL https://portaldemapas.ibge.gov.br/portal.php#mapa830 (accessed 6.25.21).

IBGE, 2021b. Matriz de Insumo-Produto | IBGE [WWW Document]. URL https://www.ibge.gov.br/estatisticas/economicas/contas-nacionais/9085-matriz-de-insumo-produto.html?=&t=o-que-e (accessed 7.17.20).

IBGE, 2022a. Produto Interno Bruto - PIB | IBGE [WWW Document]. URL https://www.ibge.gov.br/explica/pib.php (accessed 10.6.22).

IBGE, 2022b. Estimativas da população residente para os municípios e para as unidades da federação [WWW Document]. URL https://www.ibge.gov.br/estatisticas/sociais/populacao/9103-estimativas-de-populacao.html?=&t=resultados (accessed 10.6.22).

IBGE, 2023a. Censo 2022 | IBGE [WWW Document]. Inst. Bras. Geogr. e Estat. URL https://www.ibge.gov.br/estatisticas/sociais/trabalho/22827-censo-demografico-2022.html?=&t=resultados (accessed 1.21.23).

IBGE, 2023b. Matriz de Insumo-Produto | IBGE [WWW Document]. Matriz Insumo-Produto 2015. URL https://www.ibge.gov.br/estatisticas/economicas/contas-nacionais/9085-matriz-de-insumo-produto.html?=&t=resultados (accessed 2.7.23).

IEA, 2021a. The Role of Critical Minerals in Clean Energy Transitions. Paris, France.

IEA, 2021b. Net Zero by 2050: A Roadmap for the Global Energy Sector. OECD

Publishing, Paris.

IEMA, 2022. Inventário de Emissões Atmosféricas em Usinas Termelétricas: geração de eletricidade, emissões e lista de empresas proprietárias das termelétricas a combustíveis fósseis e de serviço público do Sistema Interligado Nacional (ano-base 2020).

IFPRI, 2021. IFPRI Country Programs [WWW Document]. URL https://www.ifpri.org/topic/ifpri-country-programs (accessed 4.14.21).

IIAC, 2013. A nova cara da Pobreza Rural: Desenvolvimento e a questão Regional. Instituto Interamericano de Cooperação para a Agricultura (IICA), Brasília.

ILO, 2017. How to measure and model social and employment outcomes of climate and sustainable development policies: Training guidebook.

INPE, 2021a. PRODES — Coordenação-Geral de Observação da Terra.

INPE, 2021b. Monitoramento dos Focos Ativos por Estado, Região ou Bioma - Programa Queimadas - INPE.

INPE, 2021c. Área Queimada - Programa Queimadas - INPE.

Instituto E+, 2022. Descarbonização do Setor de Energia no Brasil.

Instituto Escolhas, 2017. What Is the Impact of Zero Emissions from the Electricity Sector in Brazil.

IPEA, 2008. O que é? Amazônia Legal. IPEA Desafios do Desenvolv.

Ipeadata, 2022. Average exchange rate R$ / US$ [WWW Document]. URL http://www.ipeadata.gov.br/ExibeSerie.aspx?serid=31924 (accessed 10.6.22).

IPEADATA, 2018. IPEADATA Coeficiente de Gini [WWW Document].

IRENA, 2023. Socio economic impact [WWW Document]. URL https://www.irena.org/Energy-Transition/Socio-economic-impact (accessed 2.1.23).

ISIMIP, 2022. The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) [WWW Document]. URL https://www.isimip.org/

Jenkins, K., Warren, R., 2015. Quantifying the impact of climate change on drought regimes using the Standardised Precipitation Index. Theor. Appl. Climatol. 120, 41–54.

Johnson, O., 2016. Promoting green industrial development through local content requirements: India's National Solar Mission. Clim. Policy 16, 178–195.

Kat, B., Paltsev, S., Yuan, M., 2018. Turkish energy sector development and the Paris Agreement goals: A CGE model assessment. Energy Policy 122, 84–96.

Kiger, M.E., Varpio, L., 2020. Thematic analysis of qualitative data: AMEE Guide No. 131. Med. Teach. 42, 846–854.

Kissel, J.M., Krauter, S.C.W., 2006. Adaptations of renewable energy policies to unstable macroeconomic situations-Case study: Wind power in Brazil. Energy Policy 34, 3591–3598.

Koengkan, M., Fuinhas, J.A., 2020. The interactions between renewable energy consumption and economic growth in the Mercosur countries. Int. J. Sustain. Energy 39, 594–614.

Krol, M., Jaeger, A., Bronstert, A., Güntner, A., 2006. Integrated modelling of climate, water, soil, agricultural and socio-economic processes: A general introduction of the methodology and some exemplary results from the semi-arid north-east of Brazil. J. Hydrol. 328, 417–431.

Krugman, P.R., Wells, R., 2015. Economics / Paul Krugman, Robin Wells., Fourth edi. ed. Worth Publishers, New York, NY.

Kuntze, J.-C., Moerenhout, T., 2013. Local Content Requirements and the Renewable Energy Industry - A Good Match?

La Rovere, E.L., Mendes, F.E., 2000. Tucuruí Hydropower Complex Brazil.

Li, N., Shi, M., Wang, F., 2009. A Multi-regional CGE Model for China. In: Shi, Y., Wang, S., Peng, Y., Li, J., Zeng, Y. (Eds.), Cutting-Edge Research Topics on Multiple Criteria Decision Making. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 370–373.

Löfgren, H., Robinson, S., Harris, R.L., 2002. A Standard Computable General Equilibrium (CGE) Model in GAMS, Microcomputers in Policy Research .

Lovejoy, T.E., Nobre, C., 2018. Amazon tipping point. Sci. Adv. 4, 1–2.

Lucena, A.F.P., Clarke, L., Schaeffer, R., Szklo, A., Rochedo, P.R.R., Nogueira, L.P.P., Daenzer, K., Gurgel, A., Kitous, A., Kober, T., 2014. Climate policy scenarios in Brazil: A multi-model comparison for energy. Energy Econ. 56, 564–574.

Lucena, A.F.P., Hejazi, M., Vasquez-Arroyo, E., Turner, S., Köberle, A.C., Daenzer, K., Rochedo, P.R.R., Kober, T., Cai, Y., Beach, R.H., Gernaat, D., van Vuuren, D.P., van der Zwaan, B., 2018. Interactions between climate change mitigation and adaptation: The case of hydropower in Brazil. Energy 164.

Lydgate, E., Anthony, C., 2020. Coordinating UK trade and climate policy ambitions: A legislative and policy analysis. Environ. Law Rev. 22, 280–295.

Magalhães, A.S., 2013. Economia de baixo carbono no Brasil: alternativas de políticas e custos de reduções de emissões de gases de efeito estufa. 1–290.

Magrin, G.O., Marengo, J.A., Boulanger, J.-P., Buckeridge, M.S., Castellanos, E., Poveda, M.S.G., Scarano, F.R., Vicuña, S., 2014. Central and South America. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. pp. 1499–1566.

Maguire Moira, D.B., 2014. Doing a Thematic analysis: A practical, step by step guide for learning and teaching. Aishe-J 50, 3135–3140.

Månsson, A., 2015. A resource curse for renewables? Conflict and cooperation in the renewable energy sector. Energy Res. Soc. Sci. 10, 1–9.

Marengo, J.A., Alves, L.M., Beserra, E.A., Lacerda, F.F., 2011a. No Semiárido Brasileiro, Recursos hídricos em regiões áridas e semiáridas.

Marengo, J.A., Alves, L.M., Beserra, E.A., Lacerda, F.F., 2011b. Variablidade e Mudanças Climáticas no Semiárido Brasileiro, Recursos hídricos em regiões áridas e semiáridas.

Marengo, J.A., Cunha, A.P., Alves, L.M., 2016. A seca de 2012-2015 no semiárido do Nordeste do brasil. Rev. Climanálise 1–5.

Marengo, J.A., Galdos, M. V., Challinor, A., Cunha, A.P., Marin, F.R., Vianna, M. dos S., Alvala, R.C.S., Alves, L.M., Moraes, O.L., Bender, F., 2022. Drought in Northeast Brazil: A review of agricultural and policy adaptation options for food security. Clim. Resil. Sustain. 1, 1–20.

Margulis, S., Dubeux, C.B.S., Marcovitch, J., 2010. Economia da Mudança do Clima no Brasil: Custos e Oportunidades. IBEP Gráfica, São Paulo.

Matsuo, T., Schmidt, T.S., 2019. Managing tradeoffs in green industrial policies: The role of renewable energy policy design. World Dev. 122, 11–26.

