

**École polytechnique de Louvain**

# **Economic, energy and social impacts of a carbon tax in Colombia**

**Analysis of rates, applications and redistribution  
mechanisms**

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*This thesis utilized OpenAI's ChatGPT for assistance in sentence redaction and improvement.*



# Abstract

In the face of climate urgency, carbon pricing policies have emerged as a key instrument to support energy transitions. This master thesis analyzes the energy, economic and social impacts of a carbon tax in Colombia using a novel coupling between two models: EnergyScope Pathway, a cost-optimization energy planning tool, and GEMMES, a stock flow consistent macroeconomic model.

Colombia presents a particularly complex case study due to its dual role as both a fossil fuel exporter and a nation committed to achieving carbon neutrality by 2050. Although a carbon tax was introduced in 2016, it remains narrow in scope and relatively low in rate, covering only a fraction of emissions and generating limited revenues. This study therefore explores several potential reform scenarios.

Three main categories of scenarios are analyzed. The first explores various carbon tax rate trajectories, linear and sigmoid profiles with both early and delayed implementations to assess how different timing and intensities affect emissions, costs, energy mix and macroeconomic indicators. The second scenario group evaluates government strategies to reinvest tax revenues into renewable energy, either through fixed subsidies or subsidies proportional to carbon tax revenues. The third focuses on redistributive mechanisms, simulating income based transfers to households by disaggregating them into income quantiles, allowing for an equity focused assessment of tax burdens and welfare effects.

Results demonstrate that higher carbon taxes accelerate emissions reductions but increase total transition costs and economic impacts. An early increase in the carbon tax rate yields the best climate outcomes but causes economic shocks, while delayed action preserves stability at the cost of higher cumulative emissions. Subsidies to renewables have limited energy impact but moderately stimulate investment and raise public debt. Socially, targeted redistribution to low-income households reduces inequality most effectively, while regressive schemes worsen it. Although all scenarios indicate a growing trend in inequality over time.



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# Glossary

- AFD** Agence Française de Développement. 2, 29, 51, 54
- CAPEX** Capital Expenditures. 11, 51
- CCS** Carbon Capture and Storage. 5
- DNP** National Planning Department. 5, 30
- ESOM** Energy System Optimization Model. 2
- ETS** Emissions Trading System. 1, 5
- EUD** End-Of-Use Demand. 18, 23
- FARC** Revolutionary Armed Forces of Colombia. 15
- GCAM** Global Change Assessment Model. 5
- GDP** Gross Domestic Product. 5
- GEMMES** General Monetary and Multisectoral Macrodynamics for the Ecological Shift.  
2, 7, 51
- GHG** Greenhouse Gas. 1, 9
- GWP** Global Warming Potential. 16, 32
- HD** Household Disaggregation. x, 51, 54
- HVC** High-Value Chemicals. 23
- IDB** Inter-American Development Bank. 15
- IEA** International Energy Agency. 10
- LFO** Light Fuel Oil. 23, 32
- MEG4C** Computable General Equilibrium Model for Climate Change in Colombia. 5
- MILP** Mixed-Integer Linear Programming. 16
- MSM** Microsimulation model. 5, 50
- NDC** Nationally Determined Contributions. 1, 9, 16
- NFC** Non-Financial Corporations. 47

**OECD** Organisation for Economic Co-operation and Development. 1

**OPEX** Operating Expenses. 11, 51

**R&D** Research and Development. 13

**SDG** Sustainable Development Goals. 9

**SFC** Stock-Flow Consistent model. 2, 17

**SOS** Safe Operating Space. xi, 5, 43, 57, 59

## 1.1 Context

Climate change is undeniable and at the heart of global discussions. The Paris Agreement [Nat15], an international treaty on climate change adopted in 2015, set out multiple long-term objectives to mitigate climate change and its collateral impacts. The famous 2 degree threshold, which aligns with the objective of limiting global warming, with an aim of 1.5 degrees, was established in this treaty. Each country that ratified the agreement has set its national plans (NDC) over the coming decade to meet the global targets outlined in the Agreement. Policies and measures are being implemented, but they are not sufficient [Uni24].

One measure that has already proven its benefits is carbon pricing [Ban24], which goal is to put a price on greenhouse gas (GHG) emissions and that can be implemented in several ways. Two of the most widespread methods of carbon pricing are as follows. First, the carbon tax sets a price on emitted CO<sub>2</sub> equivalent [OEC23b]. It serves as a direct way to target those responsible for emissions while also generating government revenue that can be reinvested in various applications. The tax can be levied at different points in the supply chain, whether at the fuel production stage, consumption stage, or any intermediate point. It can also be focused on specific types of emissions. This has already been widely studied and proven effective for a considerable period [BO71; Gou95; KSH96; Pea91; PT90; SMM06]. Another method is the cap-and-trade system, such as the most well-known one, the Emissions Trading System (ETS) in Europe [Uni03]. Companies or countries receive emission permits (allowances) and can adjust their emissions relative to their allocated allowances by purchasing or selling additional permits to maintain balance. This mechanism establishes a regulated emissions market that caps the overall volume of permissible emissions. Both instruments can lead to the same outcome [Con+17]. The fundamental difference is that the first (the carbon tax) restricts the price, which then determines the emissions, whereas in the other case (the cap-and-trade system), the emissions are restricted, which results in a specific price.

From a vocabulary perspective, there is no regulated definition of a carbon tax, although there are many unofficial definitions [Yel19; OEC23b; Chu04; KS22].

*“A carbon tax is a tax that explicitly states a price on greenhouse gas emissions or that uses a metric directly based on carbon (that is, price per tCO<sub>2</sub>e).”* [Ban24].

It is essential to distinguish between the effective carbon rate and the carbon tax rate often referenced in academic and policy discussions [OEC16]. According to the OECD, the effective carbon rate includes the combined impact of specific energy taxes, explicit carbon taxes and prices from ETS. In contrast, the carbon rate typically discussed in the literature usually refers only to carbon taxes. In this thesis, the focus will be limited to carbon taxes and thus, the carbon tax rate will be the primary subject of analysis.

To assess the impact of a carbon tax, it is crucial to consider a wide range of factors, as overlooking any of them could lead to the design of an ineffective tax. Models are indispensable for predicting potential outcomes and minimizing adverse effects, allowing for a more informed approach to policy-making [Jac25]. While much of the focus in studies has been on environmental economics, a comprehensive evaluation requires considering additional aspects. A well designed carbon tax aims not only to reduce emissions but also to minimize economic disruptions, support economic growth and adapt the energy mix effectively. It is important to anticipate how the energy system adjusts to the new constraints, whether this transition is feasible and what measures need to be implemented to ensure successful adaptation while achieving the desired environmental and economic outcomes. Furthermore, the social impact must not be overlooked, carbon taxes can affect households differently, often disproportionately burdening lower income populations [Car19; Rom+18; DF23]. Equity in tax design is essential, ensuring that the tax burden is fairly distributed and does not exacerbate existing inequalities. By combining predictive models with post implementation studies, a more holistic understanding of the tax's effects on both the economy and society can be created, helping to refine policies for a just and effective transition.

To achieve the results of this thesis, two models are employed. In Pierre Jacques' thesis [Jac25], a coupling was developed between Energyscope, an ESOM (*Energy System Optimization Model*) and GEMMES (*General Monetary and Multisectoral Macrodynamics for the Ecological Shift*), an SFC (*Stock-Flow Consistent macroeconomic model*), specifically for the case of Colombia. This choice is primarily driven by the fact that GEMMES is a tool developed by the *Agence Française de Développement (AFD)* and has already been applied to countries such as Vietnam, Brazil, Colombia, Ivory Coast and Tunisia [Dévnd]. Applying it to a country outside this list would have required entirely rebuilding its macroeconomic model, significantly complicating the analysis.

Furthermore, Colombia is a particularly interesting case study. The government has a sincere intention to transition to renewable energy, which represents a major challenge and is implementing numerous measures to address climate change. At the same time, the country's economy is heavily reliant on fossil fuels exportations, creating a significant disadvantage for achieving an energy transition without triggering economic crises.

The objective is therefore to identify the most effective carbon tax in Colombia based on multiple criteria using the coupling of Pierre Jacques :

- **Energy:** minimizing CO<sub>2</sub> equivalent emissions
- **Economic:** limiting crises and macroeconomic stress
- **Social:** considering the impact on vulnerable populations and minimizing

Colombia already has a carbon tax, but it remains limited in scope and relatively low in rate (see subsection 2.1.3). However, it provides a solid foundation for exploring optimization scenarios and broadening carbon pricing mechanisms.

## 1.2 Literature Review

### 1.2.1 Worldwide

The study of carbon taxation is not a new field, as the first countries implemented their carbon taxes in the 1990s. If not limiting the focus to the implementation of a carbon tax in a single country but rather considering the general concept, existing literature can be reviewed, relying among others, on the article "*Carbon Taxation : A Review of the Empirical Literature*" [KS22] and the World Bank Group's publication "*Carbon Tax Guide: A Handbook for Policy Makers*" [Con+17].

The main points of attention highlighted in the literature regarding carbon tax implementation are the following:

- Double Dividend Hypothesis
- Competitiveness
- Leakage Effects
- Distributional Implications
- Recycling Schemes

#### *Double dividend hypothesis*

The double dividend hypothesis is an economic theory suggesting that environmental tax reforms can generate two benefits ("dividends") simultaneously [Pea91]. On one hand, the environmental dividend helps reduce emissions. On the other hand, revenue from these taxes can be used to lower other distortionary taxes (such as income or payroll taxes) [PB99], leading to greater economic efficiency and potentially improving employment or economic growth [Mig+25b].

The second dividend is widely debated, with opposing viewpoints. The *optimistic view* argues that better environmental quality enhances public health and well-being, which can boost productivity and increase labor supply. This, in turn, could stimulate economic activity and promote employment. Conversely, the *skeptical view* contends that such reforms lead to negative economic repercussions due to rising prices.

It is difficult to reach a definitive conclusion since the outcomes depend on numerous implementation parameters, such as tax rates, revenue allocation and policy scope. Even within the same region, results can be contradictory. For example, in British Columbia, the region with the most studies on carbon taxation, findings vary. One key factor suggests that full revenue recycling (by reducing social security contributions and income tax) plays a crucial role, as highlighted by Andersen and Ekins [AE09] and studies on the revenue-neutral British Columbia carbon tax [MR15; Yam17].

#### *Competitiveness*

At first glance, an inherent concern regarding the implementation of a carbon tax is competitiveness in comparison to international markets. The tax will increase prices, which could disadvantage products and services relative to those from countries without a carbon tax. The conclusion drawn in "*Carbon Pricing and Competitiveness: Are They at Odds?*" [ENV19] is that, compared to other business costs, this is not a determining factor at all. An early tax implementation can allow a country to get ahead of others that, in the current global context, will inevitably have to undergo their own transition. According to most

ex-post empirical research, energy and carbon costs have no statistically significant effect and even, sometimes positive effects on competitiveness [PAV21]. This contrasts with the findings of numerous ex-ante simulations that use economic modeling to predict how carbon taxes will affect competitiveness, which indicate negative effects [CR17].

### *Leakage Effects*

Colombia is an example of a leakage effect. Coal was excluded from carbon taxation, leading to its more intensive use. As a result, the government changed the law to expand its scope. To avoid this, it is necessary to analyze the situation and identify the risks. It is also clear that tax reducing measures, such as exemptions and reductions, will only reduce the effectiveness of the tax in terms of emissions, so it is better to avoid them as much as possible. Different leakage channels have been identified [Con+17; Int23a; MW21].

1. In the **output channel**, firms in taxed jurisdictions may lose market share to those not subject to the tax, shifting production to non-taxing regions.
2. In the **investment channel**, covered firms may reduce investment in maintenance, leading to plant closures, while investment increases in non-taxing regions.
3. In the **fossil fuel price channel**, lower fossil fuel consumption in taxed regions reduces global prices, prompting higher consumption in non-taxing areas.
4. **Reverse leakage** occurs when taxing jurisdictions develop new technologies that are more cost-effective and non-taxing jurisdictions also adopt them.

### *Distributional Implications*

The distributional effects of carbon taxation depend on various factors, including income levels, geographic location and economic structure. Empirical studies show that carbon taxes can be regressive, proportional, or even progressive, depending on tax design and revenue recycling measures [Car19]. Lower-income households tend to bear a greater burden as they spend a higher share of their income on energy, though this effect varies across countries [Mar24]. Regional disparities also exist, with carbon taxes disproportionately impacting areas reliant on emissions-intensive industries, fossil fuel extraction, or extreme climate conditions [Wie+05; Fen+10; HMM09]. While many studies indicate a regressive impact, especially in high-income countries, others highlight progressive effects when revenues are redistributed or when long-term benefits, such as health improvements and environmental gains, are considered.

### *Recycling Schemes*

Linked to the double dividend hypothesis, revenue generated from a carbon tax can be allocated in various ways. In "*Carbon Tax Guide: A Handbook for Policy Makers*" [Con+17], these options are classified into three principal approaches, revenue neutrality, expanded spending and forgoing revenue through the allowance of offsets, although the distinctions among them are not sharply defined and may, in practice, overlap or be implemented simultaneously. The first approach, revenue neutrality, ensures that overall government spending remains unchanged. The funds are either redistributed to households or businesses or used to reduce other taxes, notably those on labor, capital or consumption. However, a key issue is that tax revenues will decline over time, leading to an initial tax reduction followed by a necessary increase, which may not be optimal. The second approach, expanded spending, increases government expenditures by either integrating carbon tax revenue into the general budget, reducing public debt, or earmarking funds, most commonly for environmental initiatives. Finally, the third approach, forgoing revenue by per-

mitting offsets, allows entities to reduce their carbon tax obligations by using verified emission reduction credits instead of paying the full tax. While this reduces government tax revenue, its impact depends on whether the offsets are international, which results in lost domestic funds, or domestic, which effectively channels the forgone revenue into local emission reduction efforts. This option is not widely adopted, as it is more commonly associated with ETS. There is no universally optimal solution, as each option presents trade-offs depending on policy priorities and economic conditions.

### 1.2.2 Colombia

Finally, after this general overview, the case of Colombia is examined. The study of a carbon tax in Colombia has already been explored through qualitative approaches [Wor23; CEI18; Mig+25b]. However, when it comes to quantitative results based on models, the literature remains quite limited. The only contributions in this area come from the National Planning Department of Colombia (DNP)<sup>1</sup>. Two open-access articles that focus specifically on carbon tax modeling for Colombia are available [Cal+16] [Rom+18].

Published in 2015, the first article uses two integrated assessment models (TIAM-ECN and GCAM) and two general equilibrium models (Phoenix and MEG4C), with an analysis centered on macroeconomics. The main results are that national carbon intensity is mainly influenced by the type of electricity generation. The implementation of different carbon taxes shows a significant reduction in emissions and encourages the use of cleaner energies, which is desired. The difference lies in which new energies to introduce, as each model has its own preferences. Through increased deployment of wind and hydro as highlighted by the TIAM-ECN model; the deployment of biomass with CCS as shown in the GCAM results; or the use of coal and gas with CCS in electricity generation as shown in the Phoenix results. However, a decrease in GDP of 2-3 percent is observed.

In the second article, the study focuses on the redistributive effects of a carbon tax on Colombian households, combining a computable general equilibrium model (MEG4C) and a microsimulation model (MSM). The first evaluates the macroeconomic effects, while the second analyzes the impact of price increases on households. Two types of MSM are used: an arithmetic model, assuming constant consumption and a behavioral model, which accounts for household adjustments. The results of the behavioral MSM show that all households experience a loss of well-being, but it is less penalizing for middle-income households compared to the wealthy. The poor are also strongly impacted, just after the wealthiest households. The authors recommend designing a carbon tax that incorporates redistribution mechanisms to mitigate its regressive effects on households, drawing on the double dividend theory, which suggests that positive economic effects can be achieved if the tax is well-modeled. They also suggest gradually phasing out fossil fuel subsidies and using the tax revenues to promote energy efficiency. Finally, they emphasize the importance of analyzing the effects on household welfare and considering future impacts on overall welfare when formulating public policies.

Additionally, the GEMMES model used in this master thesis, has already been used to study transition scenarios, some of which include a carbon tax [GDM24a]. Although the focus was not specifically on the carbon tax, the conclusions indicate a generally negative macroeconomic effect. While the double dividend aspect was somewhat uncertain, with mixed views on whether the impact was positive, negative, or neutral in the case of

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<sup>1</sup>The executive agency responsible for collecting, preparing and presenting information to assist the President in shaping economic and public policy [Pla]

Colombia, research converges on the same idea: unfortunately, due to the country's dependence on fossil fuels, which represent a significant portion of its exports, the effects will be negative.

### 1.3 Contribution of this work

In the previous section (section 1.2), it was found that studies on carbon taxation in Colombia are very limited. Implementing an effective carbon tax requires considering a wide range of influencing factors. The main objective of this master's thesis is to analyze different carbon tax structures, each with a distinct emphasis.

First, since the coupling is entirely new and has never been used before, a sensitivity analysis will be conducted to review certain data from the models. Next, the first implementation of the carbon tax will address the tax rate, which is considered the most important factor in the design, as mentioned in the *"Carbon Tax Guide: A Handbook for Policy Makers"* [Con+17]. One other particularly important aspect, which has not yet been thoroughly studied in Colombia, is the available recycling schemes. Two implementations will be investigated: the first will allocate the collected revenues to renewable energy and the second will follow the recommendations of Romero's article [Rom+18], which suggests redistributing money to households based on their income quantile.

To achieve this, the coupling between Energyscope and GEMMES, as developed in Pierre Jacques' thesis [Jac25], will be enhanced to address the current limitations in implementing an effective carbon tax. The current GEMMES model does not account for specific redistribution, so the relevant equations will be improved. Additionally, the models do not differentiate between households, either in EnergyScope or in GEMMES. Therefore, it will be necessary to disaggregate households only within GEMMES to redistribute funds proportionally to their income quantile. Both the coupling and EnergyScope will be adapted, but household differentiation will not be made within EnergyScope.

## 1.4 Structure

The present report is structured as follows:

### Chapter 2: Case Study and Tools

The **Case Study** section provides all necessary information about Colombia to understand its structure and functioning, particularly in relation to the challenges of carbon taxation. This includes an overview of Colombia's stance on the energy transition, followed by three subsections detailing its energy sector, economy and current carbon tax policy.

In **Tools**, the two modeling tools, Energyscope and GEMMES, and the coupling, will be introduced, along with an assessment of their scope and limitations.

### Chapter 3: Model Implementation and Evaluation

To ensure the robustness of the coupling, a sensitivity analysis will be conducted on the parameters deemed most uncertain and impactful on the global energetic and macroeconomic behavior.

### Chapter 4: Results

This chapter presents the different scenarios and their corresponding outcomes. It begins with an overview of the scenarios developed by Pierre Jacques [Jac25]. The **baseline** is then defined based on Pierre Jacques' **Energy Transition scenario**, with the adjustments applied to this reference case detailed. Finally, the three types of scenarios explored in this thesis, along with their respective results, are analyzed. They are as follows:

- A. The **Tax Rate Scenarios** exclusively modify the parameter *gwp cost*, which represents the cost of carbon emissions. Various tax rates will be explored, including extreme scenarios and different temporal profiles between the years 2025 and 2050. No redistribution mechanism is implemented, as in the scenarios implemented by Pierre Jacques.
- B. The **Investments in Renewable Energies Scenarios** simulates the effect of government subsidies for financing renewable energy. The study will focus on how these subsidies can be implemented, what levels they might reach.
- C. The **Households Redistribution Scenarios** will divide households in GEMMES based on to their total income percentile. Subsequently, a specific fund will be redistributed to the households with different weights according to the category to which each household belongs.

### Chapter 5: Conclusion

Finally, this chapter will provide reflections on the findings, a summary of the key results and perspectives for future research.



This chapter serves as a foundation for the following sections. A characterization of Colombia has been carried out to better understand its functioning, with the aim of highlighting its specificities that will need to be considered for the implementation of a carbon tax. First, the general information, energy and economic characteristics of Colombia are outlined, along with an overview of the current carbon tax in effect. Then, the software (EnergyScope and GEMMES) used and the coupling method for simulating the different scenarios are presented.

## 2.1 Case Study : Colombia

Colombia is one of the largest economies in Latin America, after Brazil and Mexico. With a GDP of \$320 billion in 2023, the country continues to demonstrate significant economic growth. It contributes only 0.4% of global emissions and despite not being one of the largest emitters, Colombia is actively committed to combating climate change [IEA24].

In 2022, President Gustavo Petro announced that Colombia is targeting 2050 for achieving carbon neutrality [Bla24]. Additionally, Colombia submitted its first version of its Nationally Determined Contributions (NDCs) in 2015, followed by a second, updated version in 2020 [Rep20]. In alignment with global objectives, the primary focus is on mitigating greenhouse gas (GHG) emissions, adapting to climate change risks and vulnerabilities and securing the means of implementation to finance and operationalize climate actions. This includes respecting the Sustainable Development Goals (SDGs), particularly Goal 13 (climate action), which is interconnected with other goals in the broader effort to combat climate change [Nat24]. This thesis concentrates on reducing GHG emissions but also explores the social dimensions, specifically the impact of a carbon tax that affects different types of households equally. This aspect is linked to SDG 1 (no poverty) and other relevant goals. While the main objective is to reduce Colombia's emissions as much as possible, the scope of action in this study is limited to the energy sector. Indeed, 59% of Colombia's emissions are produced by AFOLU (agriculture, forestry and other land use) and only 31% from energy [TG23].

The NDCs set the objective of reducing GHG emissions by 51% by 2030 compared to a Business-As-Usual (BAU) scenario. In order to achieve this, different strategies are developed :

- Promoting renewable energy and energy efficiency.
- Reducing deforestation rates, especially in the Amazon region.
- Supporting sustainable agricultural practices and transitioning to a circular economy.
- Enhancing public transport and clean mobility infrastructure.

### 2.1.1 Energy

A carbon tax will directly impact the energy mix by prioritizing the lowest cost energy sources that emit the least emissions. The EnergyScope tool [Ene25] requires existing data divided in three categories : resources, demand and technologies, which serve as reference for the five years intervals subsection 2.2.1. It is therefore essential to understand the energy situation in Colombia and the inputs that the model will receive. Pierre Jacques has already fully set up the case in section 1.3 by making assumptions and taking data that will be questioned later in section 3.1. The data analyzed in this section comes from the International Energy Agency (IEA) [IEA24] and are the ones on which the coupling setting was mainly based [Ene23].

To have a first overall view, the graph Figure 2.1 represent the primary energy consumption from 2000 to 2023. It can be seen that the two main sources of consumed energy are non-renewable: oil and natural gas, which together account for 64% of total consumption, with 41% and 23% respectively in 2023. These two resources will need to be excluded from the future energy mix as they are the two most CO<sub>2</sub>-emitting resources, with 60% of 2022 energy emissions coming from oil and 25% by natural gas.

Overall, resources have generally increased over time, but in recent years, many seem to have plateaued or slightly declined, with the exception of oil, which continues to grow. It is expected that the total energy supply will increase, but the energy mix will be vastly different from the current one. Renewable energy sources such as hydro, wind and solar will play a more significant role in replacing oil, natural gas and coal. The energy sector will shift to electrification, particularly in the transportation industry.

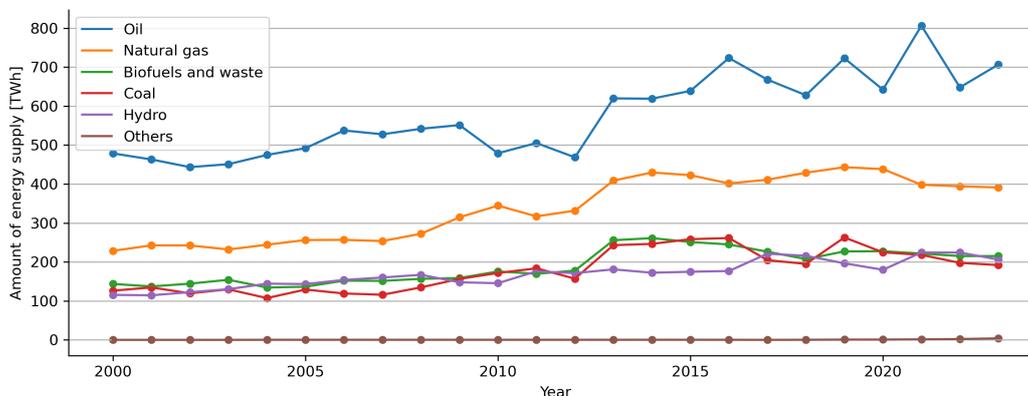


Figure 2.1: Primary energy consumption by sources <sup>1</sup> from [Int23b]

#### Renewable energies : Hydro

Regarding renewable energy, hydropower production is dominant in Colombia. This results from a historical background and a favorable geographical location, similar to much of South America. The growth of hydropower capacity is limited, with expansion slowing due to various challenges. Notably, the disagreement with indigenous populations regarding the creation of new sites of exploitation. The core of the problem has several facets: ecological, cultural and socio-political concerns [QC24]. 64% of total electricity generation is produced by hydropower. On the contrary, other renewable resources such as geothermal, wind and solar are minimal in this mix as shown on Figure 2.1. Hydropower is a powerhouse of renewables based on water, an abundant resource to produce non-emitting

<sup>1</sup>Primary energy is the energy available as resources before it has been transformed.

energy<sup>1</sup>. Unfortunately, it is highly dependent on precipitation and climate, which does not benefit the country with climate change. In Colombia, intense droughts caused by the *El Niño* phenomenon<sup>2</sup> have led to energy crises characterized by power outages and water rationing [Ame25]. The country's limited hydropower storage capacity further exacerbates the situation, hindering efforts to mitigate the impact of these events [Int23b].

#### *Renewable energies : Wind and Solar*

Historically, Colombia has not significantly invested in or actively promoted the development of renewable energy sources other than hydropower. This was largely due to concerns over the intermittency of wind and solar power, as well as the high costs, which reinforced the country's continued reliance on hydropower. For several years, the government has been working to expand its renewable energy mix to include non-conventional energy sources<sup>3</sup> [Int23b]. In 2017, the first solar power plant, *Celsia Solar Yumbo*, was inaugurated with a capacity of 9.8 MW and since then, solar infrastructure has multiplied, reaching 38 installations today for a total capacity near 2 GW [Cel22; Ini25]. Wind energy, on the other hand, was relaunched in 2021 with the *Guajira I* wind farm, after a 17-year gap since the inauguration of the first wind farm, *Jepírachi* [PRT09]. In the future, investment in these other energy sources will be inevitable in order to meet the set targets and also to mitigate the undesirable effects of hydropower, as hydropower alone cannot continue to expand and meet the country's growing energy demand [GP21]. The government has conducted auctions leading to the commissioning of over 1.1 GW of capacity for both solar PV and onshore wind by 2027. Also, the *Long-Term Auction Programme* awarded more than 2 GW of wind and solar capacity combined, with additional auctions planned for 2023 and beyond. Moreover, the government released its Offshore Wind Energy Roadmap in February 2022 [ERM22].

In some countries, such as Belgium, renewable energy is highly limited by geographical constraints, space limitations and grid issues, which is not the case for Colombia. Its territory is highly suitable for solar, wind and geothermal energy, with certain regions offering particularly favorable conditions [AGO23]. The criteria used to classify the most attractive zones are solar irradiance for solar energy and average wind speed for wind energy. As shown in Figure 2.2 (located on the next page), the highest wind speeds are along the Caribbean coast, reaching speeds of 10 m/s, reflecting the offshore wind potential. Other high-potential wind areas are located in the Andes, but these are, in practice, less feasible. Solar potential is concentrated in the North and also towards the West, particularly in the department of *La Guajira*, where the solar irradiation level is 60% higher than the global average, with an average of around 194 W/m<sup>2</sup>. This is the same department that presents the most wind potential, already hosting the new wind farm *Jepírachi*.

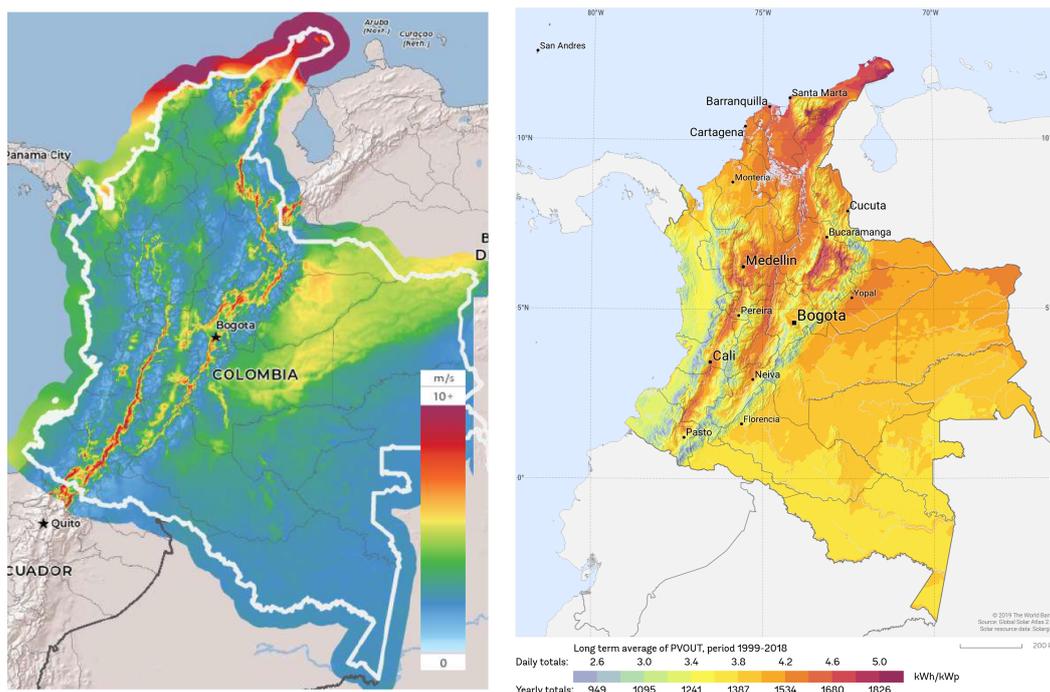
#### *Renewable energies : Geothermal*

Another emerging, unconventional renewable energy is geothermal and Colombia's location in an active tectonic zone (the Pacific Ring of Fire) provides easier access to the heat required for its exploitation. Three areas are particularly suited for this: *Aldas*, *Risaralda* and *Tolima*, thanks to volcanoes such as *San Diego*, *Nevado del Ruíz* and *Cerro Bravo*. Currently, geothermal energy is not widely used, except for one power plant that opened

<sup>1</sup>Or only to a limited extent when accounting for the installation and operational costs of the infrastructure.

<sup>2</sup>*El Niño* is a climate phenomenon where unusually warm ocean temperatures in the central and eastern Pacific disrupt global weather patterns, often causing extreme events like droughts, floods and weaker monsoons.

<sup>3</sup>Non-conventional energy refers to alternative, renewable energy sources such as solar, wind, geothermal and biomass, which are considered more environmentally sustainable compared to traditional fossil fuels.



**Figure 2.2: Wind and solar potentials : on the left average wind speeds [Glo25b], on the right solar irradiance [Glo25a]**

which is located in Campo Maracas, in *Casanare*, with a capacity of 100 kW. Evaluating the geothermal potential is a complex task that the government has assigned to the *Colombian Geological Survey*. They obtained both an optimistic and a pessimistic scenario using a volumetric method. The key figure calculated is that the geothermal potential for the optimistic scenario is 1170.20 MW [Sma+18].

### *Biomass*

Biomass is primarily used in three main ways: as wood and charcoal for traditional cooking and water heating, as cane bagasse and palm oil residues for fuel in boilers and co-generation plants to produce heat and power and, after conversion, as bioethanol and biodiesel for road transport biofuels. Other forms of using biomass for energy purposes continue to be the subject of ongoing research. The most promising form of biomass in the future is biofuels. They help reduce dependence on fossil energy while stimulating innovation. Colombia decided early, in 2001, to promote biofuels by implementing policies (Laws 697/2001, 693/2001, 939/2004, 048/2005) [Gau15]. This allowed Colombia to develop its local biofuels production by introducing mandatory blends of bioethanol and biodiesel [Sal+14]. Their goal is to continue increasing the mandatory percentage of biofuels in fuel to gradually replace traditional transportation fuels. Currently, biofuel blends with a maximum share of 8-10% are in use [VC14].