Mercure, J.-F., Paim, M.A., Bocquillon, P., Lindner, S., Salas, P., Martinelli, P., Berchin, I.I., de Andrade Guerra, J.B.S.., Derani, C., de Albuquerque Junior, C.L., Ribeiro, J.M.P., Knobloch, F., Pollitt, H., Edwards, N.R., Holden, P.B., Foley, A., Schaphoff, S., Faraco, R.A., Vinuales, J.E., 2019. System complexity and policy integration challenges: The Brazilian Energy- Water-Food Nexus. Renew. Sustain. Energy Rev. 105, 230–243.

Milani, R., Caiado Couto, L., Soria, R., Szklo, A., Lucena, A.F.P., 2020. Promoting social development in developing countries through solar thermal power plants. J. Clean. Prod. 246.

MMA, 2019. Política Nacional sobre Mudança do Clima [WWW Document]. URL http://www.mma.gov.br/clima/politica-nacional-sobre-mudanca-do-clima (accessed 3.7.19).

MME, 2015. Boletim Mensal de Acompanhamento da Indústria de Gás Natural Dezembro de 2015.

MME, 2019. Informe - Comparações de Preços de Gás Natural: Brasil e Países Selecionados.

MME, 2023. Alexandre Silveira assume Ministério de Minas e Energia e anuncia Secretaria Nacional de Transição Energética [WWW Document]. Ministério Minas e Energ. URL https://www.gov.br/mme/pt-br/assuntos/noticias/alexandre-silveira-assume-ministerio-de-minas-e-energia-e-anuncia-secretaria-nacional-de-transicao-energetica

Montenegro, R.C., Fragkos, P., Dobbins, A.H., Schmid, D., Pye, S., Fahl, U., 2021. Beyond the Energy System: Modeling Frameworks Depicting Distributional Impacts for Interdisciplinary Policy Analysis. Energy Technol. 9.

Monyei, C.G., Jenkins, K., Serestina, V., Adewumi, A.O., 2018. Examining energy sufficiency and energy mobility in the global south through the energy justice framework. Energy Policy 119, 68–76.

Moretto, E.M., Gomes, C.S., Roquetti, D.R., Jordão, C. de O., 2012. Histórico, tendências e perspectivas no planejamento espacial de usinas hidrelétricas brasileiras: a antiga e atual fronteira Amazônica. Ambient. Soc. 15, 141–164.

Morris, M., Robbins, G., Hansen, U., Nygard, I., 2021. The wind energy global value chain localisation and industrial policy failure in South Africa. J. Int. Bus. Policy.

MRE, 2019. Brazil's Third Biennial Update Report to the United Nations Framework Convention on Climate Change. Brasília-DF, Brazil.

MTE, 2020. RAIS 2019 [WWW Document]. URL http://www.rais.gov.br/sitio/tabelas.jsf (accessed 8.26.20).

Mu, Y., Cai, W., Evans, S., Wang, C., Roland-Holst, D., 2018a. Employment impacts of renewable energy policies in China: A decomposition analysis based on a CGE modeling framework. Appl. Energy 210, 256–267.

Mu, Y., Wang, C., Cai, W., 2018b. The economic impact of China's INDC: Distinguishing the roles of the renewable energy quota and the carbon market. Renew. Sustain. Energy Rev. 81, 2955–2966.

Mulugetta, Y., Ben Hagan, E., Kammen, D., 2019. Energy access for sustainable development. Environ. Res. Lett. 14.

Neri, M., 2022. Mapa da Nova Pobreza 40.

Nobre, C.A., Sampaio, G., Borma, L.S., Castilla-Rubio, J.C., Silva, J.S., Cardoso, M., 2016. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. Proc. Natl. Acad. Sci. 113, 10759–10768.

Nogueira de Oliveira, L.P., Rodriguez Rochedo, P.R., Portugal-Pereira, J., Hoffmann, B.S., Aragão, R., Milani, R., De Lucena, A.F.P., Szklo, A., Schaeffer, R., 2016. Critical technologies for sustainable energy development in Brazil: Technological foresight based on scenario modelling. J. Clean. Prod. 130, 12–24.

Nong, D., 2020. Development of the electricity-environmental policy CGE model (GTAP-E-PowerS): A case of the carbon tax in South Africa. Energy Policy 140.

Normile, D., 2020. China again boosts R&D spending by more than 10%. Science (80-.).

NREL, 2023. Jobs and Economic Development Impact (JEDI) Models | NREL [WWW Document]. URL https://www.nrel.gov/analysis/jedi/ (accessed 2.1.23).

Ochuodho, T.O., Lantz, V.A., Olale, E., 2016. Economic impacts of climate change considering individual, additive, and simultaneous changes in forest and agriculture sectors in Canada: A dynamic, multi-regional CGE model analysis. For. Policy Econ. 63, 43–51.

ONS, 2018. Operador Nacional do Sistema - Histórico da Operação DADOS HIDROLÓGICOS / VOLUMES [WWW Document]. URL http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/dados_hidrologicos_volumes.aspx

ONS, 2021a. Comitê de Monitoramento do Setor Elétrico (CMSE) Nota Informativa – 1º de março de 2021.

ONS, 2021b. Páginas - Histórico da Operação [WWW Document]. Operador Nac. do Sist. - GERAÇÃO Energ. URL http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/geracao_energia.aspx (accessed 4.10.21).

ONS, 2021c. Reservatórios [WWW Document]. Natl. Syst. Oper. URL http://www.ons.org.br/paginas/energia-agora/reservatorios (accessed 6.25.21).

Our World in Data, 2021. Share of primary energy from wind [WWW Document]. URL https://ourworldindata.org/grapher/wind-share-energy?tab=chart&country=CHL~BRA~CHN~COL~DEU~GBR~USA~ARG (accessed 8.29.21).

Our World in Data, 2022. The price decline of electricity from renewable sources [WWW Document]. Why did renewables become so cheap so fast? URL https://ourworldindata.org/cheap-renewables-growth (accessed 2.28.22).

Paglialunga, E., Coveri, A., Zanfei, A., 2022. Climate change and within-country inequality : New evidence from a global perspective. World Dev. 159, 106030.

Paim, M.A., Dalmarco, A.R., Yang, C.H., Salas, P., Lindner, S., Mercure, J.F., de Andrade Guerra, J.B.S.O., Derani, C., Bruce da Silva, T., Viñuales, J.E., 2019. Evaluating regulatory strategies for mitigating hydrological risk in Brazil through diversification of its electricity mix. Energy Policy 128, 393–401.

Pereira, E.B., Martins, F.R., Abreu, S.L. De, Rüther, R., 2017. Atlas Brasileiro da Energia Solar 31.

Pereira, M., Kelman, R., Fontes, J., 2019. Energy Systems of the Future: Integrating

Variable Renewable Energy Sources in Brazil's Energy Matrix.

Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. Renew. Sustain. Energy Rev. 33, 74–86.

Phimister, E., Roberts, D., 2017. Allowing for uncertainty in exogenous shocks to CGE models: the case of a new renewable energy sector. Econ. Syst. Res. 29, 509–527.

Prefeitura Municipal de Caetité, 2021. Prefeitura e Renova Energia dialogam sobre geração de empregos em Caetité [WWW Document]. URL https://caetite.ba.gov.br/prefeitura-e-renova-energia-dialogam-sobre-geracao-de-empregos-em-caetite/ (accessed 10.7.22).

Probst, B., Anatolitis, V., Kontoleon, A., Anadón, L.D., 2020. The short-term costs of local content requirements in the Indian solar auctions. Nat. Energy 5, 842–850.

PSR, 2022a. PSR - About us [WWW Document]. URL https://www.psr-inc.com/psr-en/presentation/ (accessed 6.11.22).

PSR, 2022b. Software | PSR – Energy Consulting and Analytics [WWW Document]. URL https://www.psr-inc.com/softwares-en/ (accessed 6.16.22).

Pye, S., Li, F.G.N., Price, J., Fais, B., 2017. Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era. Nat. Energy 2, 1–8.

Rajão, R., Soares-Filho, B., Nunes, F., Börner, J., Machado, L., Assis, D., Oliveira, A., Pinto, L., Ribeiro, V., Rausch, L., Gibbs, H., Figueira, D., 2020. The rotten apples of Brazil's agribusiness. Science (80-.). 369, 246–248.

Rennkamp, B., Westin, F., Grottera, C., 2020. Política de conteúdo local e incentivos financeiros no mercado de energia eólica no Brasil. In: Camila Gramkow (org.).2020/1), CEPAL, S. (Ed.), ", Investimentos Transformadores Para Um Estilo de Desenvolvimento Sustentável: Estudos de Caso de Grande Impulso (Big Push) Para a Sustentabilidade. Santiago.

Ribeiro, L.C.D.S., Domingues, E.P., Perobelli, F.S., Hewings, G.J.D., 2018. Structuring investment and regional inequalities in the Brazilian Northeast. Reg. Stud. 52, 727–739.

Robinson, S., 2006. Poverty, Inequality and Development, Economic Studies in Inequality, Social Exclusion and Well-Being. Springer US, Boston, MA.

Rochedo, P.R.R., Soares-Filho, B., Schaeffer, R., Viola, E., Szklo, A., Lucena, A.F.P., Koberle, A., Davis, J.L., Rajão, R., Rathmann, R., 2018. The threat of political bargaining to climate mitigation in Brazil. Nat. Clim. Chang. 8, 695–698.

S&P Global, 2022. Sichuan drought jeopardizes hydropower in China's decarbonization roadmap [WWW Document]. Commod. Insights. URL https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/082222-sichuan-drought-jeopardizes-hydropower-in-chinas-decarbonization-roadmap

Saget, C., Vogt-Schilb, A., Luu, T., 2020. Jobs in a net-zero emissions future in Latin America and the Caribbean. ISBN 978-92-2-133158-2.

Santos, J.A. dos, 2013. Impacto na economia brasileira pela substituição dos combustíveis fósseis por etanol e biodiesel, no período de 2010 a 2030 110.

Santos, M.J., Ferreira, P., Araújo, M., Portugal-pereira, J., Lucena, A.F.P., Schaeffer, R., 2017. Scenarios for the future Brazilian power sector based on a multi- criteria assessment 167, 938–950.

Santos, M.J., Ferreira, P., Araújo, M., Portugal-Pereira, J., Lucena, A.F.P., Schaeffer, R., 2018. Scenarios for the future Brazilian power sector based on a multi-criteria assessment. J. Clean. Prod. 167, 938–950.

Sarkki, S., Ludvig, A., Nijnik, M., Kopiy, S., 2022. Embracing policy paradoxes: EU's Just Transition Fund and the aim "to leave no one behind," International Environmental Agreements: Politics, Law and Economics. Springer Netherlands.

Sathaye, J., Lucon, O., Rahman, A., Christensen, J., Denton, F., Fujino, J., Heath, G., Mirza, M., Rudnick, H., Schlaepfer, A., Shmakin, A., Angerer, G., Bauer, C., Bazilian, M., Brecha, R., Burgherr, P., Clarke, L., Creutzig, F., Edmonds, J., Hagelüken, C., Hansen, G., Hultman, N., Jakob, M., Kadner, S., Lenzen, M., Macknick, J., Masanet, E., Nagai, Y., Olhoff, A., Olsen, K., Pahle, M., Rabl, A., Richels, R., Roy, J., Schei, T., von Stechow, C., Steckel, J., Warner, E., Wilbanks, T., Zhang, Y., Demkine, V., Elgizouli, I., Logan, J., Kadner, S., 2011. Renewable Energy in the Context of Sustainable Development. In: von Stechow, C., Hansen, G., Seyboth, K., Edenhofer, O., Eickemeier, P., Matschoss, P., Pichs-Madruga, R., Schlömer, S., Kadner, S., Zwickel, T., Sokona, Y. (Eds.), Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 707–790.

Scaramucci, J.A., Perin, C., Pulino, P., Bordoni, O.F.J.G., da Cunha, M.P., Cortez, L.A.B., 2006. Energy from sugarcane bagasse under electricity rationing in Brazil: A computable general equilibrium model. Energy Policy 34, 986–992.

Schaeffer, R., Lucena, A.F.P., Szklo, A.S., Borba, B.S.M.C., Nogueira, L.P.P., Rathmann, R., Soria, R.A., 2010. Energia e Economia Verde: Cenários Futuros e Políticas Públicas. Rio de Janeiro, Brazil.

SEBRAE, 2017. CADEIA DE VALOR DA ENERGIA SOLAR FOTOVOLTAICA NO BRASIL.

SEEG, 2021. Emissões Totais de Gases de Eefeito Estufa no Brasil.

Seiceira, D. do E.S.C., Pereira, F., Azevedo, R.L.S. de, 2013. Potencial exportador da indústria eólica brasileira para o Cone Sul e o papel do financiamento. Bndes 5–32.

Shadikhodjaev, S., 2015. Renewable Energy and Government Support: Time to “Green” the SCM Agreement? World Trade Rev. 14, 479–506.

Siegmund-Schultze, M., Köppel, J., Sobral, M. do C., 2018. Unraveling the water and land nexus through inter- and transdisciplinary research: sustainable land management in a semi-arid watershed in Brazil’s Northeast. Reg. Environ. Chang. 18, 2005–2017.

Silva, V., de Oliveira, S., Hoekstra, A., Dantas Neto, J., Campos, J., Braga, C., de Araújo, L., Aleixo, D., de Brito, J., de Souza, M., de Holanda, R., 2016. Water Footprint and Virtual Water Trade of Brazil. Water 8, 517.

Simas, M., 2012. Energia eólica e desenvolvimento sustentável no Brasil: estimativa da geração de empregos por meio de uma matriz insumo-produto ampliada.

Simas, M., Pacca, S., 2014. Assessing employment in renewable energy technologies: A case study for wind power in Brazil. Renew. Sustain. Energy Rev. 31, 83–90.

Sobrosa Neto, R. de C., Berchin, I.I., Magtoto, M., Berchin, S., Xavier, W.G., Guerra, J.B.S.O. de A., 2018. An integrative approach for the water-energy-food nexus in beef cattle production: A simulation of the proposed model to Brazil. J. Clean. Prod. 204, 1108–1123.

Solano-Rodríguez, B., Pye, S., Li, P.-H., Ekins, P., Manzano, O., Vogt-Schilb, A., 2021. Implications of climate targets on oil production and fiscal revenues in Latin America and the Caribbean. Energy Clim. Chang. 2, 100037.

Soria, R., Portugal-Pereira, J., Szklo, A., Milani, R., Schaeffer, R., 2015. Hybrid concentrated solar power (CSP)-biomass plants in a semiarid region: A strategy for CSP deployment in Brazil. Energy Policy 86, 57–72.

Sovacool, B.K., Ali, S.H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., Mulvaney, D., 2020. Sustainable minerals and metals for a low-carbon future. Sci. Mag. 367, 30–33.

Stenzel, F., Greve, P., Lucht, W., Tramberend, S., Wada, Y., Gerten, D., 2021. Irrigation of biomass plantations may globally increase water stress more than climate change. Nat. Commun. 12, 1–9.

Strand, J., Soares-Filho, B., Costa, M.H., Oliveira, U., Ribeiro, S.C., Pires, G.F., Oliveira, A., Rajão, R., May, P., van der Hoff, R., Siikamäki, J., da Motta, R.S., Toman, M., 2018. Spatially explicit valuation of the Brazilian Amazon Forest's Ecosystem Services. Nat. Sustain. 1, 657–664.

Taconet, N., Méjean, A., Guivarch, C., 2020. Influence of climate change impacts and mitigation costs on inequality between countries. Clim. Change 160, 15–34.

Tancredi, M., Abbud, O.A., 2013. Por que o Brasil está trocando as hidrelétricas e seus reservatórios por energia mais cara e poluente? Núcleo Estud. e Pesqui. do Senado 42.

Tavares, M.C., 2000. Auge e declínio do processo de substituição de importações no Brasil. In: Bielschowsky, R. (Ed.), Cinquenta Anos de Pensamento Na CEPAL. Economic Commission for Latin America and the Caribbean.

The New York Times, 2022. Heat and Drought in Europe Strain Energy Supply - The New York Times [WWW Document]. URL https://www.nytimes.com/2022/08/18/world/europe/drought-heat-energy.html (accessed 10.23.22).

Thompson, J.R., Gosling, S.N., Zaherpour, J., Laizé, C.L.R., 2021. Increasing Risk of Ecological Change to Major Rivers of the World With Global Warming. Earth's Futur. 9.

Thornley, P., Rogers, J., Huang, Y., 2008. Quantification of employment from biomass power plants. Renew. Energy 33, 1922–1927.

Tollefson, J., 2018. China declared world's largest producer of scientific articles. Nature 553, 390.

Tolmasquim, M.T., 2016. Energia Renovável: Hidráulica, Biomassa, Solar, Oceânica. Empresa de Pesquisa Energética, Rio de Janeiro.

Trutnevyte, E., McDowall, W., Tomei, J., Keppo, I., 2016. Energy scenario choices: Insights from a retrospective review of UK energy futures. Renew. Sustain. Energy Rev. 55, 326–337.

U.S. Bureau of Labor Statistics, 2020. Occupational Employment Statistics [WWW Document]. Occup. Employ. Stat. URL https://data.bls.gov/oes/#/home (accessed 8.26.20).

UCL, 2018. UCL Energy Institute Models [WWW Document]. Univ. Coll. London. URL https://www.ucl.ac.uk/energy-models/models

United Nations, 2023. Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs [WWW Document]. URL https://sdgs.un.org/2030agenda (accessed 2.7.23).