### *Fossil Fuels Dependence*

An important aspect, both from an energy and economic perspective, is the dependence on fossil fuel exports. In 2023, net energy exports accounted for 56.8% of total energy production, primarily from oil and coal [Int23b]. This represents 8% of Colombia's GDP, \$24.7bn in revenue in 2023 [Dan24]. Energy-exporting countries are sensitive to external events, such as COVID-19, which can cause a drop in global energy prices, leading to major

economic shocks. Colombia is the second-largest exporter in South America, after Brazil. This position poses a challenge in the context of the ongoing transition, as new sources of revenue must be found to avoid negative economic repercussions. A study conducted with GEMMES, the same tool used in this thesis, has been conducted to assess the impact of reducing fossil fuel exports [GDM24b]. This shows that a transition to a low-carbon economy with a focus on reducing fossil fuel exports leads to a worsened current account balance, increased external debt and lower foreign reserves, raising the country's vulnerability [GDM24a]. Inflation and exchange rate depreciation contribute to economic instability and higher poverty. The labor market suffers with higher unemployment and lower income, while public finances face growing deficits. The private sector experiences higher debt ratios and increased financial fragility. Volatility is higher in a delayed transition scenario, though long-term recovery is possible through currency depreciation. Overall, the transition exacerbates macroeconomic instability.

To offset the loss caused by the decline in fossil fuel exports and keep the current account deficit below 2.5–3% of GDP, Colombia will need to reduce its imports while increasing its exports of other products [Wor23]. However, a major challenge lies in the country's low export diversification, as it remains heavily reliant on basic commodities such as agriculture (coffee, fruits, etc.) and cut flowers (world second largest exporter behind Netherlands) [Dan24; OS24].

*“Without a doubt, in order to substitute the revenues from fossil fuels, the economy must be diversified,”* says Andrés Camacho, minister of mines and energy [Fin24].

The **key question**, therefore, is: What products could Colombia export to replace fossil fuels?

The government has already addressed the issue and established its policies. Investments are planned in renewable energy, critical minerals and hydrogen production [IEA24], with the goal of transitioning to a diversified clean energy economy. It is necessary to invest in R&D of deployment of clean energy to achieve this goal. The Petro government aims to ensure that Ecopetrol, Colombia's leading oil and gas company, which accounts for about 60% of the country's hydrocarbon production [Eco25], plays a major role in this transition. Regarding hydrogen, a roadmap was established in September 2021, as this technology was identified as promising and could become a new player in exports [MIN21]. Its impact on the country's transition would be the decarbonization of the industrial and transport sectors, as well as helping to stabilize the electricity grid. The roadmap outlines the potential, objectives and actions to be implemented. Among them, one key goal is to produce green hydrogen at a price of USD 1.7/kg, aiming to be competitive with countries like Chile and Australia<sup>1</sup>.

### 2.1.2 Economy

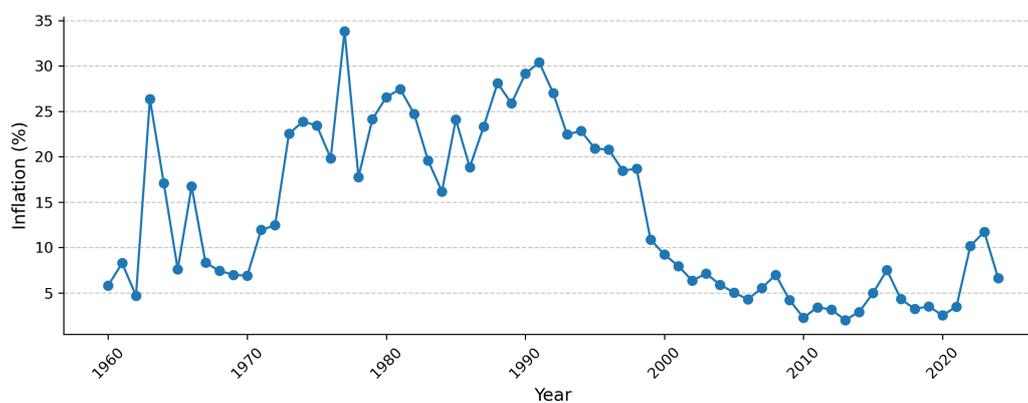
Colombia stands as the third-largest economy in South America. However, its current economic growth remains modest, with a projected rate of 1.8% in 2024 following the post-COVID rebound. Forecasts suggest a potential recovery to 2.8% by 2025, but challenges persist [OEC24].

One of the most pressing issues in recent years has been inflation. In 2023, it peaked at 13.3% in March before being brought under relative control, falling to 6.1% in 2024 [Wor24].

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<sup>1</sup>Discussing hydrogen production in these countries.

OECD23a]. In response, the Central Bank of Colombia adopted a restrictive monetary policy, significantly raising interest rates. While this helped to curb inflation, it also led to a decline in domestic consumption and investment. As a result, economic growth slowed dramatically to just 0.6% in 2023, down from 7.5% in 2022. This sluggish growth is particularly concerning in the context of Colombia's necessary transition toward renewable energy, a shift that requires substantial investment.



**Figure 2.3: Evolution of inflation as measured by the consumer price index in Colombia [Wor24]**

Colombia remains a major global producer of coffee, oil and coal. Nevertheless, its economy is still heavily reliant on the export of raw material, especially fossil fuels (see subsection 2.1.1) which makes it vulnerable to international price fluctuations. This dependence on commodity exports continues to expose Colombia to external shocks and limits the diversification of its economy. In 2023, foreign trade declined significantly: exports fell by 12.5%, while imports dropped by 33.6%, which helped reduce the country's trade deficit. The United States and China were Colombia's main trading partners, representing a combined 42% of its foreign trade (26.8% and 14.8%, respectively) [Dir24]. However, recent tariff measures proposed by Donald Trump pose a potential threat to this commercial relationship with the U.S.

Social inequality is another significant challenge. Wealth distribution in Colombia is highly uneven, with disparities between urban and rural areas. These regional inequalities are reflected in wide gaps in per capita income. Cities like Bogotá and Medellín continue to grow rapidly, attracting investment and offering better employment opportunities. In contrast, rural regions struggle with persistent poverty and limited access to quality education, healthcare and basic public services. This imbalance hinders the country's overall development. According to OECD data, Colombia remains one of the most unequal countries in the world, with a high poverty rate fueled by large informal economy, leading to a Gini index of 54.8.

Despite government efforts, the unemployment rate remained high in 2023, hovering around 10%. Furthermore, approximately 56% of the active labor force is employed in the informal sector. This limits improvements in working conditions and restricts access to social protections tied to formal employment. In addition, the informal sector contributes minimally to national tax revenues, undermining the government's fiscal capacity.

Security issues also continue to impact economic stability. Although notable progress has been made since the signing of the 2016 peace agreement<sup>1</sup>, violence and drug trafficking

still affect certain regions, deterring investment and development in those areas.

On the policy front, President Petro's ambitious reform agenda presents both opportunities and risks. These reforms including fiscal, healthcare, pension and labor system changes aim to build a more inclusive and equitable society. However, they also raise concerns about fiscal sustainability. In an effort to comply with the fiscal rule, the Colombian government announced a \$14.6 billion budget cut for 2024. While significant, this measure is considered insufficient by the Independent Fiscal Rule Committee (CARF), which estimates that at least \$51 billion in cuts are necessary to meet debt obligations and offset declining tax revenues.

In "*Country Climate and Development Report (Colombia)*" by the World Bank Group [Wor23], various financial needs for transition were identified, estimating that an average of 2.8 percent of GDP in additional resources will need to be mobilized annually between 2030 and 2050, compared to a (costly) scenario without climate action. Four key challenges were highlighted: the need for increased investment, a decline in exports, reduced government revenues due to decarbonization and the necessity of increased public spending to protect the most vulnerable. These are all issues that had already been discussed previously.

### 2.1.3 Carbon tax

Since 2016, a carbon tax (Law 1819) has been implemented in Colombia [Rep16; Rep17]. The tax involves imposing a fixed rate on all sales within Colombian territory for the following fuels: natural gas, liquefied petroleum gas, gasoline, kerosene and jet fuel, ACPM (diesel fuel) and fuel oil, as detailed in Table 2.1. This tax covers 24% of the emissions produced by Colombia [Ban24].

Fossil fuel	Unit	Tariff/unit COP	Tariff/unit USD
Natural gas	Cubic meter	27	0.0087
Liquefied petroleum gas	Gallon	95	0.028
Gasoline	Gallon	135	0.040
Kerosene and jet fuel	Gallon	148	0.044
ACPM	Gallon	152	0.046
Fuel oil	Gallon	177	0.053

**Table 2.1: Tariffs per unit of fossil fuels [Mog20]**

The implementation of the tax is straightforward: the consumer pays the tax directly as part of the product's price. The tax is collected by the producer or importer, who is responsible for paying it to the DIAN (Tax Government Agency).

The revenue generated by this tax amounted to \$159 million USD in 2017, \$98 million in 2018 and \$128 million in 2019. The low cost per ton of CO<sub>2</sub> equivalent and the focus only on certain fossil fuels explain the low revenue generated. Colombia's tax revenue was 70 billion USD in 2018, with the carbon tax representing only 0.23% of it. As analyzed by Castelbalanco [Cas22] and according to data from the Inter-American Development Bank (IDB), Colombia needs 3 billion USD per year to finance its climate commitments and energy transition. This highlights the need to increase carbon tax revenues, as the revenues generated by the carbon tax represent 5% of the annual needs in 2017, 3% of the needs in 2018 and 4% of the needs in 2019.

<sup>1</sup>The 2016 Peace Agreement in Colombia was an accord between the Colombian government and the Revolutionary Armed Forces of Colombia (FARC), aimed at ending over 50 years of armed conflict.

Colombia has chosen to apply earmarking, meaning the revenues are allocated to specific purposes. By law, 80% of these funds are to go to finance climate action aimed at furthering the country's low-carbon development and measures provided for in its NDC. These funds are administered by the Sustainability and Climate Resilience Fund (FONSUREC). The remaining 20% of these revenues is channelled into the National Illicit Crop Substitution Programme (Fondo Colombia en Paz) [Mig+25a]. However, this approach has faced criticism due to a lack of transparency regarding where the money is actually being invested.

Although it is a good start, several highly greenhouse gas-emitting resources are not included and may therefore be used more intensively than before. This is the case with coal, prompting the government to consider improving the carbon tax to address its shortcomings. For instance, coal became taxable in certain circumstances in 2022 under Act No. 2277 [Fun22] and the tax rate increased with inflation adjustments, reaching approximately \$6.5 per ton in 2024 [Mig+25a]. These updates are a response to critiques that the initial scope of the tax was too narrow. It shows that the tax can evolve to address its shortcomings.

Several lessons have emerged from Colombia's experience with the carbon tax, along with potential improvements to enhance its effectiveness. To improve the tax, several measures could be considered: increasing tax rates to align with international benchmarks, broadening its scope to include more emission sources, expanding coverage to additional economic sectors, removing exemptions that undermine its effectiveness and implementing policies to support economic stability and financing during the transition.

## 2.2 Tools

Following the contextual overview of Colombia, the analysis tools used in this research are introduced, starting with EnergyScope, then GEMMES and concluding with the coupling.

### 2.2.1 EnergyScope Pathway

EnergyScope is an open-source energy planning model based on mathematical linear optimization that identifies the most optimal design and operations of energy systems composed of sectors (electricity, heat, mobility and non-energy demand) given fixed end-use demands, for a target year [Lim+19]. The energy system is modeled over a reference year divided into representative periods, using typical days to reduce computational time. In a first step, a MILP-based approach is used to determine the typical days that minimize the clustering error. Then, the linear optimization of the energy system takes place. EnergyScope is coded in python but uses AMPL to optimize the system.

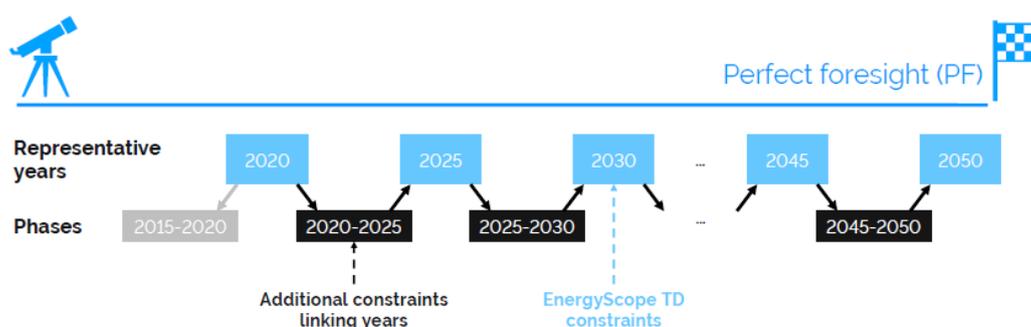
Its operation is based on a set of input data, including:

- Sectoral energy demand : electricity, heat, transport, industry
- Technologies : available production, storage and conversion technologies
- Resources : oil, gas, biomass, uranium, ...

All system components are expressed as constraints within the optimization framework. The model also incorporates environmental and policy constraints, such as CO<sub>2</sub> emission reduction targets or limitations on certain energy infrastructures. The objective function can either minimize costs or GWP limit emissions. In this case, the objective is to minimize costs while assigning a carbon price, which indirectly forces the model to limit its GWP by

making emissions financially restrictive. Through its optimization process, EnergyScope selects the most suitable combinations of technologies and resources by considering investment and operational costs, system efficiency and regulatory requirements. It models energy flows from production to consumption, including different transformation and storage stages. The results obtained help analyze the optimal energy mix, installed capacities of each technology, associated CO<sub>2</sub> equivalent emissions and the overall system cost, providing a solid foundation for evaluating energy transition scenarios and developing sustainable energy policies.

EnergyScope has several variants and applications. In this context, the EnergyScope Pathway version is used for the case study of Colombia developed by Pierre Jacques [Lim+24]. While the standard EnergyScope model operates on a single-year basis, Pathways optimizes transition trajectories over the long term by dividing time into five-year periods, each representing a step. Each step has its own initial parameters while maintaining a continuous solution, ensuring system coherence.



**Figure 2.4: Schematic explaining the functioning of EnergyScope Pathways with the representative years and phases from Xavier Rixhon's thesis [Rix25]**

The main advantage is that linear optimization significantly reduces computation time, allowing for fast simulations. On the other hand, it limits certain aspects of case implementation. EnergyScope has only one cell dimension, which restricts the representation of energy exchanges between countries. However, for a transition in Colombia, it would be relevant to represent energy flows to and from abroad, given its status as a major fossil fuel exporter and its ambitions in hydrogen exports.

### 2.2.2 GEMMES

GEMMES [Dévnd] is a macroeconomic tool designed to simulate various policy pathways and their impacts. It is a Stock-Flow Consistent (SFC) model in continuous time that ensures the internal consistency of all economic flows<sup>1</sup> and stocks<sup>2</sup>, such as income, debt and investment across five sectors including households, firms, government, banks and the rest of the world. The model is particularly well suited for small open developing economies, which are often exposed to both financial volatility and environmental shocks. It incorporates features of financialization (e.g., interest rates, external debt, capital flows), allowing for dynamic simulations of how policy interventions, such as carbon taxes, green investment or debt restructuring can influence long-term growth, inequality, sustainability and macroeconomic stability. Furthermore, GEMMES explicitly models a detailed representation of open financial accounts, allowing for gross cross-border capital flows (not just net),

<sup>1</sup>A flow is a quantity measured over a period of time.

<sup>2</sup>A stock is a quantity measured at a specific point in time.

making it especially realistic for countries facing volatile capital movements. In contrast to neoclassical models, which assume markets always clear with supply equaling demand, GEMMES allows prices and quantities to adjust dynamically over time (continuous disequilibrium), offering a more realistic depiction of real-world economic behavior.

Even without coupling, the GEMMES model can incorporate the ecological dimension through environmental trajectories, with for example, the increased scarcity of extractive natural resources, in order to assess their monetary and financial risks. Other couplings with biophysical models have also been developed within the GEMMES framework, such as crop production models under different climate scenarios [Yil+23] and energy models like LEAP, applied to countries such as Morocco and Vietnam (ongoing work).

The model has been adapted and calibrated to country-specific versions, including for Vietnam, Tunisia, Colombia and Morocco, to better reflect national contexts and economic structures.

However, the model has several limitations. First, its complexity requires detailed, high-quality data, which may not be readily available in many developing countries. Second, while SFC models are strong in maintaining accounting consistency, they are highly sensitive to initial assumptions, particularly those related to behavioral parameters, technological progress and the extent of climate impacts. Third, due to its deterministic structure, GEMMES may not fully reflect the uncertainties and non-linearities of ecological and socio-political systems. Finally, the model demands significant technical expertise to calibrate, interpret and adapt to specific contexts, which can limit its practical accessibility for governments and institutions with limited modeling capacity.