Vagliasindi, M., Gorgulu, N., 2021. What Have We Learned about the Effectiveness of Infrastructure Investment as a Fiscal Stimulus ? A Literature Review. Policy Res. Work. Pap. No. 9796, World Bank.

Valor Econômico, 2021. Reservatório em baixa faz encargo explodir - Brasil Valor Econômico [WWW Document]. URL https://valor.globo.com/brasil/noticia/2021/03/30/reservatorio-em-baixa-faz-encargo-explodir.ghtml (accessed 4.11.21).

Valor Econômico, 2022a. Produção de painéis não é competitiva no Brasil e Ásia atende 95% do mercado [WWW Document]. URL https://valor.globo.com/publicacoes/suplementos/noticia/2022/05/30/producao-de-paineis-nao-e-competitiva-no-brasil-e-asia-atende-95-do-mercado.ghtml (accessed 9.23.22).

Valor Econômico, 2022b. Bolsonaro sanciona lei que prorroga incentivos para indústria de semicondutores até 2026 | Brasil | Valor Econômico [WWW Document]. URL https://valor.globo.com/brasil/noticia/2022/01/10/bolsonaro-sanciona-lei-que-prorroga-incentivos-para-indstria-de-semicondutores-at-2026.ghtml (accessed 9.27.22).

Vasconcellos, H.A.S., Caiado Couto, L., 2021. Estimation of socioeconomic impacts of wind power projects in Brazil's Northeast region using Interregional Input-Output Analysis. Renew. Sustain. Energy Rev. 149, 111376.

Veiga, J.P.S., Malik, A., Lenzen, M., Ferreira Filho, J.B. de S., Romanelli, T.L., 2018. Triple-bottom-line assessment of São Paulo state's sugarcane production based on a Brazilian multi-regional input-output matrix. Renew. Sustain. Energy Rev. 82, 666–680.

Verikios, G., Hanslow, K., Bahyl, D., Gharibnavaz, R., 2020. A Multi-Sector Model of the United Kingdom: Theory , Data and Parameters.

Viola, E., Basso, L., 2015. Brazilian Energy-Climate Policy and Politics towards Low Carbon Development. Glob. Soc. 29, 427–446.

Walz, R., Pfaff, M., Marscheider-Weidemann, F., Glöser-Chahoud, S., 2017. Innovations for reaching the green sustainable development goals –where will they come from? Int. Econ. Econ. Policy 14, 449–480.

Wang, N., Wei, W., 2019. China's regional rebound effect based on modelling multi-regional CGE. Appl. Econ. 51, 5712–5726.

Wasti, A., Ray, P., Wi, S., Folch, C., Ubierna, M., Karki, P., 2022. Climate change and the hydropower sector: A global review. Wiley Interdiscip. Rev. Clim. Chang. 13, 1–29.

Web of Science, 2022. CGE AND Renewable AND Energy (All Fields) – 218 – Web of Science Core Collection [WWW Document]. Clarivate Web Sci. URL https://www.webofscience.com/wos/woscc/summary/e8b05da6-2829-4035-83d3-0a08adfa664f-3995101a/relevance/1 (accessed 5.22.22).

WEG, 2022. WEG to launch a 7 MW wind turbine [WWW Document]. URL https://www.weg.net/institutional/BR/en/news/products-and-solutions/weg-to-launch-a-7-mw-wind-turbine (accessed 9.24.22).

Willcox, L.D., Araújo, B.P. De, 2018. Reflexões Críticas Sobre a Experiência Brasileira de Política Industrial no Setor Eólico 163–220.

Wills, W., 2013. Modelagem dos Efeitos de Longo Prazo de Políticas de Mitigação de Emissão de Gases de Efeito Estufa na Economia do Brasil. Universidade Federal do Rio de Janeiro.

Wittwer, G. (Ed.), 2017. Multi-regional Dynamic General Equilibrium Modeling of the U.S. Economy, Advances in Applied General Equilibrium Modeling. Springer International Publishing.

World Bank, 2016. Cenário de Baixa Hidrologia para o Setor Elétrico Brasileiro (2016-2030) Cenário de Baixa Hidrologia.

World Bank, 2018. World Bank Open Data | Data [WWW Document]. URL https://data.worldbank.org/ (accessed 11.12.18).

World Bank, 2021. GNI per capita, Atlas method (current US$) | Data [WWW Document]. World Bank Natl. accounts data, OECD Natl. Accounts data files. URL https://data.worldbank.org/indicator/NY.GNP.PCAP.CD (accessed 7.16.21).

World Bank, 2022. WDI - Poverty and Inequality [WWW Document]. URL https://datatopics.worldbank.org/world-development-indicators/themes/poverty-and-inequality.html (accessed 9.14.22).

WWF, 2012. Além de grandes hidrelétricas.

Zhang, W.W., Zhao, B., Gu, Y., Sharp, B., Xu, S.C., Liou, K.N., 2020. Environmental impact of national and subnational carbon policies in China based on a multi-regional dynamic CGE model. J. Environ. Manage. 270.

Zhao, Y., Xu, K., Dong, N., Wang, H., 2022. Projection of climate change impacts on hydropower in the source region of the Yangtze River based on CMIP6. J. Hydrol. 606.

APPENDIX A: MULTI-REGIONAL CGE MODEL

Sectors of the TERM-BR E15 Model in simulations

Sectors (Industries)
Agriculture
Sugar Cane
Livestock
Fishery
Mining
Natural Gas Production
Oil
Fish and Meat
Dairy
Sugar
Food and Beverage
Textiles and Leather
Wood and Cellulose
Other Fuels
Fuel Oil
Diesel and Biodiesel
Ethanol
Chemicals
Other Manufacturing
Metallurgy
Electronics
Vehicles

Machinery and Equipment
Natural Gas Distribution
Other Sources Electricity
Wind Electricity
Petroleum Products Electricity
Nuclear Electricity
Coal Electricity
Natural Gas Electricity
Hydropower Electricity
Solar PV Electricity
Transmission and Distribution of Electricity
Sewage
Construction
Retail and Wholesale
Transportation
Services
R&D
Engineering services

CGE MODEL CLOSURE FOR THE SIMULATIONS CONDUCTED

Common closure to all steps

Variable - Size - Description

Exogenous acap ; ! IND*DST Capital-augmenting technical change

Exogenous alnd ; ! IND*DST Land-augmenting technical change

Exogenous aprim_i ; ! DST Driver for aprim(i,d) for hist sim

Exogenous atot ; ! IND*DST All-input-augmenting technical change

Exogenous atradmar_cs ; ! MAR*ORG*DST Tech change: margin m on goods going from r to d

Exogenous bint_scd ; ! IND Driver: intermediate tech change

Exogenous bint_sd ; ! COM*IND Intermediate tech change

Exogenous blab_o ; ! IND*DST Labor technical change b

Exogenous blab_oid ; ! 1 Labor tech change, general

Exogenous capslack ; ! 1 Slack variable to allow fixing aggregate capital

Exogenous delPTXRATE ; ! IND*DST Change in rate of production tax

Exogenous delUnity ; ! 1 Dummy variable, always exogenously set to one

Exogenous fgovgen ; ! 1 Economy-wide govt demand shift

Exogenous fgovtot ; ! DST Government demand shifter

Exogenous fgov_s ; ! COM*DST Government demand shifter

Exogenous finv1 ; ! IND*DST Investment shift variable

Exogenous flabsupA ; ! OCC*DST Labour migration shifter

Exogenous flabsup_id ; ! OCC National wage shifter

Exogenous flab_id ; ! OCC National wage shifter

Exogenous flab_io ; ! DST Wage shifter

Exogenous flab_iod ; ! 1 National wage shifter

Exogenous fpexp ; ! COM*SRC Export price shift variable

Exogenous fqexp ; ! COM*SRC Export quantity shift variable

Exogenous fqexp_cs ; ! 1 Export quantity shift variable, general

Exogenous frnorm ; ! IND*DST Shifter of Normal gross rate of return

Exogenous frnorm_id ; ! 1 Shifter of Normal gross rate of return

Exogenous fxmig ; ! OCC*REG*DST Bilat Migr by occ shifter

Exogenous fxmig_o ; ! REG*DST Bilat Migr shifter

Exogenous fxmig_or ; ! DST Migr by DST shifter

Exogenous gtrend ; ! IND*DST Trend investment/capital ratio

Exogenous houslack ; ! 1 Consumption slack variable to accommodate national constraint

Exogenous invslack ; ! 1 Investment slack variable for exogenizing national investment