### 2.2.3 Coupling

The coupling between GEMMES and EnergyScope is bi-directional and follows a soft-linking approach [Fat+23; Pav+22]. This soft coupling is implemented through the exchange of .CSV files containing the relevant variables for the models. This method was chosen primarily because the two models are developed in different programming languages and because GEMMES is not open-source, unlike EnergyScope. A shared control script coordinates the execution of both tools, establishing an iterative feedback loop that continues until convergence is reached. The convergence is based on End-Of-Uses Demand (EUD) variables and typically converge within three iterations for baseline scenarios.

The core function of the coupling is to enable EnergyScope to feed GEMMES with energy costs and the distribution of energy imports and exports. In return, GEMMES provides EnergyScope with inputs as EUD, the discount rate and the exchange rate (Figure 2.5). Several adjustments were required to ensure compatibility, as explained in Pierre Jacques thesis [Jac25]. One of the key adaptations involved post-processing energy costs from EnergyScope to disaggregate them into GEMMES's four macroeconomic categories (households, firms, government and the rest of the world). Another technical challenge arises from the difference in time resolution: EnergyScope operates in five-year intervals, while GEMMES runs on an annual basis. This discrepancy requires data interpolation and temporal alignment to maintain consistency.

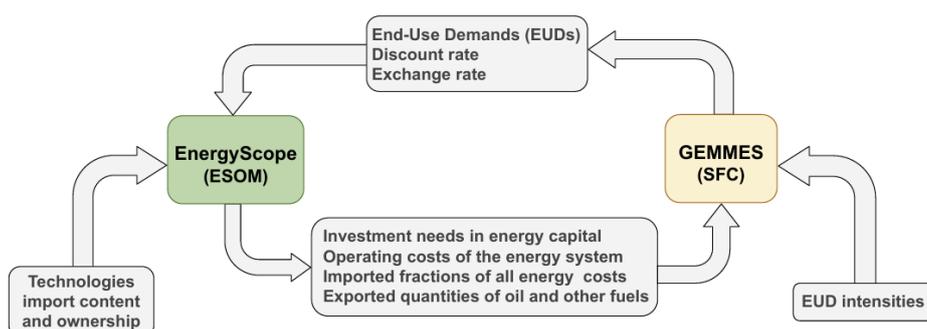


Figure 2.5: Coupling of GEMMES with EnergyScope

The objective of the coupling is to analyze the dynamic interactions between the economic and energy systems and to understand how these systems evolve under different policy and transition scenarios. Assessing the performance of the coupling is essential to identify its current limitations and determine areas for improvement before applying it to more complex economic and energy pathways.

Pierre Jacques established an evaluation of his coupling and it indicated that the energy system exerts a greater influence on GEMMES than the macroeconomic system does on EnergyScope, suggesting that energy trajectories remain relatively stable under current conditions. However, two key areas require enhancement. First, the impact of energy transition prices on energy demand is currently underrepresented. In reality, rising energy prices tend to reduce consumption, a behavioral response that can be modeled using demand elasticity functions [LLL17]. This approach is already adopted in several studies and worth integrating into the coupled framework. Second, the propagation of energy costs through general price levels is not fully captured, limiting the ability to assess inflationary effects and feedbacks on real income and investment. In addition, the current structure of GEMMES treats energy costs as distributed across all sectors, rather than modeling energy producing firms as a distinct category. Introducing a dedicated sector for energy firms would allow for a more realistic representation of pricing mechanisms, investment decisions and profit dynamics within the energy sector.

Impacts	Strength
EnergyScope → GEMMES	++
GEMMES → EnergyScope	+
Entire feedback loop	+
Retroactive impact of the energy transition on energy demand	-
Propagation of energy costs through prices	-

Table 2.2: Assessment of the strength of the links in the coupling. For each link, a sign indicates its strength and impacts on the dynamics of the coupled model. "++" = strong. "+" = moderate. "-" = low. "--" = very low from Pierre Jacques' thesis [Jac25].



Now that the global context relevant to our analysis has been established and the model has been presented, this chapter will focus on evaluating the assumptions made about the input parameters of the model.

## 3.1 Sensitivity analysis of actual coupling

The current coupling relies on hundreds of parameters on both the EnergyScope and GEMMES sides. Since GEMMES has already been extensively used and thoroughly investigated, reliance will be placed on the calibration initially performed by Godin and al. [GDM24b]. The evaluation of initial parameters focuses on the energy model, particularly the inputs of EnergyScope. The aim is to identify which parameters are most likely to influence the final results and determine whether adjustments are necessary to better align the model with reality. Specifically, this involves assessing whether these parameters could completely reverse global behaviors or merely introduce slight quantitative variations. This step helps confirm the accuracy and credibility of the results presented later. In subsection 2.1.1, the data used to reproduce the energy history of 2021 and set up the model is considered established and accurate. Instead, the emphasis is placed on future data applied in each phase, represented by a five-year span. Maintaining a clear perspective on the objective of the analysis remains crucial. The goal is to implement a carbon tax leading to carbon neutrality by 2050 while accounting for energy, economic and social factors. There will be a shift in the energy mix, with a gradual phase-out of hydrocarbons and other high-emission energy sources, reaching zero, while clean energy sources increase. The focus is therefore on the pace at which renewable energy can be deployed, as this is the most critical factor. Due to necessary investments, discussions with communities and other logistical challenges, a significant amount of time is needed to reach the capacity required for renewable energy, as described in subsection 2.1.1. These limitations must be acknowledged and incorporated into the analysis. Renewable energy sources considered in this study include hydropower, solar, wind and geothermal energy. However, since geothermal energy has a relatively minor impact, it is considered acceptable as is. Additionally, it should be noted that the transport settings are based on data from Belgium, which is not accurate. No link was established, the association was made purely for the sake of convenience. However, finding comprehensive data to reconstruct the setup is a significant undertaking and beyond the scope of this master's thesis, though it would be a valuable task for future research.

The case used to perform our sensitivity study is the transition case developed by Pierre Jacques [Jac25], which corresponds to the case where a linear carbon tax, "*Energy Transition*", incorporates a carbon tax that increases linearly from 0 USD per ton of CO<sub>2</sub> in 2021 to 70 USD per ton of CO<sub>2</sub> in 2051. This is the baseline transition case then exploited for different scenarios (see section 4.1).

Below is Table 3.1 summarizing the initial values and new values derived from calculations and literature, which will allow to perform the sensitivity analysis. The maximum installation capacity is the parameter that will be investigated, as it best represents the constraint that has an impact on our system and particularly, the deployment of renewables energy.

The two following reports will provide quantitative data for a comparison with the baseline.

- The CREE report "*Estudio para la Hoja de Ruta de la Transición Energética Colombia 2050*," [Gon+23] a strategic study aimed at outlining the path Colombia will follow to transition toward a more sustainable and low-carbon energy system by 2050. Four scenarios were established and simulated using the TIMES-COL model <sup>1</sup>.
- The report "*Quantifying the 2050 Scenarios for Colombia's Electricity Sector Transition*" employs system dynamics to model the evolution of Colombia's electricity system [Par+25]. Only the Chess scenario is considered, which is defined by a favorable environment for energy transition and an economy with high fossil fuel prices. This is the most interesting scenario, as highlighted in subsection 2.1.1 and subsection 2.1.2.

Parameter	Author	Scenarios	Max. Capacity [GW]
Hydro	Baseline		24.8
	Report "Quantifying Colombia's 2050 Electricity" Report CREE	A	17
		B	19
		C	32
		D	35
Solar	Baseline		/ <sup>2</sup>
	Report "Quantifying Colombia's 2050 Electricity" Report CREE	A	12
		B	25
Wind	Baseline		56.1
	Report "Quantifying Colombia's 2050 Electricity" Report CREE Calculations (Slow deployment <sup>3</sup> offshore)	A	14
		B	25
		C	56.1

**Table 3.1: Comparison of maximal installation capacity [GW] for different renewables energy sources in 2050 (EnergyScope input values)**

## 3.2 Results

### 3.2.1 General conclusions

All the presented cases have a minimal impact on the GEMMES variables and the macroeconomic system. GEMMES mainly has repercussions through EnergyScope costs and as shown, most cases have relatively similar costs, except in 2050. The same trend is observed

<sup>1</sup>Linear programming model to optimize energy systems as EnergyScope.

<sup>2</sup>The restriction does not come from the maximum installed capacity, but from a constraint on the maximum area available for the installation of solar panels.

<sup>3</sup>The maximum capacity in 2050 remains the same as the baseline scenario, but the increase is more gradual over the years.

in GEMMES, with very small differences in the early years that increase slightly over time from 2035 but remain negligible.

The EUD data is initially provided every five years as input, but it changes due to the coupling mechanism that ensures convergence between the EUD values of the two programs, which must align. The variations compared to the baseline are as follows: for hydro, -0.06%, -0.03%, -0.02%, -0.01% for cases A, B, C and D respectively; for solar, -0.09% and -0.05% for cases A and B respectively; and for wind, -0.2%, -0.09%, -0.21% for cases A, B and C respectively. These variations are considered negligible. Since the demand is considered identical across the cases, the energy system will need to adjust to produce enough energy to meet this demand.

Due to the carbon tax, the reduction of emissive resources such as coal, heavy fuel oil (LFO), diesel, electricity and gas occurs similarly in all cases, except in 2050, where some scenarios continue to use LFO. The major difference lies in the renewable energy mix.

One key observation is that hydropower is always used at its maximum capacity in all simulated scenarios, which can be explained by two factors: costs and emissions. Although the emissions caused by the construction of hydropower plants are higher than those of wind power, with wind emissions being 29.42% lower than those of hydropower, they are still lower than those of photovoltaic, which have 19.64% higher emissions than hydropower for the same amount of energy produced. The investment cost in wind is 63.2% lower than in hydropower, while the investment cost in photovoltaic is 22.95% higher than in hydropower. From a construction and investment perspective, wind power appears to be the most optimal choice. However, when considering maintenance costs, which are higher for wind, despite their variations over time, hydropower becomes more advantageous. On average, maintenance costs for hydropower are half those of wind. In the long run, hydropower proves to be more profitable, especially considering its longer lifespan of 40 years compared to 30 years for wind and 25 years for solar PV. Ultimately, wind and solar power will complement the energy mix, balancing each other based on the maximum capacity constraint of the renewable energy sources (hydro, solar and wind). The total renewable energy production is not constant, as illustrated in Figure 3.1, Figure 3.2, Figure 3.3. The gap needed to maintain a stable energy output across scenarios is primarily filled by LFO, with small variations in the use of import electricity and wood.

The LFO is found in various EUD, primarily in the oil to HVC process, but it can also be used in heating applications (*Dec\_boiler\_oil*, *Dec\_cogen\_oil*, *Dhn\_boiler\_oil*, *Ind\_boiler\_oil*). Depending on the specific case, LFO will be used to achieve the desired HVC, which is given as input to the model every five years. In cases where LFO is absent (i.e., LFO is at 0), HVC is produced from methanol, which is itself produced through the biomethanation process, along with a much smaller proportion of methane to methanol and an insignificant quantity of biomass to methanol. Initially, HVC is produced from oil, specifically LFO, from 2020 until 2040 and it is only in 2040 that production shifts to methanol and biomass.

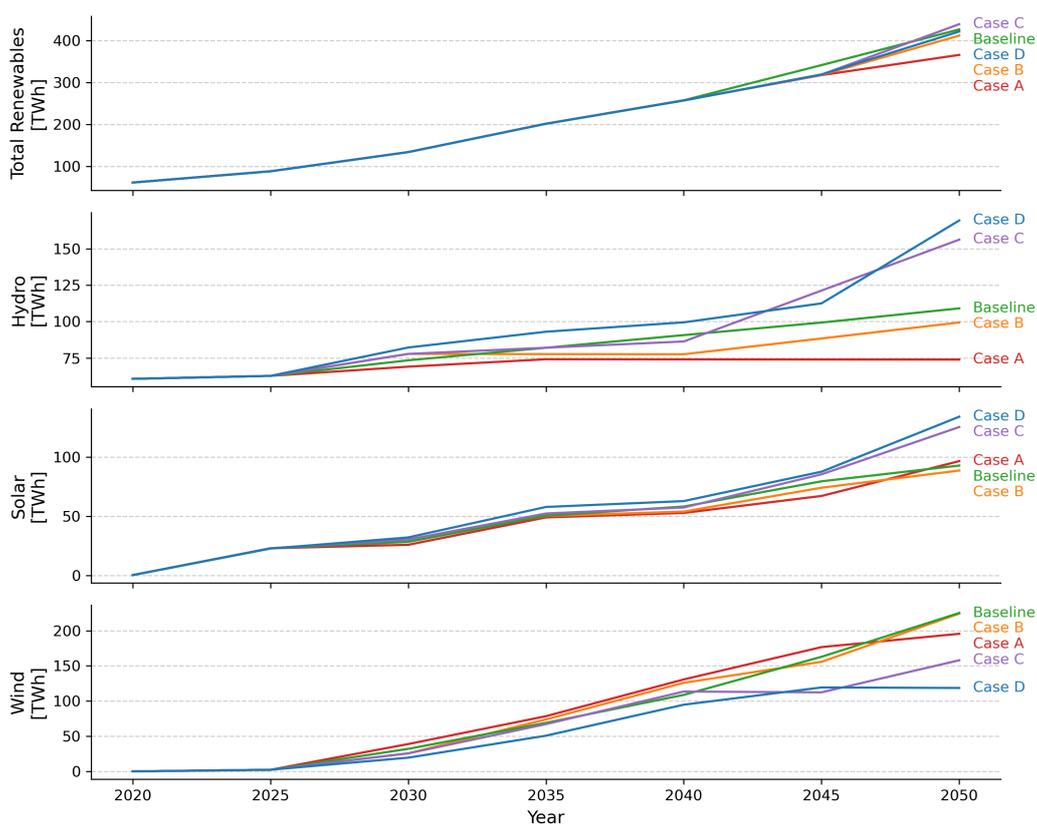
A final scenario was designed to test the system's limits. The most restrictive installation capacities for hydropower, solar and wind (all data from report "Quantifying Colombia's 2050 Electricity" [Par+25]) were applied to evaluate whether, under the worst-case scenario, it would still be possible to phase out non-renewable resources and successfully achieve the energy transition. By severely restricting all three renewable energy sources, the transition is effectively hindered, despite the incentive provided by the carbon tax. With no viable alternatives beyond these three main renewable sources, the system continues to rely on emitting resources. In 2050, emissions reach 59.95 MtCO<sub>2</sub>-eq, starting from 95.59 MtCO<sub>2</sub>-eq in 2020. Given the goal of achieving carbon neutrality by 2050, ex-

cessive constraints on renewable energy deployment would result in completely missing the required trajectory. Moreover, the total cost in 2045 and 2050 are the highest among all simulations (compared to Table 3.2, Table 3.4, Table 3.5), reaching 488.78 GUSD, whereas in previous years, it was among the least expensive trajectories.

### 3.2.2 Hydro

It is assumed that 8.4 GW were installed before 2020 and from 2025, an additional 2.4 GW capacity is added through the opening of the HitroLuantago plant (subsection 2.1.1). The values for the following years are questioned and adjusted according to Table 3.1. Hydro dams and rivers are differentiated, with approximations made based on the smallest maximum capacity of a river compared to that of dams. The same approximations as Pierre Jacques have been used, considering the limited expansion capacity of rivers and focusing on the enlargement of dam capacities. One of the CREE cases is not analyzed because its value is very close to that of the baseline, as shown in Table 3.1 .

As stated in the general conclusions, hydroelectricity always reaches its maximum installation capacity. Until 2040, the cumulative renewable energy consumed is identical across all scenarios, with primarily variations in wind energy complementing hydroelectric power. However, by 2050, the cumulative deployment of renewable energy sources varies significantly across scenarios.



**Figure 3.1: Evolution of renewable energy consumption: total, hydroelectric, solar and wind with varying cases of maximum hydroelectric capacity**

Case A notably diverges from the others, constrained by its limited hydroelectric capacity. Scenarios with reduced hydro potential (Cases A and B) tend to rely more heavily on wind

energy, whereas those with greater hydro capacity (Cases C and D) exhibit a comparatively higher contribution from solar technologies.

The total costs, which include investment costs, maintenance costs and the carbon tax, exhibit very similar behavior over time. Before 2050, Case D consistently has higher costs on average, while Case C and the other cases are almost identical to the baseline. Emissions are the same until 2040, after which differences start to emerge, although they remain small. Higher costs for greater hydro installation capacity arise from the investment required to install these new hydraulic infrastructures. Emissions decrease with the increase in hydro installation capacity, except for Case D. This is directly related to LFO consumption, which produces 0.3115 ktCO<sub>2</sub>-eq./GWh. LFO consumption decreases from Case A to Case C (almost zero), whereas for Case D, it remains significant.

	GWP [MtCO <sub>2</sub> -eq]	Cost [GUSD]	LFO [TWh]
Case A	24.70	454.19	56.43
Case B	13.57	469.87	20.72
Baseline	10.47	475.68	9.74
Case C	9.26	478.13	0.47
Case D	14.03	481.68	14.58

**Table 3.2: Comparison of total emissions, total costs and consumption of LFO with varying cases of maximum wind capacity**

When comparing to real data, the largest hydro projects available online are listed below Table 3.3. As seen, if Hidroituango, which has just started operations [Ren22], is excluded, the cumulative installed capacity is expected to exceed 2.5 GW by 2030. The baseline case shows an initial added hydro capacity of 2.46 GW between 2025 and 2030, which closely aligns with the available data, with a projected upper limit of 21.22 GW by 2050. However, it is important to consider that the commissioning of projects does not always equate to their actual completion. Significant construction timelines must be taken into account and several projects may have been commissioned but lack accessible data. While this estimate is somewhat high, it still appears realistic.

Installation	Installed Capacity [MW]	Beginning Year
Hidroituango	2400	2025 (opening)
Patia I	520	2024 (construction)
PCM La Paz 1	66.58	2024 (construction)
PCM La Paz 2	275	2025 (comissioned)
PCM La Paz 3	287	2025 (comissioned)
Patia II	570	2027 (comissioned)
Micay	800	2029 (comissioned)

**Table 3.3: Data on future hydroelectric installations, including projects that are being opened, under construction, or already commissioned [Pow24]**

The results indicate a minimal impact on GEMMES and total costs, with emissions increasing due to the reduction in hydro capacity, which leads to higher LFO consumption. Since only the distribution of renewable energy sources is affected and the results are consistent with real data, the baseline values will be retained. These values are considered acceptable, though uncertainty regarding the forecast of maximum capacity will persist.

### 3.2.3 Solar

For solar energy, the limiting constraint is different and corresponds to the maximum available area. The data initially come from a study that calculates the potential area for solar installations [AGO23]. It is much easier to find maximum capacity values in studies than area values. This approach will be used for the two cases analyzed.

The results and trends are similar to those observed for hydro. A reduction in PV capacity leads to more intensive use of LFO, resulting in higher emissions. Higher costs are associated with larger investments in PV infrastructure. In all cases, the photovoltaic capacity is utilized to its maximum potential, similar to hydro, whereas wind capacity is not fully utilized.

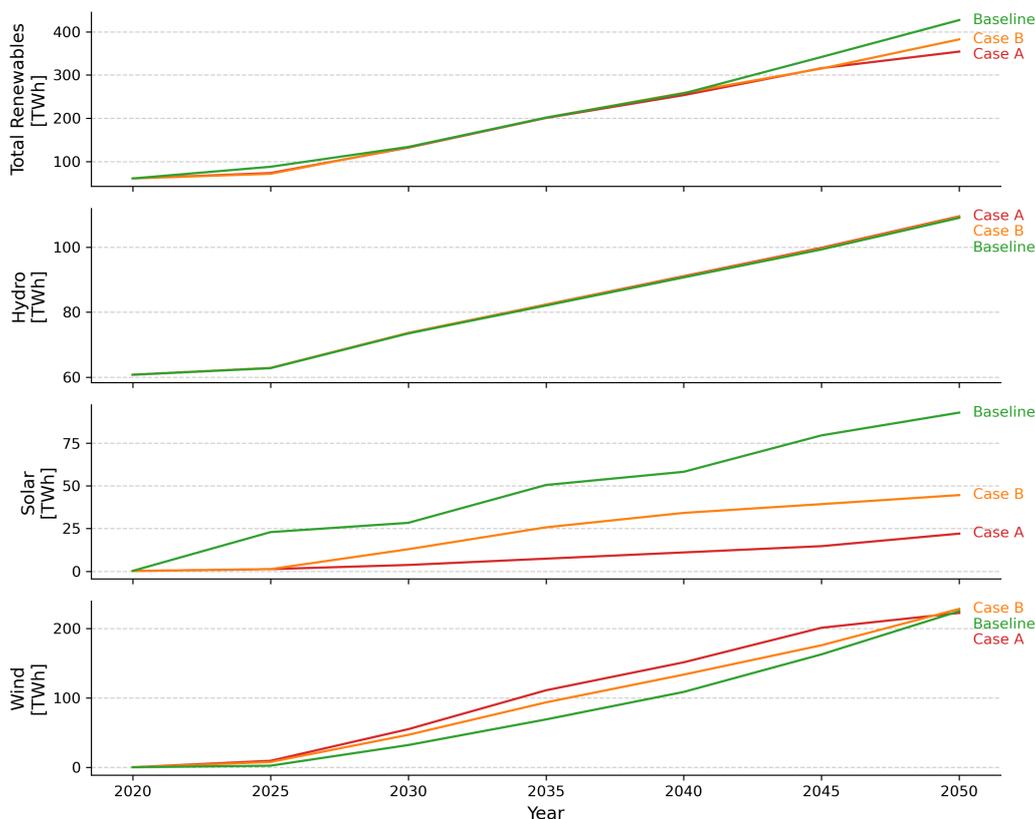


Figure 3.2: Evolution of renewable energy consumption: hydroelectric, solar and wind with varying cases of maximum PV capacity

	GWP [MtCO <sub>2</sub> -eq]	Cost [GUSD]	LFO [TWh]
Case A	21.12	459.318	55.34
Case B	15.46	472.329	33.56
Baseline	10.47	475.68	9.74

Table 3.4: Comparison of total emissions, total costs and consumption of LFO with varying cases of maximum PV capacity

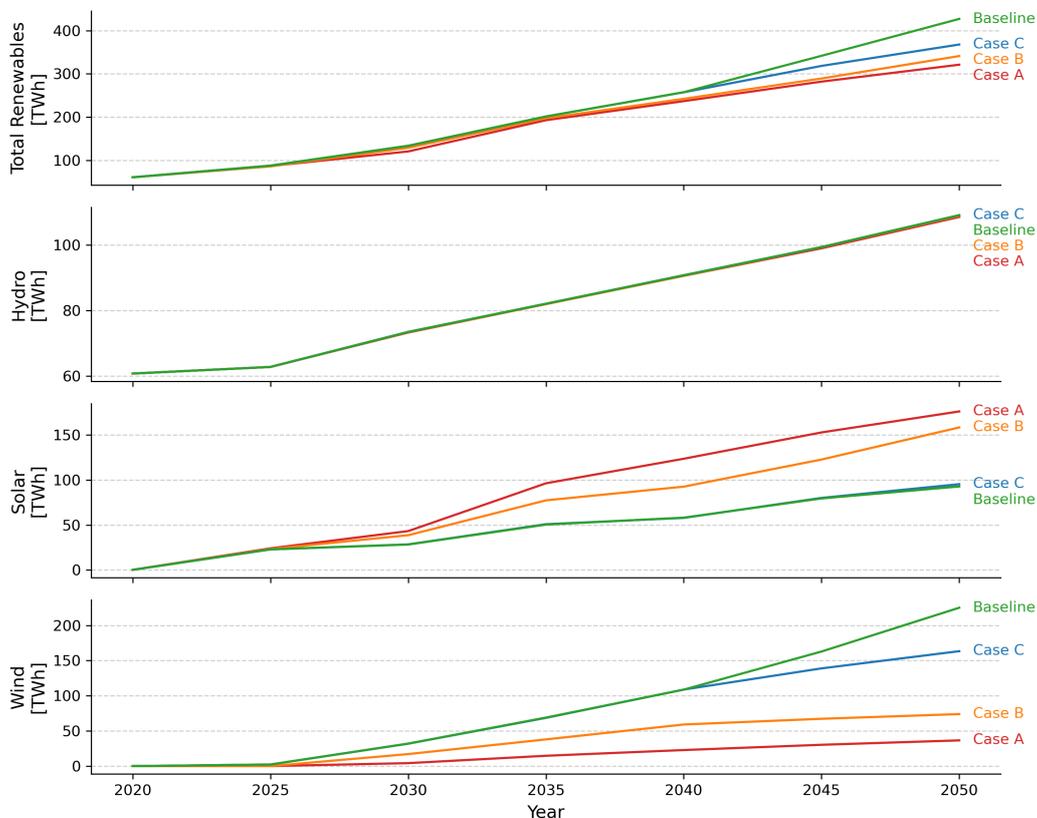
Finding data for solar is more challenging as it is only beginning to develop now. Therefore, the baseline value is retained due to its minimal impact on the results.

### 3.2.4 Wind

In Table 3.1, the data represents the sum of the capacities for both offshore and onshore wind, but in EnergyScope, wind energy is divided into onshore and offshore categories. These values are the most optimistic data from the analysis regarding offshore wind. Currently, 20 MW comes from an onshore wind farm, *Guajira I* and a new one, *Guajira II*, has just started operations with a capacity of 19.65 GW, corresponding to 0.0395 TWh of onshore wind for 2025 and none for offshore (subsection 2.1.1). By 2030, the baseline scenario sets a maximum capacity of 48.8 GW for offshore wind, which remains constant in all future years, an approach that is entirely unrealistic. Regarding onshore wind, by 2050, the baseline reaches 7.3 GW, which is considered feasible. Therefore, offshore wind will be limited in the scenarios.

The 48.8 GW value is derived from a study that refines wind and solar potential maps [AGO23] and has been utilized by the government [Min23], which identified 14 sites with suitable conditions for this cumulative installed capacity. However, no deployment timeline has been considered. The scenario Case C will analyze the impact of increasing offshore capacity linearly to reach 48.8 GW, but only by 2050.

The results are still similar to those for wind and solar, with the same underlying explanations. A higher average use of LFO is observed, resulting in greater emissions compared to wind and solar (Table 3.5). In Case C, although the maximum installed capacity for wind in 2050 is the same as in the baseline scenario, actual wind consumption remains lower. This is because the system faces greater constraints on wind expansion, making it neither cost effective nor emission efficient to install the full capacity by 2050.



**Figure 3.3: Evolution of renewable energy consumption: hydroelectric, solar and wind with varying cases of maximum wind capacity**

As a result, the total renewable generation is lower in this case. To better reflect reality, the values from Case C will be adopted for the subsequent simulations.

	<b>GWP [GtCO<sub>2</sub>-eq]</b>	<b>Cost [MUSD]</b>	<b>LFO [TWh]</b>
Case A	36.24	433.64	81.41
Case B	34.98	448.11	80.55
Case C	24.20	448.98	54.46
Baseline	10.47	475.68	9.74

**Table 3.5: Comparison of total emissions, total costs and consumption of LFO with varying cases of maximum wind capacity**

# Results and discussion

# 4

In this chapter, the different scenarios and associated results will be presented.

## 4.1 Scenarios Overview

### 4.1.1 Old scenarios

Pierre Jacques created four scenarios in his thesis [Jac25]. The first is the “Baseline” scenario, which does not include any energy transition. The second scenario, “Energy Transition”, incorporates a carbon tax that increases linearly from 0 USD per ton of CO<sub>2</sub> in 2021 to 70 USD per ton of CO<sub>2</sub> in 2051. These values were chosen through trial and error to achieve a carbon-neutral system by 2051. The third scenario, “Green Industrialization”, builds upon the second by incorporating a lower import content for technologies such as photovoltaic, onshore wind, offshore wind, electric cars and electric motorcycles. The final scenario extends the third by adding the possibility of exporting green hydrogen, thereby reflecting the government’s focus on hydrogen as detailed in subsection 2.1.1.

It is important to note that when a carbon tax is applied in these scenarios, no specific redistribution mechanism is implemented. In GEMMES, the carbon tax is incorporated into the costs of production of firms but is redistributed equally among the households, firms, bank and government that paid the tax. As stated in Pierre Jacques’ thesis:

“So we do not model a direct redistributive effect of the carbon tax through government intervention.” [Jac25]

### 4.1.2 Adjustments applied

All scenarios generated in this master thesis are based on the “Energy Transition” case. The transition is inevitable and Colombia is making efforts to stay on course. Some adjustments have been made to adapt the case to the objectives of this thesis.

1. Regarding the coupling, particularly in GEMMES, the cases implemented by Pierre Jacques are sufficiently stable. However, when parameters are modified, given the economic pressures in Colombia, highly volatile results and economic crisis scenarios can emerge, as described in Godin and all [GDM24a]. To prevent such situations, one parameter has been adjusted compared to the scenarios of Pierre Jacques, allowing for greater flexibility without immediately triggering a crisis.

In the report published by AFD titled “*Modelling low-carbon transitions in Colombia: macrofinancial opportunities and risks*”, different economic scenarios of oil and coal exports are compared and categorized into three groups: decrease in exports, stable export levels and increase in exports. To accurately model a transition, fossil fuel exports must decline, with the key change being the rate of this reduction (*reducXr0*). The initial value of 8.5 (i.e., a reduction of coal exports by 12% and oil exports by 6% per year) represented the most adverse case. This scenario appears unlikely, so the

rate has been adjusted to a lower value. This modification is justified, as the 8.5 rate represented the most extreme scenario. Without this adjustment, a rapid increase in the carbon tax would trigger hyperinflation, leading to rising prices, inflation, reduced demand, massive currency depreciation and an overall economic slowdown. Allowing an adaptation period for the system prevents this outcome. A lower fossil fuel export reduction rate helps mitigate negative effects, as a high reduction rate endangers the economy due to substantial revenue losses fossil fuels currently account for 55% of Colombia's exports (subsection 2.1.1). With the adjusted *reducXr0* value, none of the cases presented below result in crises. Had the 8.5 value been maintained, all cases with a rapidly increasing tax rate, particularly the sigmoid cases (subsection 4.2.2 and subsection 4.2.3) would have led to crises. This hypothetical crisis arises from non-linear carbon tax trajectories, as they trigger substantial investment requirements over a short period due to a sudden increase in the tax rate.

2. Furthermore, the carbon tax value had not been correctly updated to reflect real prices. It has now been adjusted by accounting for inflation, giving it a greater impact than in Pierre Jacques' simulations while making it more accurate. The effect is principally that unitary cost are bigger so consumption inflation too.
3. The consistency of the prices shared in the coupling is ensured by an *adjustment factor* that rescales the outputs of EnergyScope to match the real cost of the energy system in 2021, as provided by the DNP. This fitting was applied to all transition prices. The carbon tax was also included in this fitting, which did not make much sense because, in GEMMES, the impact of the carbon tax was underestimated (real prices were much lower than EnergyScope prices). The *adjustment factor* was therefore removed for the carbon tax. Later, for subsidy scenarios section 4.3, subsidies were implemented and the adjustment factor will also not be applied.

### 4.1.3 Scenarios

In this thesis, the analysis focuses on the carbon tax. Accordingly, scenarios are examined each addressing a particular facet of carbon tax implementation. They are as follows:

- A. The **Tax Rate Scenarios** exclusively modify the parameter *gwp cost*, which represents the cost of carbon emissions. Various tax rates will be explored, including extreme scenarios and different temporal profiles between the years 2025 and 2050. No redistribution mechanism is implemented, as in the scenarios implemented by Pierre Jacques.
- B. The **Investments in Renewable Resources Scenarios** simulates the effect of government subsidies for financing renewable energy. The study will focus on how these subsidies can be implemented, what levels they might reach.
- C. The **Households Redistribution Scenarios** will divide households in GEMMES based on the percentile of their total income. Subsequently, a specific fund (sourced from carbon tax revenues) will be redistributed to the households with different weights according to the income group each household belongs.

## 4.2 Tax Rates Scenarios

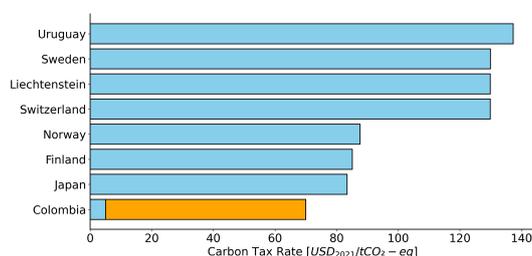
In order to find the most suitable carbon tax, the impact of the tax rate and its evolution from 2025 to 2050 will be evaluated. The goal is to minimize the negative economic impact as much as possible and possibly even achieve a positive impact, although this is highly unlikely due to Colombia's critical context regarding its high dependency on fossil fuel exports and foreseen decline due to depletion of reserves and lower international demand. The redistribution and social aspect has not yet been studied for this type of scenario.