Exogenous nhou ; ! DST Number of households

Exogenous nwork ; ! DST work force: population from 15 to 65

Exogenous pfimp ; ! COM*ORG Import prices, foreign currency

Exogenous phi ; ! 1 Exchange rate, local currency/$world

Exogenous tuser_d ; ! COM*SRC*USR Tax shifter by commodity and user

Exogenous twistelec ; ! COM*DST Twist towards COM (z) by T&D at d

Exogenous xcap ; ! IND*DST Capital usage

Exogenous xhouhtot ; ! DST*HOU Total real household consumption

Exogenous xlnd ; ! IND*DST Land usage (efficiency units)

Rest endogenous; ! end of TABmate automatic closure

swap phi = Natmacro("GDPPI"); ! change numeraire

swap xhouhtot = fhou; ! make regional consumption follow wage income

swap houslack = natfhou; ! fix national propensity to consume

swap natfhou = shrBOTnom;

swap fgovtot = fgovtot2; ! make regional real gov follow regional real hou

swap xcap = faccum; ! switch on capital accumulation

swap finv1 = finv4; ! use dynamic investment rule

swap flabsup_id =labslack; ! switch off national labour supply mechanism

swap flabsupA = flabsupC;

First five years: model update with short-run closure with exogenous GDP growth

Short

! old exog new exog

```
swap fgovgen = Natmacro("Realgov");
swap blab_oid = NatMacro("RealGDP");
!swap shrBOTnom2 = NatMacro("RealHou");
swap natfhou = NatMacro("RealHou");
swap fqexp_cs = Natmacro("ExpVol");
!swap invslack = Natmacro("RealInv");
swap frnorm_id = Natmacro("RealInv");
swap faccum(ELECIND,DST) = xcap(ELECIND,DST);

swap natfhou = shrBOTnom;
swap finv4(ELECIND,DST) = xinvitot(ELECIND,DST);


swap xhouhtot = fhou; ! make regional consumption follow wage income
swap houslack = natfhou; ! fix national propensity to consume
swap fgovtot = fgovtot2; ! make regional real gov follow regional real hou

swap xcap = faccum; ! switch on capital accumulation
swap finv1 = finv4; ! use dynamic investment rule
swap flabsup_id =labslack; ! switch off national labour supply mechanism
swap flabsupA = flabsupC;
```

Baseline closure addition

```
swap blab_oid = NatMacro("RealGDP");

swap finv4(ELECIND,DST) = xinvitot(ELECIND,DST);
```

Policy closure addition

```
swap finv4(ELECIND,DST) = xinvitot(ELECIND,DST);
```

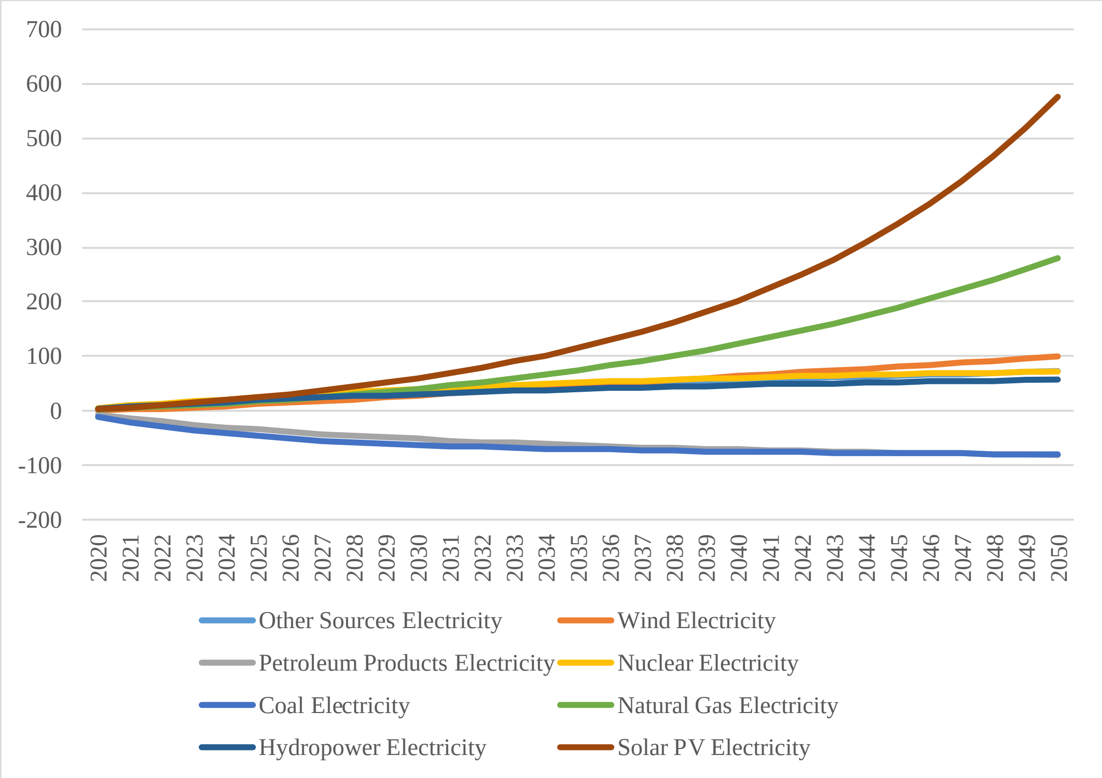
APPENDIX B: BASELINE SCENARIO ASSUMPTIONS

Economically active population growth:

IBGE Official Projections

WorkForceVar	North	Northeast	South	Southeast	Centre West
15 Y2015	2.07	1.19	0.84	0.95	1.74
16 Y2016	2.10	1.17	0.84	0.87	1.79
17 Y2017	2.01	1.11	0.75	0.78	1.68
18 Y2018	1.93	1.05	0.66	0.70	1.58
19 Y2019	1.85	0.99	0.57	0.61	1.49
20 Y2020	1.76	0.92	0.49	0.53	1.40
21 Y2021	1.68	0.84	0.41	0.45	1.31
22 Y2022	1.59	0.77	0.34	0.37	1.23
23 Y2023	1.50	0.69	0.26	0.30	1.14
24 Y2024	1.42	0.61	0.19	0.23	1.06
25 Y2025	1.33	0.52	0.12	0.17	0.97
26 Y2026	1.25	0.44	0.05	0.11	0.89
27 Y2027	1.17	0.36	-0.02	0.05	0.82
28 Y2028	1.09	0.29	-0.07	0.00	0.74
29 Y2029	1.01	0.22	-0.10	-0.04	0.68
30 Y2030	0.94	0.17	-0.12	-0.07	0.62
31 Y2031	0.87	0.11	-0.15	-0.11	0.56
32 Y2032	0.79	0.05	-0.18	-0.14	0.50
33 Y2033	0.72	-0.01	-0.20	-0.18	0.43
34 Y2034	0.65	-0.07	-0.23	-0.21	0.37

35 Y2035	0.57	-0.13	-0.26	-0.25	0.31
36 Y2036	0.50	-0.19	-0.28	-0.29	0.25
37 Y2037	0.43	-0.25	-0.31	-0.32	0.19
38 Y2038	0.35	-0.31	-0.34	-0.36	0.12
39 Y2039	0.28	-0.37	-0.36	-0.39	0.06
40 Y2040	0.21	-0.43	-0.39	-0.43	0.00
41 Y2041	0.13	-0.49	-0.42	-0.47	-0.06
42 Y2042	0.06	-0.55	-0.45	-0.50	-0.13
43 Y2043	-0.01	-0.62	-0.47	-0.54	-0.19
44 Y2044	-0.09	-0.68	-0.50	-0.57	-0.25
45 Y2045	-0.16	-0.74	-0.53	-0.61	-0.31
46 Y2046	-0.24	-0.80	-0.55	-0.65	-0.38
47 Y2047	-0.31	-0.86	-0.58	-0.68	-0.44
48 Y2048	-0.38	-0.92	-0.61	-0.72	-0.50
49 Y2049	-0.46	-0.98	-0.63	-0.75	-0.56
50 Y2050	-0.53	-1.04	-0.66	-0.79	-0.62



Note that the increase in solar PV is distorted by the fact that it was very near zero in the base year.

APPENDIX C: ETHICS APPLICATION AND APPROVAL

This appendix consists of the low-risk ethics application form submitted to the UCL Research Ethics Committee in order to conduct the expert elicitation performed, as well as the review and approval form obtained from the Bartlett School of Environment, Energy and Resources (BSEER) Department Research Ethics Committee.

LONDON'S GLOBAL UNIVERSITY

UCL

UCL Research Ethics Committee

Before completing this form, check that your research is low risk - using Step 4 checklist.

Step 5: Application For Ethical Review (Low Risk) [(BSEER version)]

Include all relevant information about your research in this application form as your ethical approval will be based on this. Anything not included will not be part of any ethical approval.