Several types of temporal evolutions are examined. First, the most conventional approach involves a tax that increases linearly over time. Next, a sigmoid function is considered, which delays the implementation of the tax while allowing for rapid growth followed by a plateau just before reaching 2050. This simulates a late political decision making process but with a quick ramp-up in the tax rate (*Sigmoid profil : Late action*). Finally, to mitigate the negative effects of the previous case, another sigmoid is applied, starting rapidly from 2025 but remaining relatively constant after 2035, essentially the same as the previous one but shifted to the left (*Sigmoid profil : Quick action*).

### 4.2.1 Linear profil

Pierre Jacques' baseline scenario is nearly linear, though not perfectly so. The linear scenario was adjusted to match the same slope as the baseline but in a fully linear form.

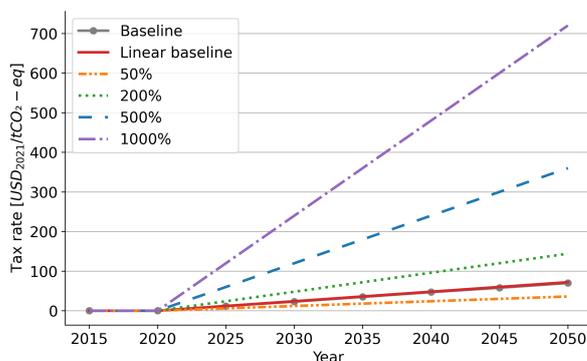
The final rate of 70 USD<sub>2021</sub>/tCO<sub>2</sub>-eq. is relatively modest. When compared to other countries, it appears that the baseline 2050 tax rate is lower than the actual current carbon tax rate in some countries such as Uruguay and Sweden (see Figure 4.1) [OEC23b; RR22]. Of course, each country's context is different. For example, Sweden was a pioneer in this field, introducing its tax in 1991 while also implementing an ETS system [Gov23]. This nonetheless demonstrates a significant potential for progress in Colombia. Comparing to France, where the Quinet report [Qa19] defines an average price of 775 €<sub>2018</sub>/tCO<sub>2</sub>-eq. for 2050 corresponding to 966.5 USD<sub>2021</sub>/tCO<sub>2</sub>-eq.<sup>1</sup> with an uncertainty range extending from 600 to 900 €<sub>2018</sub> [Gro+24; Qa19] i.e. 749.1 to 1065.3 USD<sub>2021</sub>. It is observed an order of magnitude difference of factor 10 and more between the baseline simulation and the French targets. According to the High-Level Commission on Carbon Prices, which met in 2017, the explicit carbon price needed to align with the Paris Agreement's temperature goal should be at least 40–80 USD<sub>2021</sub> in 2020 and increase to 50–100 USD<sub>2021</sub>/tCO<sub>2</sub>-eq. by 2030 [Sti+17]. This range is the most commonly used in the literature and is considered a reference point.



**Figure 4.1: Top countries with the highest carbon taxes compared to Colombia : blue data from [KS22] and orange representing the baseline simulation for the 2050 tax rate.**

<sup>1</sup>The amount of 775 €<sub>2018</sub>/tCO<sub>2</sub>-eq. was adjusted for inflation to 817 €<sub>2021</sub>/tCO<sub>2</sub>-eq. using the cumulative inflation rate of 5.4% between 2018 and 2021, as reported by Eurostat [Eur21b]. This was then converted to USD<sub>2021</sub> using the average exchange rate of 1 €= 1.183 USD in 2021, according to the European Central Bank [Eur21a].

For this reason, the focus will be on increasing the linear tax by a specific factor, although a reduction case will also be considered. The cases will be expressed as a percentage of the baseline linear tax, with Figure 4.2 illustrating the scenarios and Figure 4.3 providing the relevant information.



**Figure 4.2: Carbon tax profile in the linear scenario**

Tax rate (2050) [USD <sub>2021</sub> /tCO <sub>2</sub> -eq.]	Pourcentage [%]
36	50
72	100
144	200
360	500
720	1000

**Figure 4.3: Percentage of each scenario relative to the linear baseline scenario, for the 2050 tax rate**

#### 4.2.1.1 Emissions and costs

The first conclusions focus on greenhouse gas emissions (Figure 4.4). It is immediately noticeable that by 2050, all scenarios converge towards the same emission levels, except for the 50% reduction case, which fails to meet the set objectives. The explanation is the same as for the sensitivity analysis (section 3.1): the use of LFO to compensate for renewables leads to higher emissions (Figure 4.6). The two scenarios with the most extreme taxes result in minimal GWP in 2035, which then slightly increases due to construction emissions that grow over time. Meanwhile, emissions from operation reach zero in 2035 and therefore cannot decrease any further.

The total cost, including operation, construction, maintenance costs and carbon tax, increases in all cases (Figure 4.5). For the 500% and 1000% scenarios, there is a very high total cost in 2035/2040, originating from massive investments. Indeed, when the carbon tax is high, the transition is faster and requires more investments in a short time frame, which can also be seen in Figure 4.7c. The cost of the carbon tax is quite negligible compared to the total costs, despite changing global behaviors. This can be explained by the fact that the system aims to minimize costs and will thus prioritize using lower emission resources to avoid paying excessively high carbon related costs. By 2050, all costs are quite similar except for the two extreme cases (50% and 1000%), with the main difference lying in the trajectory taken to reach that year.

The threshold at which emissions differ from the baseline in 2050 has been identified at a tax rate of 87%. It is observed that emissions increase rapidly with the reduction of the tax, as can already be seen in the case where it is halved.

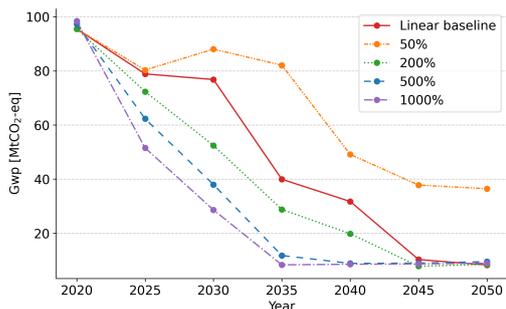


Figure 4.4: Evolution of total emissions : construction and operations with varying cases of tax rates linear case

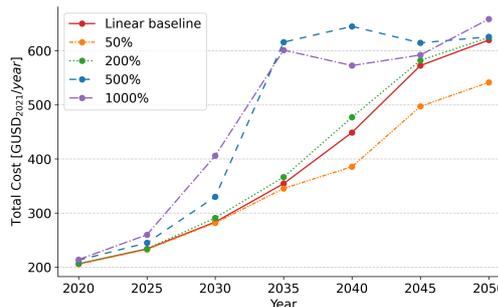


Figure 4.5: Evolution of total costs of the system : investments, maintenance, operation, carbon with varying cases of tax rates linear case

4.2.1.2 Energy

In terms of energy distribution, changes occur mainly between 2030 and 2045 and for other years only in the case of a 50% reduction. This difference is primarily due to variations in wind and solar energy. While hydropower operates at full capacity and solar energy remains less competitive under current conditions, wind energy becomes the main lever for adaptation. The observed change can be attributed to the fact that a higher carbon tax acts as a catalyst, accelerating the transition toward less carbon-intensive technologies. Ultimately in 2050, in all scenarios except for the case of a 50% reduction, the carbon price becomes high enough to discourage the use of emitting energy sources. As a result, raising the tax further does not significantly impact outcomes after 2040, as the system will have already been "forced" to decarbonize. It's noteworthy that cases 500% and 1000% exhibit similar energy mixes, as do the baseline and 200% cases. This indicates also that the system's behavior is non-linear.

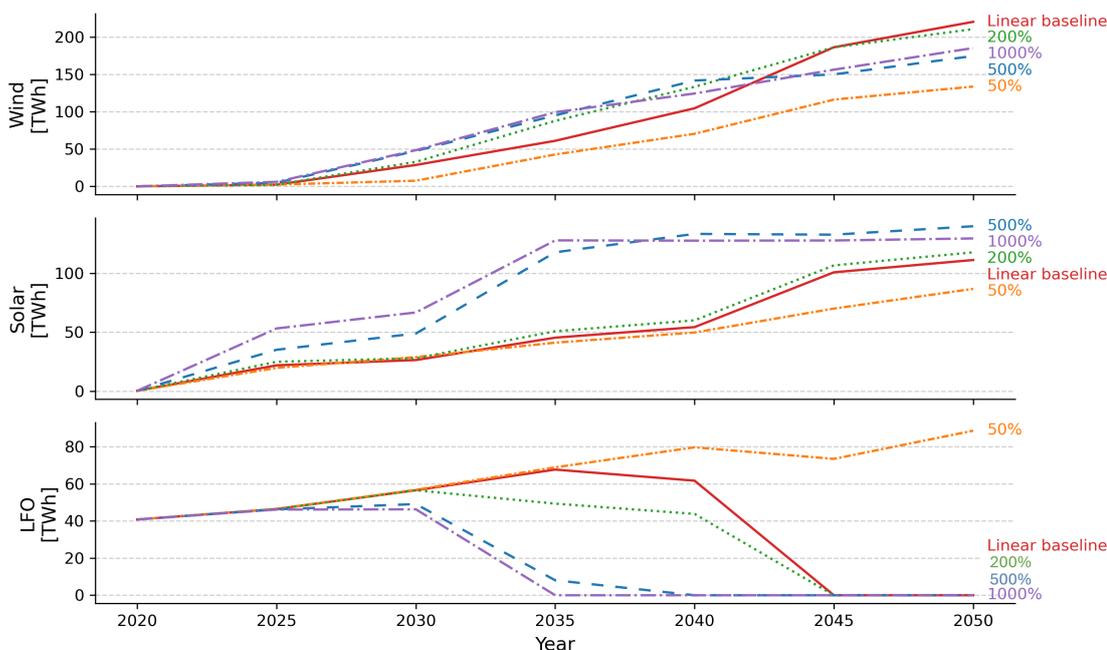


Figure 4.6: Evolution of energy consumption: Wind, solar and LFO with varying cases of tax rates linear case

### 4.2.1.3 Macroeconomic effects

The macroeconomic effects of the transition reveal a common pattern across all scenarios, including both the *linear* trajectories and the sigmoid shaped *Late Action and Quick Action* pathways. GDP initially grows (Figure 4.7b), driven by energy investments, before reaching a peak and subsequently declining, more or less sharply depending on the case. This turning point corresponds to the energy investment peak (Figure 4.7c): while public and private investments boost economic activity, the simultaneous rise in the carbon tax increases production costs and consumer prices (Figure 4.7d), partially offsetting growth. Since a significant portion of energy investments comes from abroad, investment peaks also lead to increased imports, putting pressure on the exchange rate (Figure 4.7e) and fueling inflation. This phenomenon is amplified by the structural decline in fossil fuel exports and foreign direct investment in the sector, as shown in previous studies by Pierre Jacques and Antoine Godin [Jac25; GDM24a], leading to a real depreciation of the Colombian peso across all scenarios. Several past crises have resulted in significant inflationary surges, comparable to the cases analyzed in this study. For example, in 2023, during the post-COVID period, inflation peaked at 11.3% [Wor24]. Another instance was in 2016, when inflation reached 7.5% due to a combination of factors (El Niño, falling oil prices, ...). Other macroeconomic indicators mirror this trajectory. The unemployment rate falls during the initial economic boost, before rising again after the turning point, as shown in Figure 4.7f. Inflation follows a similar trend (Figure 4.7d), driven by higher energy prices and increased import costs. Public debt as a share of GDP (Figure 4.7h) also peaks before the turning year, as national savings prove insufficient to finance the surge in investments. It then gradually decreases, following economic adjustments prompted by fiscal and monetary policy.

The intensity and timing of these effects vary significantly with the carbon tax trajectory. The higher the tax rate, the earlier and sharper the economic impacts. GDP growth peaks in 2030 for the 1000% scenario, just before 2035 for the 500% case, around 2040 for the 200% case, shortly after 2040 for the baseline and around 2045 for the 50% case. Higher tax rates also lead to more pronounced inflation and greater initial declines in GDP growth due to accelerated transition efforts and larger investment needs (Figure 4.7c, Figure 4.7g). Interestingly, the peso reaches its lowest point sooner in the 500% and 1000% cases, then stabilizes, signaling a return to economic equilibrium. The peso depreciates more with higher carbon tax rates, which can be explained by the fact that imports increase, as it is necessary to import the technologies required to support massive investments. GDP growth similarly recovers after its sharp decline in these scenarios, suggesting a post-transition rebound. For lower tax scenarios, this recovery occurs after 2050, making it less visible in the short term. However, an unrealistic outcome arises in the 500 and 1000 cases: unemployment rates temporarily fall below zero. This stems from a model limitation in GEMMES, which assumes constant productivity growth and is independent of new investments. In a rapidly growing economy, labor demand can exceed the available workforce in the model, producing paradoxical results. Introducing a cap on employment could improve the model's realism.

One remark, in the Linear 1000% scenario, the sharp initial increase in the carbon tax (Figure 4.7a), inflation (Figure 4.7d) and peso depreciation (Figure 4.7e) dampens non-energy investment (Figure 4.7g), whose share of GDP declines. This contributes to weaker economic momentum compared to other scenarios. This relative slowdown is also explained by a crowding-out effect: massive energy investments absorb financial resources, reducing overall corporate debt between 2030 and 2035. Finally, the real profitability of investment is lower (due to higher costs), which slows down the recovery in non-energy sectors.

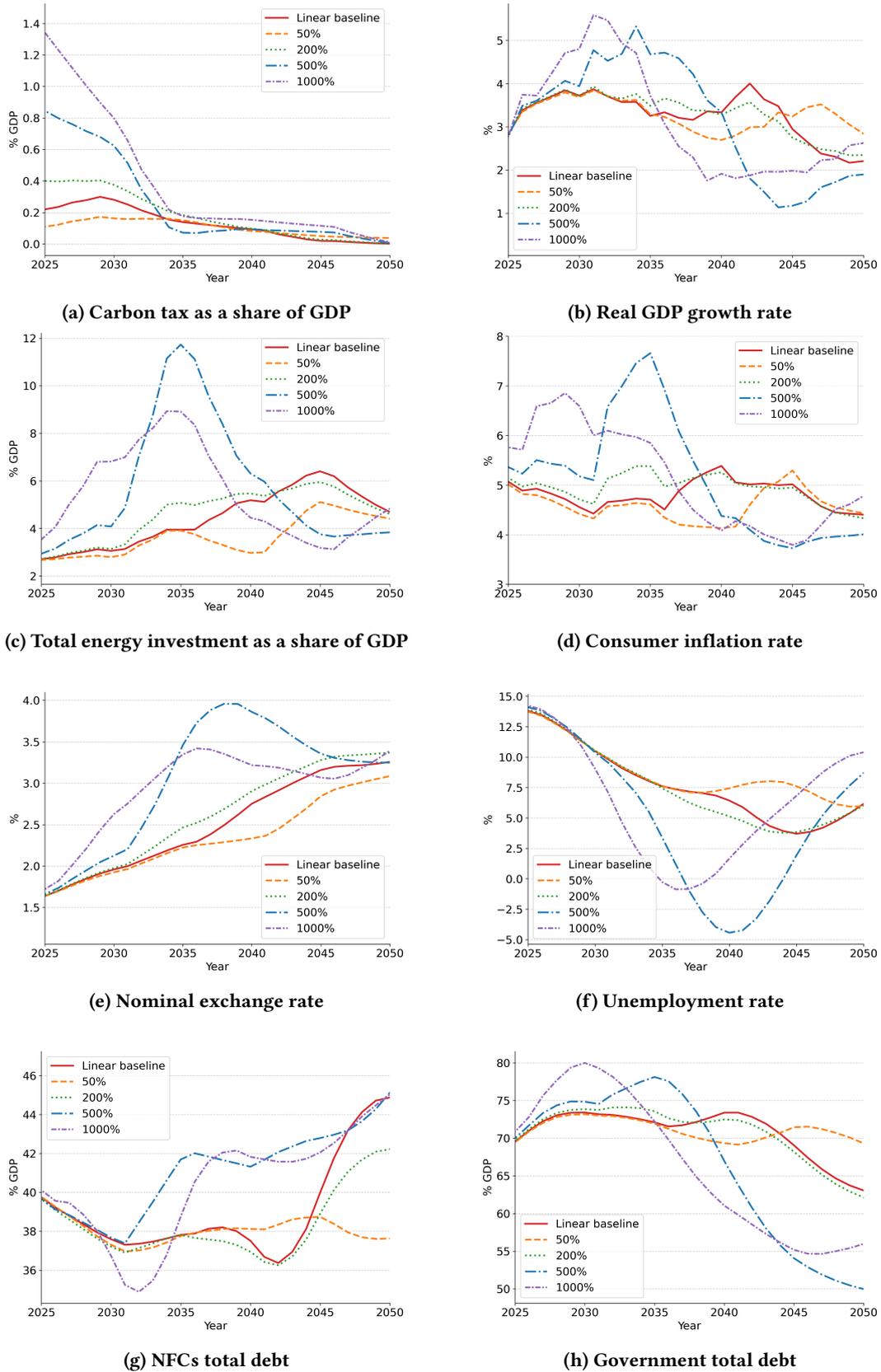


Figure 4.7: Macroeconomic dynamics of the linear tax scenarios

Finally, the baseline and 200% scenarios yield very similar results, while the 500% scenario unexpectedly shows more pronounced peaks than the 1000% case (see Figures 4.7c, 4.7d, 4.7e and 4.7f), possibly due to nonlinear interactions within the model that warrant further investigation. The diminution case of 50% shows very slight peaks and is smoother.