BSEER ethics evaluators are not a drafting service! If the application does not address one or more issues adequately and requires re-submission, the revised application will only be considered a *minimum* of two weeks after the applicant was advised to re-submit. To avoid this, applicants are advised to pay particular attention to Section F on Data Protection, Q30a on Consent (including any information sheets). The completed form must be thoroughly checked and signed by the supervisor or principal investigator before submission.

Data collection cannot start until the project has research ethics approval.

Section A: Applicant details		
1	**Faculty/Department**	BSEER
2	**Institute** *(Energy / IEDE / ISH / ISR):*	ISR
3	**Principal Investigator** ***Note:*** *Visiting staff/students cannot be Principal Investigators. Visitor hosts can be.* **Name: Lilia Caiado Coelho Beltrao Couto** **Position:** ☐ Staff – specify role: ☐ Honorary Staff – specify role: ☒ Research Student (e.g. PhD) – specify degree programme: PhD in Sustainable Resources ☐ Taught Student (e.g. MSc) – specify degree programme: **Contact Details:** UCL Email: [redacted]@ucl.ac.uk Telephone: [redacted]	
4	**UCL Supervisors (for student projects)**	

	Name: Michael Grubb Position: Professor/ISR Deputy Director Institute (Energy/IEDE/ISH/ISR): ISR UCL Email: [redacted]@ucl.ac.uk	Name: Julia Tomei Position: Lecturer/ISR Interim Director Institute (Energy/IEDE/ISH/ISR):ISR UCL Email: [redacted]i@ucl.ac.uk
5	**Co-Investigators/Partners/Collaborators who will work on the project.** ***Note:*** *This includes those with access to the data such as transcribers.*	
	Name: Position: Faculty/Department: Location (UCL/other UK uni/overseas): Email:	Name: Position: Faculty/Department: Location (UCL/other UK uni/overseas): Email:
	If you do not know the names of all collaborators, please explain their roles:	

Section B: Project details

6	**Title of Project**	Socioeconomic Implications and Resource Management for Long-Term Renewable Electricity Generation in Brazil
7	**Proposed start date**	**01/10/2021**
8	**Proposed end date**	01/03/2022
9	**Funding (if not self-funded)** Is the project funded? Yes *Note: This includes non-monetary awards such as laboratory facilities* If YES, Funder Name: CAPES If YES, Is the funding confirmed? Yes	
10	**Sponsor (if not UCL)** Is the sponsor UCL? Yes *The Sponsor is the organisation taking responsibility for the project.* If NO, Sponsor Name:	

The following questions relate to the objectives, methods, methodology and location of the study. Please ensure that you answer each question in lay terms.

Questions 11-13 have been included in Questions 1-10 of this BSEER version.

14	**Provide a *brief* (300 words max) background to the project, including its intended aims.**
The objective of the PhD thesis is to estimate the socioeconomic impacts of the investment in AR electricity plants in Brazil, with a focus on the Northeast - Brazil's least developed region. The method of this research is Computable General Equilibrium modelling, with a national multi-region approach. Long-term electricity installed capacity expansion scenarios are modelled, estimating the impacts of such investment on macroeconomic variables like job creation, GDP impacts and household income generation. Modelling, of course, has its limitations associated mostly with assumptions that may fail to reflect relevant social aspects. Therefore, expert elicitation will be used to provide insights on the results and proposed policy solutions. A range of experts, including policymakers, electricity sector agents and academics, will be consulted. In order to better discuss policy implications and resource management strategies for future electricity capacity expansion, 10 experts will be interviewed.	

15	**Methodology & Methods (highlight all that apply)**

☒ Interviews	☐ Collection/use of senor or locational data
☐ Focus groups	☐ Controlled trial
☐ Questionnaires (including verbal)	☐ Intervention study (including changing environments)
☐ Action Research	☐Systematic review (See Section D)
☐ Observation	☐Secondary data analysis (See Section E)
☐ Use of personal records	☐ Advisory/consultation
☐ Audio/visual recordings (including photographs)	☐Other, give details:

16a **Provide an overview of the project; focusing on your methodology** and including information on what data/samples will be taken (including a description of the topics/questions to be asked), how data collection will occur and what (if relevant) participants will be asked to do. This should include a justification for the methods chosen.

Please do not just copy and paste a research proposal or case for support.

The methodology of this study is predominantly quantitative. It uses a macroeconomic multisectoral model to estimate the impacts of energy scenarios on socioeconomic variables. In addition to using modelling, it is important to analyse the political economy of Brazilian regions, especially the Northeast, in order to understand the political and social factors that will shape the outcomes of different energy futures, and to propose appropriate policies and strategies. To address these issues, the research methodology will incorporate expert elicitation.

For the purpose of this study, the main sectors to be modelled in the CGE framework are: wind farms, biomass-fired plants and photovoltaic panels value chain; agriculture and land use; and, energy generation alternatives, such as hydropower and thermal power plants. The CGE model will also be used to analyse the income levels of the population, so that the distributional impacts can be assessed for different socioeconomic groups. Thus, through an interregional national CGE model, the effects of national future energy policy scenarios can be measured. Through the modelling of the whole economy, it will be possible to measure how much the supposed changes in a) energy generation, b) industry development to produce solar power plants components, and c) in natural resources demand, will affect variables such as employment, income, value added and government revenue. Impacts on jobs and income will then represent impacts on households which will change the region's scale

	and pattern of consumption, as well as its natural resource consumption patterns. The CGE model will also quantify forward-chaining effects in sectors that should experience economic dynamisation through broader access to energy. Expert elicitation will be used to identify trends and address the limitations of modelling results. Policymakers, electricity sector agents and other experts will be consulted to provide insights that are typically outside of the modelling scope. In order to assess socioeconomic implications, resource use and better discuss the socioeconomic development implications of scenarios for future electricity capacity expansion, 10 interviews with be conducted with the following key stakeholders: • Policymakers from the national and northeast region governments; • Electricity sector companies; • Experts from the Brazilian and NE region development banks; and, • Academics and consultants who are experts on the Brazilian electricity system. Interviews will be recorded if participants consent.
16b	**Questions / Topic Guides / Tests** *Please attach a copy of any interview questions / questionnaires / workshop topic guides / tests (e.g. psychometric), etc.* 1) How do you see the challenge posed by hydropower generation limits to the electricity sector in Brazil? 2) In your opinion, what sources should be prioritised in the electricity capacity expansion in Brazil until 2050? Why? 3) What is the role of the Northeast region for the expansion of the Brazilian electricity generation capacity in the long run (2050)? 4) Modelling results indicate that the investment in solar and wind power being concentrated in the Northeast yields larger GDP growth and labour force migration to the region. Do you think this means propelling regional development, overcoming historical barriers that made this region lag behind the others? 5) How much of personnel employment, industrial goods and services demanded by plants recently installed in the NE were actually procured from the region? 6) What actions could national, regional governments and companies take to ensure that these co-benefits are retained in the NE region? 7) How do you see the interactions between water, energy and food access in the NE region? 8) How do you think that future electricity generation in the NE could impact access to these resources? 9) Do you think that the interlinkages between these resources are normally considered in their governance? How does this impact access to them?

	What questions / topic guides / tests are attached? Questions. *Are they in final or draft form? Draft*

17	**Please state which code of ethics will be adhered to for this research (for example, BERA, BPS, etc). If none, please state.**
None	

18	**Please indicate where this research is taking place.** ☐ UK only (Skip to 'location of fieldwork' Q21) ☐ Overseas only ☒ UK & overseas
19	**If the research includes work outside the UK, is ethical approval in the host country (local ethical approval) required*?** Yes ☐ No ☒ **If no,** please explain why local ethical approval is not necessary/possible. There is no clear risk, information will be used generally and anonymised, experts will provide their own views and obtain approval from the institutions they are affiliated to on an ad hoc basis. Brazil does require ethical approval in this case. **If yes,** provide details below including whether the ethical approval has been received. **Note:** Full UCL ethical approval will not be granted until local ethical approval (if required) has been evidenced. *To check which local ethics committee you may need to apply to, the International Compendium of Human Research Standards contains information on over 100 countries, including key organisations such as local ethics committees. http://www.hhs.gov/ohrp/international/compilation-human-research-standards/index.html

20	**Does the research place you or any other members of the research team at any risk greater than in your daily life?** • *EG Lone working in non-public places.* • *EG Working in potentially unsafe environments.* • *EG Overseas research where the UK Foreign and Commonwealth Office (www.fco.gov.uk) advises against travel to that region? If necessary, submit a travel insurance form to UCL Finance (see application guidelines for more details). This can be accessed here: https://www.ucl.ac.uk/finance/secure/fin_acc/insurance.htm* Yes ☐ No ☒ **If yes, has a project risk assessment, signed by the supervisor / Principal Investigator / Head of Department been submitted?** Yes ☐ No ☐

21	**State the location(s) where the research will be conducted and data collected. For example public spaces, schools, private company, using online methods, postal mail or telephone communications.** Internet-based communications (Zoom)
22	**Does the research location require any additional permissions (e.g. obtaining access to schools, hospitals, private property, non-disclosure agreements, access to biodiversity permits (CBD), etc.)?** Yes ☐ No ☒ **If yes, please state the permissions required.**
23	**Have the above approvals been obtained?** Yes ☐ No ☒ N/A **If yes,** please attach a copy of the approval correspondence. **If not,** confirm they will be obtained prior to data collection. Yes ☐ No N/A ☒

Access to data	
24	If you are using data or information held by third party, please explain how you will obtain this. You should confirm that the information has been obtained in accordance with the UK Data Protection Act 1998. N/A

Reporting / Publishing / Disseminating / Sharing Results	
25	How will the results be reported, published, shared and otherwise disseminated (including communication of results with participants)? The results will be reported anonymously and aggregated in groups of stakeholders. They will be published in the PhD thesis and they are expected to be published in journal papers.