#### 4.2.2 Sigmoid profil : Late action

For the *sigmoid late action* scenario, the characteristic is to rapidly increase the tax over a short period. This represents a strong and quickly applied political decision starting from 2030. The same percentages as the *linear scenario* are used, as mentioned above in subsection 4.2.1, shown in Figure 4.8.

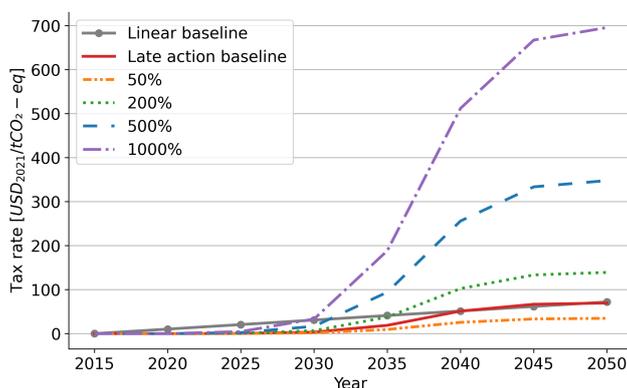


Figure 4.8: Sigmoid late action profil

##### 4.2.2.1 Costs and emissions

The overall behavior remains similar to the linear cases. However, in terms of emissions, the focus shifts to an abrupt decline in the curves. Comparing the linear baseline to the sigmoid baseline reveals a convergence around 2040. Nonetheless, between 2025 and that point, emissions are significantly higher in the sigmoid baseline due to a much lower initial tax that then rises sharply. In terms of cost, the differences are less pronounced but remain slightly higher for the linear baseline, which reaches the same cost level in 2050 as the 1000% sigmoid scenario.

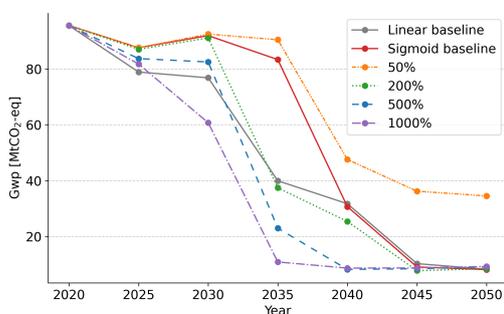


Figure 4.9: Evolution of total emissions : construction and operations with varying cases of tax rates (late action scenario)

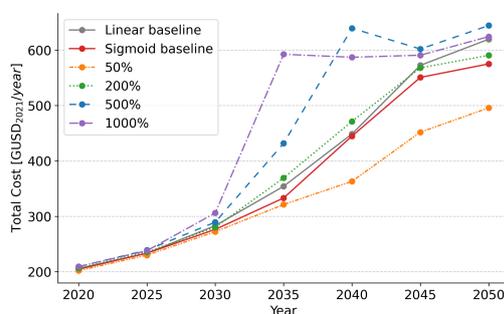
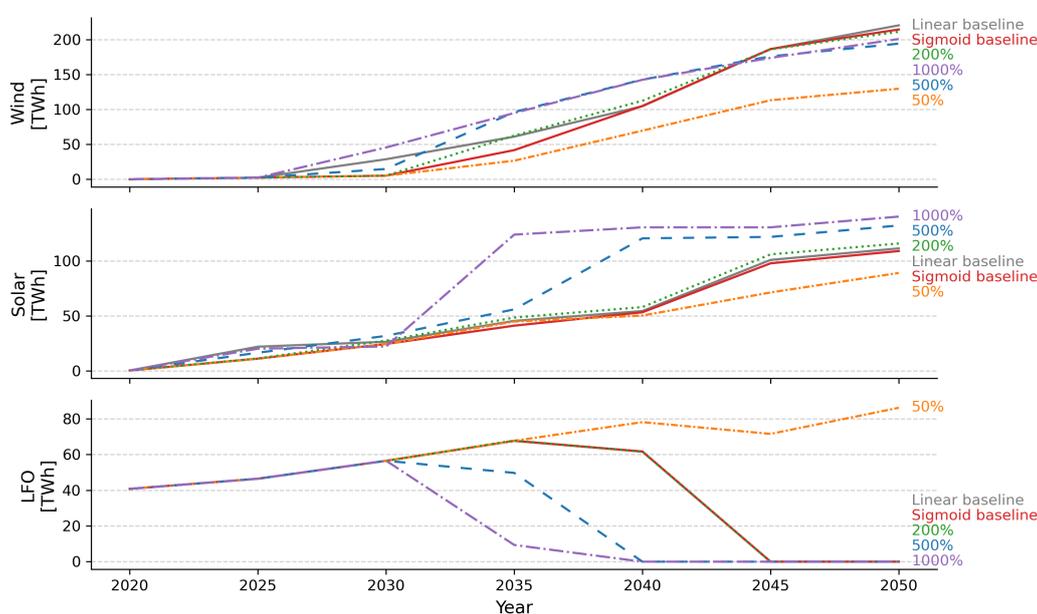


Figure 4.10: Evolution of total costs of the system : investments, maintenance, operation, carbon with varying cases of tax rates (late action scenario)

### 4.2.2.2 Energy

The sigmoid baseline, 200% and linear baseline cases display almost identical behavior. Compared to their linear counterparts, a delay in the transition dynamics is observed for the sigmoid trajectories, except for the baseline case, which remains unchanged. The more aggressive the tax rate, the more pronounced this delayed response becomes. This behavior is attributable to the observation that: at low tax rates, the difference between the linear and sigmoid profiles for a given rate is less pronounced than at higher rates. This behavior is inherent to the nature of the profiles and also applies to the *sigmoid quick action* profile.

In particular, the LFO reaches zero in 2040 in the sigmoid 500% and 1000% cases, while in the linear 500% and 1000% cases, this occurs five years earlier, in 2035. As the LFO declines, renewable energy sources such as wind and solar increase their share, hydropower, by contrast, remains constant at its maximum level. This indicates that the energy transition is shifted by approximately five years in *sigmoid scenarios*, but only when the tax is strong enough to drive a decisive shift away from fossil fuels.

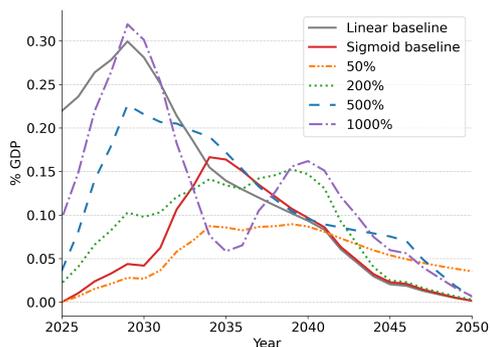


**Figure 4.11: Evolution of energy consumption: Wind, solar and LFO with varying cases of tax rates late action case**

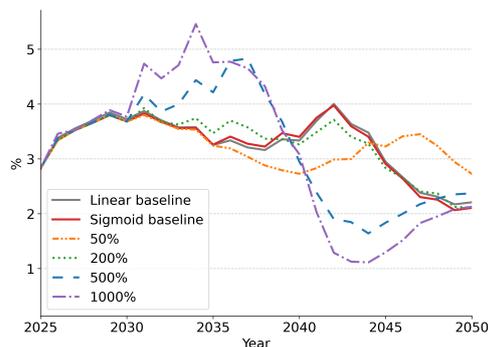
### 4.2.2.3 Macroeconomic effects

Once again, the overall behavior follows exactly the same logic as in the *linear scenario*, still impacted by the carbon tax (Figure 4.12a) and massive investments (Figure 4.12c).

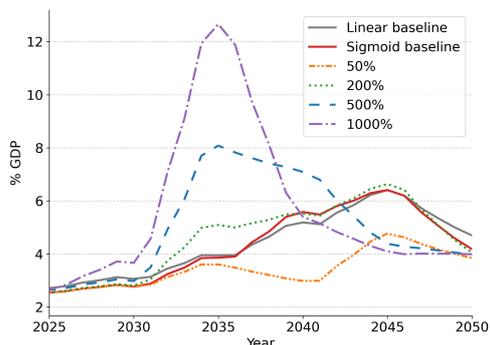
The main difference lies in the shift of the curves. For the 500% and 1000% sigmoid tax cases, the peaks (GDP growth, consumer inflation,...) occur simultaneously, whereas in the *linear scenario*, these peaks are separated by five years. Unlike the *linear scenario*, where the timing of the shock varies with its magnitude, the sharp and abrupt increase in the sigmoid trajectories reduces the system's sensitivity to differences in shock intensity. In the linear baseline, sigmoid baseline and 200% scenarios, the peak occurs in 2040 and finally, in the 50% scenario, it happens in 2045. When comparing the intensity and overall behavior of the peaks with the *linear scenario*, they remain quite similar.



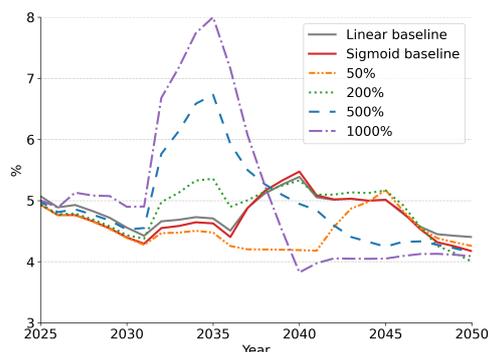
(a) Carbon tax as a share of GDP



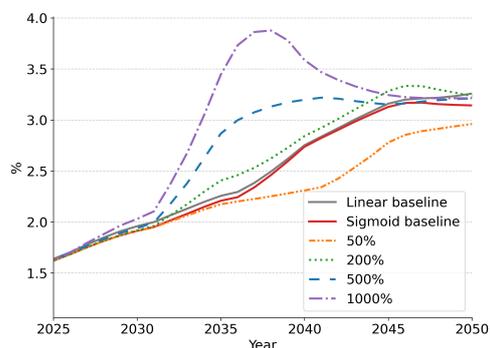
(b) Real GDP growth rate



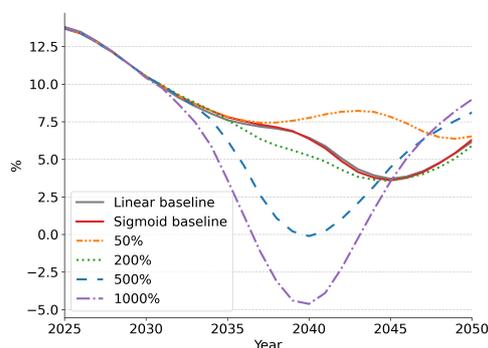
(c) Total energy investment as a share of GDP



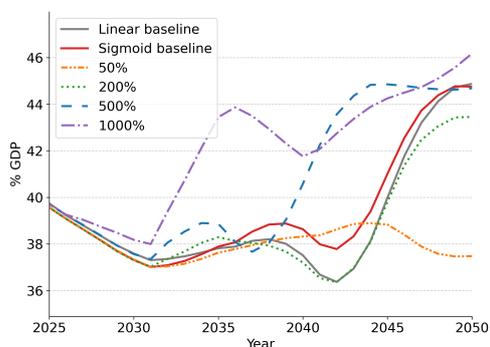
(d) Consumer inflation rate



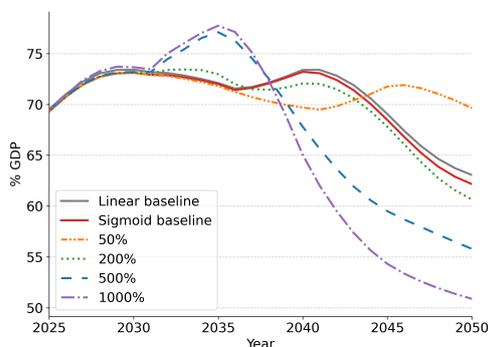
(e) Nominal exchange rate



(f) Unemployment rate



(g) NFCs total debt



(h) Government total debt

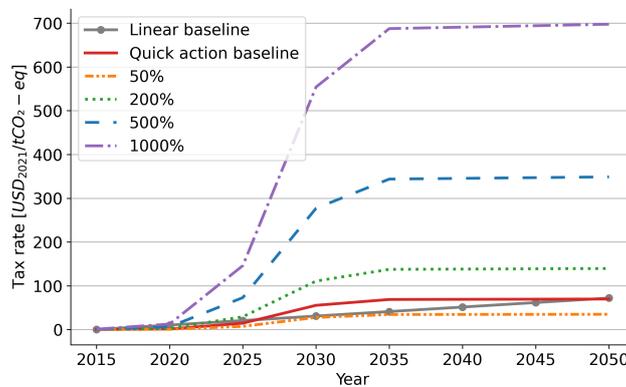
Figure 4.12: Macroeconomic dynamics of the four scenarios of sigmoid late action tax rates

A more detailed comparison will be made in the final reflections on tax rates, subsection 4.2.4.

It is easy to conclude that postponing taxation to 2030 with a high rate increase offers no advantage, as behaviors will simply shift to five years later. However, this raises the question: if this phenomenon is anticipated, could delaying this sharp increase actually be beneficial?

**4.2.3 Sigmoid profil : Quick action**

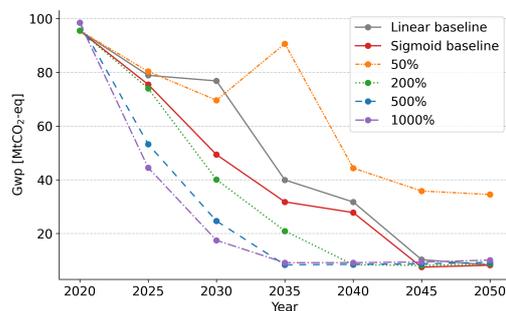
For the *sigmoid quick action* scenario, the characteristic is the same as the *sigmoid late action scenario*: rapidly increasing the tax. Given the observation that a late action shifts linear behaviors, the same profile will be implemented but shifted by 5 years. Therefore, the political decision will be made in 2025 to analyze the possible benefits that could be gained. The same percentages are used as mentioned above, referenced in Figure 4.13.



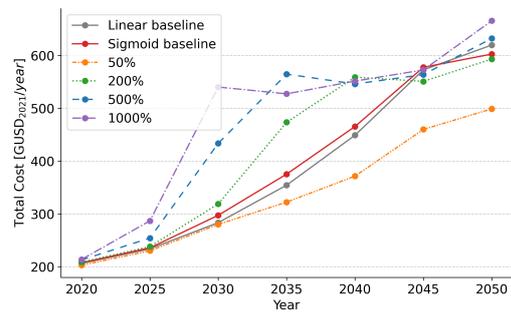
**Figure 4.13: Sigmoid quick action profil**

It is apparent that emissions drop exponentially as the carbon tax increases. As expected, behaviors shift earlier in time, with massive investments occurring five years earlier.

The peak of total cost is significantly lower than in the other two sets of scenarios, reaching around 550 instead of 600 (for the 1000%).



**Figure 4.14: Evolution of total emissions : construction and operations with varying cases of tax rates quick action case**



**Figure 4.15: Evolution of total costs of the system : investments, maintenance, operation, carbon with varying cases of tax rates quick action case**

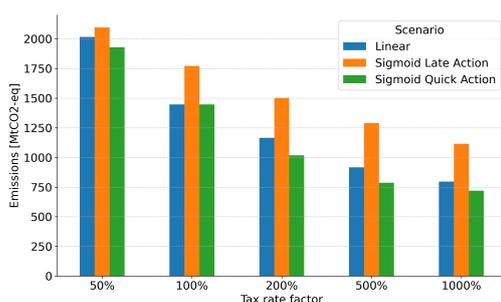
Since the energy and economic outcomes behave similarly across the sets of scenarios, they are no longer shown or detailed here but can be found in Appendix A. Instead, all scenarios will be compared in the following section.