Section C: Details of Participants

In this form 'participants' means human participants and their data (including sensor/locational data, observational notes/images, tissue and blood samples, as well as DNA).

26	**Does the project need participants or data from participants?** *EG Will you ask people to complete a survey or be interviewed? EG Will you monitor people in some way – observation, location data, etc.?*
Yes ☒ Complete all parts of this Section. **No** ☐ Move to Section D.	

27	**I confirm that I have read the high risk checklist and this study will not include participants or data from participants that fall under sections 1-3.**
Yes ☒ Complete all parts of this Section. **No** ☐ Complete the high risk checklist and apply to the UCL Research Ethics Committee.	

Participant Details

28	Approximate Number of participants required: 10 Approximate Upper age limit: 70 Lower age limit: 30 Justification for the age range and sample size: participants are experts of the electricity sector in Brazil working for companies, the government and academia. They are expected to be at a level of seniority that would be unlikely to encompass professionals under 30, nor retired people, so 70 is expected to be the upper age limit. A small number is to facilitate the section on implications for policy and begin dissemination of research.
Inviting / Enrolling / Recruiting / Admitting / Including Participants	
29	Describe how potential participants will be invited, enrolled, recruited, admitted or otherwise included into the study. **NOTE:** This should include reference to how you will identify and approach participants. For example, will participants self-identify themselves by responding to an advert for the study or will you approach them directly (such as in person or via email)? Invitation / recruitment documents must be written in clear language appropriate to the target audience – see the accompanying guidance on writing information sheets. Potential participants will be identified according to the sector they work in and their job position. If they are considered to be a potential participant in the research, they will be contacted by e-mail. The e-mail invitation, including the information sheet and consent form, is attached to this application.
Consent	
30a	Describe the process you will use when seeking to obtain consent. **Note:** This should include reference to what participants are being asked to consent to, such as whether their contribution will be identifiable/anonymous, limits to confidentiality and whether their data can be withdrawn at a later date. For guidance on preparing information sheets and obtaining and recording consent see: • accompanying guidance on writing information sheets in clear language appropriate to the target audience • https://ethics.grad.ucl.ac.uk • http://www.ucl.ac.uk/srs/research-ethics-committee/pages/ioe • http://www.data-archive.ac.uk/create-manage/consent-ethics/consent

	Once participants have expressed interest in participating in the study, a 60-90 minute online meeting will be arranged at their convenience. Prior to the meeting, they will receive another email containing the attached consent form, which they will be asked to return via email confirming that they have read the information and understood what their participation will involve, their rights to withdraw and how the information provided will be used. This will also include permission to record the interview. If the participant does not wish the meeting to be recorded, detailed notes will be taken instead.
30b	**Consent Attachments** Please list them below: *Ensure that a copy of all invitation / recruitment documentation (recruitment emails/posters, information sheet/s, consent form/s) have been attached to the application.* The invitation email, information sheet and consent form are attached to this application.
30c	If you are ***not*** intending to seek consent from participants, clarify why below:

Section D: Secondary data analysis

31	**Does your study involve the use of previously collected data?** **Yes** ☒ Complete all parts of this Section. **No** ☐ Move to Section E.
32	**Name of dataset/s:** National Accounts, National Energy Balance, Electricity Auction results, National Household Sample Survey, Household Budget Survey
	Owner of dataset/s (if applicable): Brazilian Institute of Geography and Statistics, Energy Research Company, Ministry of Economics of Brazil, National Agency of Electric Energy
33	**Are the data in the public domain?** Yes ☒ No ☐

	If no, do you have the owner's permission/license? Yes ☐ No* ☐	
34	**Are the data anonymised?** Yes ☒ No ☐ **If no:** i. Do you plan to anonymise the data? Yes ☐ No* ☐ ii. Do you plan to use individual level data? Yes* ☐ No ☒ iii. Will you be linking data to individuals? Yes* ☐ No ☒	
35	Are the data sensitive (DPA 1998 definition)?	Yes* ☐ No ☒
36	Will you be conducting analysis within the remit it was originally collected for?	Yes ☒ No* ☐
37	If no, was consent gained from participants for subsequent/future analysis?	Yes ☐ No* ☐
If you ticked any boxes with an asterisk (*), please ensure that you give further details in Section F: Ethical Issues.		

Section E: Ethical Issues

Ethical Issues	
38	Please address clearly any ethical issues that may arise in the course of this research, including those highlighted earlier in the form, and how they will be

addressed. Possible harms include physical, psychological, emotional, economic, reputational, and legal. The potential severity, duration and probability of harm vary from minimal to high.

Note: All ethical issues should be addressed - *do not leave this section blank*. If you think there are no ethical issues, you need to provide an explanation as to why.

There are no clear ethical issues or risks to participants as this research will not assess any aspect of their personal lives, nor touch on sensitive topics. Questions will refer to understandings of national trends for the economy, the electricity sector and resource use. Furthermore, results will be published in aggregate, without disclosing participants' identities or attributing opinions.

However, to ensure confidentiality and consent from participants, the following steps will be taken:

1. Prior to elicitation, the participants of this research will be provided with information about the purpose and objectives of the research, and they will only be interviewed if they consent.
2. All data will be securely stored at the UCL server which has safety measures in line with the General Data Protection Regulation, and UK Data Protection Act 2018.
3. From the research data, it will not be possible to identify individuals as it will be stored separately from identifiers.
4. To ensure integrity, interview data will be reported accurately, without any distortion or misrepresentation of participant's views.
5. All stages of the research will be documented.

Risks & Benefits	
39	If there are *benefits* to participants of taking part in the study (e.g. have their views heard, feedback, access to services, incentives), please state these: Participants will have the opportunity to have their views heard and to ensure that the results, including policy recommendations, incorporate these views rather than relying solely on modelling outputs. It is also hoped that the results of this thesis will be used to inform policy in the northeast and elsewhere in Brazil.
40	Do you intend to offer incentives or compensation, including access to free services)? Yes ☐ No ☒

	If yes, specify the amount to be paid and/or service to be offered **as well as a justification for this**.
41	Please state any *risks* to participants and how these risks will be managed. There are no anticipated risks to the participants of the research. Any potential reputational risks will be minimised through the steps identified above to anonymise all contributions.

Section F: Confidentiality, Data Storage & Security

Please ensure that you answer each question and include all hard and electronic data.

42	**Will the research involve the collection and/or use of personal data (this includes when individual participants are only identifiable by the researcher)?** ***Personal data*** *is data which relates to a living individual who can be identified from that data OR from the data and other information that is either currently held, or will be held by the data controller (the researcher). This includes:* – *Obviously identifiable data such as email/postal addresses, many names, etc.* – *any expression of opinion about the individual and any intentions of the data controller or any other person toward the individual.* – *sensor, location or visual data which may reveal information that enables the identification of a face, address, etc (some postcodes cover only one property).* – *combinations of data which may reveal identifiable data, such as names, email/postal addresses, date of birth, ethnicity, descriptions of health diagnosis or conditions, computer IP address (if relating to a device with a single user).* – **Yes** ☒ **No** **All research projects using personal data must be registered with UCL Legal Services (http://www.ucl.ac.uk/legal-services/research) before the data is collected.**

	This process will help researchers, supervisors and investigators meet their legal obligations under the UK Data Protection Act 1998 (the UK legislation implementing the EU Data Protection Directive 1995). *To complete this process you will need to think about how the data is being protected, e.g. whether personal data will be stored separately from the research data and linked using a link code, and whether personal data will be shared outside the research team. The following may be helpful:* *. UCL Data Protection Policy Section 5 Security of Personal Data & Section 9 Research using personal data:* https://www.ucl.ac.uk/informationsecurity/policy/public-policy/DataProtectionPolicy1016.pdf *. A practical note for researchers on the limited exemptions from the UK Data Protection Act is here:* http://www.adls.ac.uk/publications-and-documents/ **Please provide your UCL Data Protection registration number:** **Z6364106/2021/08/35 social research**
43	**Is the research collecting or using** – *Special category* personal data as defined by Data Protection legislation (includes data that reveals: physical or mental health, provision of health care services, sexual orientation or sex life, political opinions, trade union membership, religious or philosophical belief, racial or ethnic origin) or criminal records data? – data which might be considered sensitive in some countries, cultures or contexts. **Yes** ☐ **No** ☒ **If yes,** state whether explicit consent will be sought for its use and what data management measures are in place to adequate manage and protect the data.

During the project *(including the write up and dissemination period)*

44	**State what data will be generated from this project (i.e. transcripts, videos, photos, audio tapes, field notes, etc).** Video and audio recordings, transcripts and notes.
45	**How will data be stored, including where and for how long? This includes all hard copy and electronic data on laptops, share drives, usb/mobile devices.** It will be stored in my UCL file store at UCL central file storage.
46	**Who will have access to the data, including advisory groups and during transcription?** Only myself.
47	**Do you confirm that all personal data will be stored and processed in compliance with the Data Protection Act 1998 (DPA 1998).** Yes ☒ No ☐ **If no,** please clarify why.
48	**Will personal data be processed or be sent outside of the European Economic Area (EEA)?*** Yes ☐ No ☒ **If yes,** please confirm that there are adequate levels of protection in compliance with the DPA 1998 and state what arrangements are below. ***Please note** that if you store your research data containing identifiable data on UCL systems or equipment (including by using your UCL email account to transfer data), or otherwise carry out work on your research in the UK, the processing will take place within the EEA and will be captured by Data Protection legislation.

After the project	
49	i. What data will be stored and how will you keep it secure? Interview audio files and transcripts. I will be the only person to have access to them. ii. Where will the data be stored and who will have access?

	The data will be stored using UCL file storage, which is password protected and accessed only by myself. iii. Will the data be securely deleted? Yes ☒ No ☐ **If yes,** please state when will this occur: 2 years after the final thesis is submitted. iv. Will the data be archived for use by other researchers? Yes ☐ No ☒ **If yes,** please provide further details including whether researchers outside the European Economic Area will be given access.

Applicant Declaration: I confirm that the information in this form is accurate to the best of my knowledge.

Supervisor's Declaration: I confirm that I have checked this completed form and that the information in it is accurate to the best of my knowledge.

Signature	
Date	17/08/21
If student Supervisor Name:	Julia Tomei
Supervisor Signature:	[redacted]
Date:	16/08/21

THE BARTLETT SCHOOL OF ENVIRONMENT, ENERGY AND RESOURCES

BSEER Research Ethics – Low Risk Application – Review (v1.11)

Applicant UCL email address: lilia.couto@ucl.ac.uk
ISR
Student
Supervisor (if student): Michael Grubb
Title of Study: Socioeconomic Implications and Resource Management for Long-Term Renewable Electricity Generation in Brazil
Date of Application: 17 August 2021

	Unsatisfactory	Satisfactory	N/A
STUDY DETAILS			
Sufficient study details provided to evaluate ethical implications		x	
Study does not seem to include sensitive topics (see High Risk checklist)		x	
Sufficient sampling details provided to evaluate ethical implications		x	
Sample does not seem to include vulnerable individuals (see High Risk checklist) & active steps to exclude <18yo		x	
CONSENT			
Information for participants covers necessary issues adequately (Researcher & says if student, Institution, funder, study title & purpose, how participant selected, excludes <18yo, what happens to participant, how long it will take, benefits, potential risks/harms, anonymity/confidentiality, voluntariness, right to withdraw, contact details)		x	
Information for participants is sufficiently concise		x	
Information for participants is written in an appropriate style (Study title and content appropriately phrased for participants, level of detail appropriate for participants)		x	
(Where participants known to researcher) appropriate procedures to ensure participants feel free to not participate & withdraw from the study		x	
EVALUATION & MITIGATION OF HARM			
Risk of harm to participants seems to be minimal (see High Risk checklist)		x	
Recognises & addresses potential risks/harms to participants		x	
(Where risks to researcher beyond those experienced in daily life) has appropriate risk assessment been completed?		x	
DATA PROTECTION & PRIVACY			
Correctly identifies whether/not personal data are being collected / used / processed (Definition of personal data is embedded in the low risk form Q42…check whole application to ensure applicant answered this Q correctly)		x	
Correctly identifies whether/not *special category or criminal records* personal data are being collected / used / processed (Definitions embedded in the low risk form Q43…check whole application to ensure applicant answered this Q correctly)		x	
(If personal data are being collected / used / processed) has registered study with UCL Data Protection Officer		x	
(Where participants are known to researcher) appropriate procedures to protect participants' privacy (EG data collected &/or collection method)		x	

Review (delete as applicable):

☒ Study is low risk and may commence.

☐ Study is low risk and may commence AFTER you obtain a UCL Data Protection number from UCL Legal – you are collecting personal data

☐ Study is low risk and may commence AFTER you meet the following conditions and demonstrate that to the evaluators:

☐ Study requires revised submission to BSEER Research Ethics Team. Data collection/processing cannot start until the research is evaluated as low risk.

☐ Study requires approval from UCL Research Ethics Committee prior to data collection/processing.

Name(s) of BSEER reviewer(s): Will McDowall

Date: 24th August 2021

APPENDIX D: CONTRIBUTIONS OF THE THESIS RESEARCH TO PUBLISHED ARTICLES

As seen in the impact statement of this thesis, the outputs of the different parts and stages of this research during the PhD process have turned into contributions to four published papers (Caiado Couto et al., 2021; Cronin et al., 2021; Milani et al., 2020; Vasconcellos and Caiado Couto, 2021). These publications have not been directly inserted as parts of the thesis as such, but clearly my contribution and authorship of these publications were byproducts of this thesis' research. As stated before, the actual results chapters of this thesis will be submitted to academic journals for publication as separate articles, they have not been published by the time of submission of the final PhD Thesis. The contribution of the PhD research to each of the four papers is explained as follows:

1. Caiado Couto et al. (2021): This article named *Water, waste, energy and food nexus in Brazil: Identifying a resource interlinkage research agenda through a systematic review* was published in the journal Renewable and Sustainable Energy Reviews in 2021. In this paper, I did a comprehensive assessment of natural resource availability in Brazil, their importance to economic activities and economic development, and the extent to which the uses of different natural resources are interlinked, the challenges, trade-offs and potential benefits of such interlinkages. It was critical for me to understand the role of variable renewable electricity sources in long term development in Brazil, also through the lenses of the extent to which it reduces the pressure on other resources, mostly water by redesigning the role of hydropower in the system. Chapter 2 and Chapter 3 of this thesis benefitted from the research done for this article.
2. Cronin et al. (2021): *Embedding justice in the 1.5°C transition: a transdisciplinary research agenda* is an article developed with several colleagues of the UCL Energy and Development Group published in the journal Renewable and Sustainable Energy Transition in 2021. I led the section named *The distribution of economic gains and losses* that analyses qualitatively at a global level the existing evidence of the economic impacts of

the energy transition, including employment effects of replacing electricity sources. This paper relates to the research I did for Sections 3.3 and 3.4.

3. Milani et al. (2020): This article named *Promoting social development in developing countries through solar thermal power plants* was published in the Journal of Cleaner Production with colleagues from the Energy Planning Programme of the Federal University of Rio de Janeiro, in Brazil. I performed the Input-Output modelling that estimated the direct, indirect and induced economic impacts of a programme of solar power plants in the Northeastern state of Bahia. We conducted an analysis of industrial capabilities to supply the solar power plants in Brazil and in Bahia, that resulted in local content scenarios for industrial components. I ran these industrial scenarios, and this paper I consider the basis for the much more comprehensive and complex analysis I did in this thesis.
4. Vasconcellos and Caiado Couto (2021): *Estimation of socioeconomic impacts of wind power projects in Brazil's Northeast region using Interregional Input-Output Analysis* is a paper I co-authored with Henrique Vasconcellos, whose MSc dissertation I supervised at the UCL Masters Programme Economics and Policy of Energy and Environment. I suggested that Henrique applied the same methodology I developed for Milani (2020) to the wind power projects procured through recent auctions, which I were analysing for this thesis. The database Henrique used was the same as the main database of the thesis, I taught Henrique how to apply the methodology, and I gave him the data for the wind projects whose economic impacts would be estimated.

All of these papers were cited where relevant throughout the thesis.