## 4.2.4 Final reflections on tax rates

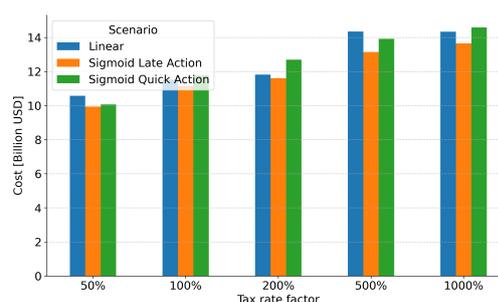
How can we determine the best carbon tax and which criteria should be used? If the analysis focused solely on the climate impact, choosing the highest tax would be the obvious decision. However, it is crucial to find a balance between emission reduction and the negative effects of the tax on the economy.

### 4.2.4.1 Emissions and costs

First, it has been observed that all tax levels lead to the same emission reductions by 2050, except in the case of a 50% reduction, but the cumulative emissions are different. In Figure 4.16, it is immediately evident that cumulative emissions decrease with tax rates and this is also true for all sets of scenarios : *Sigmoid Quick Action*, followed by *Linear* and then *Sigmoid Late Action*. However, the total cumulative cost of the transition (Figure 4.17) shows the opposite trend, increasing with the rate and is minimum for *Late Action*, then *Linear* and finally *Quick Action*. One can directly link this with the speed of transition. This speed is also represented by cumulative emissions because the faster the transition occurs, the lower the cumulative emissions will be and conversely. Depending on the tax rate and the transition profile, a temporal shift also occurs in economic behavior, associated with varying intensities of economic peaks.



**Figure 4.16:** Total cumulative emissions for different sets of scenarios grouped by tax rates



**Figure 4.17:** Total cumulative cost for different sets of scenarios grouped by tax rates

### 4.2.4.2 Economy

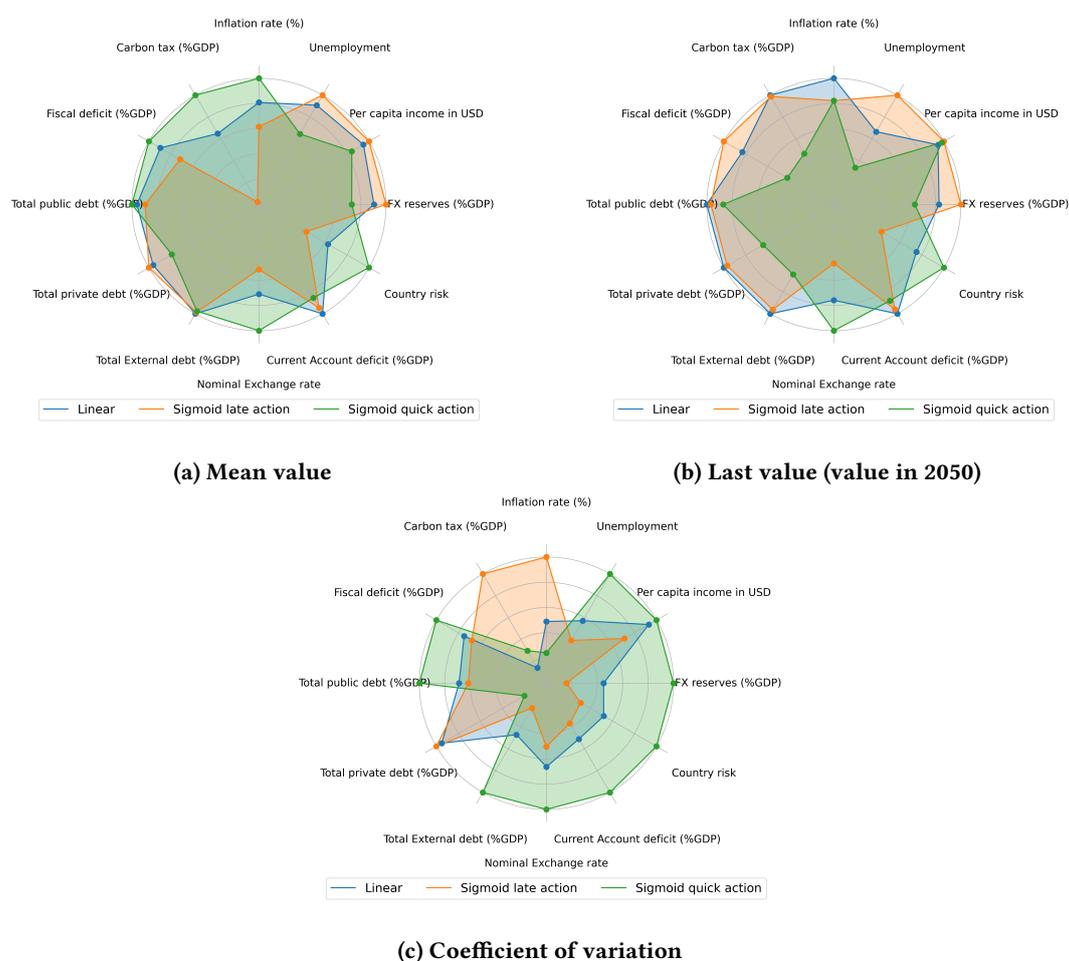
The three following graphs highlight a metric that allows comparison of the sets based on the average value, the last value (in 2050) and the standard deviation <sup>1</sup> which helps to measure volatility of economic indicators. The goal is to achieve results as close to the center as possible, meaning minimum values, except for per capita income and FX reserve as share of GDP. For carbon tax as a share of GDP, interpretation is nuanced, a high value may indicate high emissions, implying high tax revenues, making it difficult to determine whether a higher or lower value is inherently better.

The first point to highlight is the average value of the carbon tax collected as a share of GDP (Figure 4.18a), which is highest in the *Quick Action* scenario, followed by the *Linear scenario* and lowest in the *Late Action scenario*. This outcome is consistent with expectations, as in the *Late Action* scenario, the energy transition is already partially underway by the time the

<sup>1</sup>The values are normalized as follows: the mean and last values are scaled using the minimum and maximum values across all scenarios and time steps, while the standard deviation is normalized by the minimum and maximum values among the three scenarios.

carbon tax reaches its peak. Since the energy mix has already been partially decarbonized, residual emissions and therefore tax revenues are lower than in the other two cases.

On the other hand, the *Sigmoid Quick Action scenario* performs worst on average (Figure 4.18a), showing the highest fiscal deficit, total public debt, total external debt, nominal exchange rate and country risk with low per capita income in USD. However, it is associated with low unemployment. Large upfront investments are necessary to achieve the transition goals. The resulting high fiscal deficits reflect government spending that exceeds revenues. To finance this, both domestic and foreign borrowing increase, leading to a rise in total and external debt. The total private debt is the lower driving by the massive investments. These rapid interventions induce currency depreciation and generate inflationary pressure (also, coming from high carbon tax) and a heightened perception of country risk. Employment is temporarily boosted due to the surge in investment. However, per capita income in USD remains low, a result of the weakened local currency and sluggish private sector growth. This scenario appears to create significant economic strain, likely due to heavy upfront investments that weigh on public finances.



**Figure 4.18: Mean, last values and coefficient of variation of economic indicators in scenarios Linear, Sigmoid Late Action and Sigmoid Quick Action for tax rate baseline (100%).**

In contrast, the *Late Action scenario* shows better results across several macroeconomic indicators, notably with highest per capita income but higher unemployment. This suggests that delaying the transition can help maintain economic stability in the short and medium term, though it may pose greater climate related challenges.

The *Linear scenario* generally falls in between the two extremes, offering a moderate balance between climate ambition and macroeconomic stability. However, it performs less favorably in terms of the current account deficit.

The final value (Figure 4.18b) indicates that the *linear and late sigmoid scenarios* yield very similar outcomes, as both follow a comparable adjustment path. In contrast, the *quick action scenario* performs better in terms of the final value, since the system had more time to adapt and return to a more stable state, resulting in lower levels.

In terms of volatility (Figure 4.18c), the *sigmoid quick action scenario* generates the most. The only indicators where it does not reach the highest values are total private debt, carbon tax and the inflation rate, where the late action scenario records higher values.

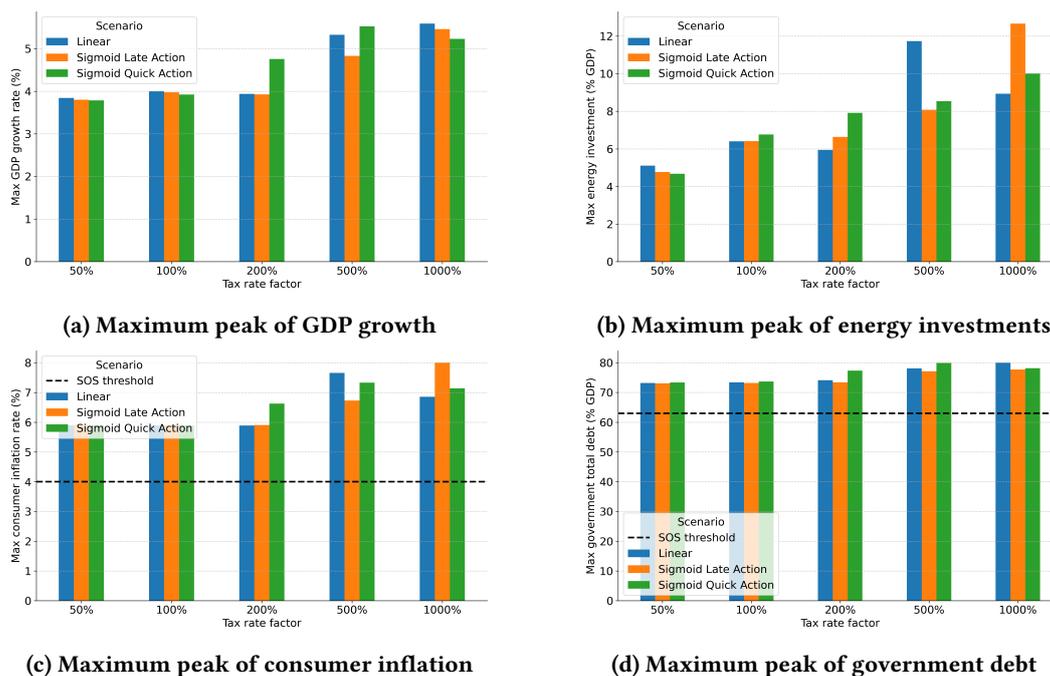
The mean, last value and coefficient of variation are important indicators, but knowing the maximum value of an economic indicator for a specific scenario helps identify its limits. In terms of the intensity of economic shocks, higher tax rates correspond to more pronounced peaks. This is evident in metrics such as maximum GDP growth rate, energy investment, inflation and total government debt (the latter being slightly less pronounced) on Figure 4.19.

At the 50% or baseline level, peak values are relatively similar across all three scenario types. However, under the 200% tax rate, only the *Sigmoid Late Action* scenario displays a significantly higher peak. The most notable differences occur at the highest tax rates (500% and 1000%).

The *Sigmoid Late Action* scenario under high tax rates is not recommended, as it requires the most substantial investments as a share of GDP (Figure 4.19a), leading to the highest inflation (Figure 4.19c) and the most severe economic repercussions, without delivering a rapid reduction in emissions. Under such conditions, the *Linear* and *Quick Action* scenarios are more suitable, offering a more favorable balance between transition timing and economic impact.

*The real question, therefore, is whether these changes are acceptable for the Colombian economy to accelerate emission reductions and whether such a high level of taxation is truly necessary.*

There is no universal answer; it all depends on the government's priorities, how quickly it wants to carry out the transition and what socio-economic impacts it is willing to accept. In a country like Colombia, where weak social protection, high labor informality (which limits workers' ability to index wages to inflation) and widespread poverty and inequality persist, the distributive costs of high inflation and increasing carbon prices can be substantial and should not be overlooked (as analyzed in section 4.4).



**Figure 4.19: Maximum peak of economic indicators (GDP growth, energy investment, inflation and government debt) for different sets of scenarios grouped by tax rates**

In connection with this, Antoine Godin defined a Safe Operating Space (SOS) for the Colombian economy, which corresponds to a range of values for economic indicators within which they must remain to maintain economic stability. Minimum and maximum thresholds were established (can be found in Appendix B) and the results indicate that both the peak inflation rate (Figure 4.19c) and the peak of government debt<sup>1</sup>(Figure 4.19d) exceed the SOS limits, therefore, no case is considered valid under this criteria.

#### 4.2.4.3 Mitigating policies

If none of the cases meet these criteria, it is necessary to consider restrictive policies to mitigate their macroeconomic impact, particularly if a high rate and high speed of transition are selected. It should be noted that a modest reduction in fossil fuel exports has already been implemented (subsection 4.1.2) and further increases in this reduction will exacerbate negative behaviors.

Two types of policies can be differentiated based on who sets them: monetary tools, which correspond to central banks, and fiscal policies, which are implemented by the government. Central banks use tools like adjusting interest rates, conducting open market operations, setting reserve requirements and implementing quantitative easing to control borrowing, spending and the money supply in the economy. It can be noted that GEMMES already includes the Taylor Rule<sup>2</sup> with an inflation control targeting mechanism, which implies that the central bank attempts to manage inflation within the model, but it is clear that this is not sufficient on its own. The second type adjusts government spending and taxation. Both aim to have a certain leverage on the economy. It has been proven that, in the case of energy price surges and inflation, targeted fiscal policy instruments, such

<sup>1</sup>Other economic indicators, such as unemployment, also exceed the acceptable threshold ranges.

<sup>2</sup>The Taylor Rule is a formula used by central banks to determine the optimal interest rate based on economic conditions.

as energy subsidies, can nearly neutralize the effects of energy price spikes (as will be also shown in the following section, section 4.3) [GW24]. It should not be forgotten that the economy is under pressure due to massive investments and the carbon tax, so support mechanisms for investment are also needed. Subsidies targeting energy producers and firms prove more effective than consumption-based tax cuts. Compared to monetary policy tools, targeted fiscal measures are more effective in managing energy price spikes. Additionally, energy price caps are effective in reducing inflation, inequality and household financial vulnerability regardless of the source of funding [CR25].

In this context, green financing instruments offer an additional mechanism to support the low-carbon transition while stabilizing macroeconomic conditions and many ways exist to implement it, each offering significant advantages. When they come with long maturities, lower interest rates, or are based on grants or donations, they can reduce financing costs and the level of indebtedness required for upfront investments. If the financing is provided in foreign currency from international sources, it increases the availability of foreign exchange, particularly USD, within the domestic economy, alleviate pressure on the exchange rate and helping to manage inflationary pressures.

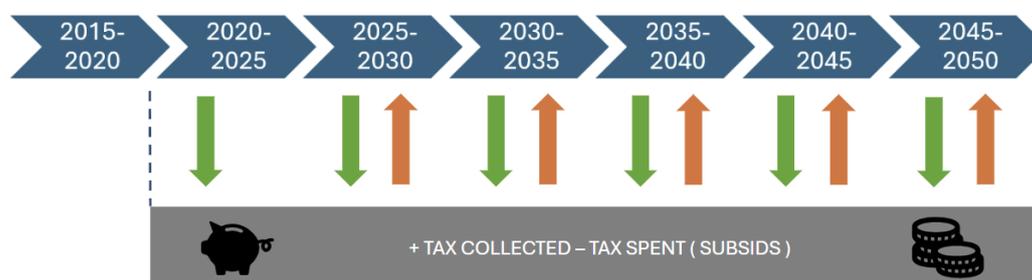
As discussed in subsection 2.1.1, identifying alternative export sectors to replace fossil fuel revenues can mitigate macroeconomic vulnerabilities. One promising avenue is the development of green hydrogen exports, as highlighted in the thesis by Pierre Jacques, which demonstrates favorable outcomes for both growth and external balance. Furthermore, increasing the domestic content of technologies can reduce reliance on imports, an aspect also emphasized in Jacques' green industrialization scenarios. This, in turn, alleviates pressure on the current account and helps stabilize the exchange rate.

### 4.3 Investments in Renewable Energies Scenario

#### 4.3.1 Model

The first case of redistribution focuses on allocating part or even all of the collected tax to subsidizing renewable energies. This is a subsidy that the government grants after collecting the tax. From a more practical perspective, the investment cost of renewable energies ( $c_{inv\_ren}$ ) will be reduced thanks to the tax collected every five years. The total amount is divided into four to be distributed among renewable energies (wind onshore, wind offshore, hydro and solar)<sup>1</sup>. The distribution is not evenly divided into four equal parts. Instead, a higher percentage is allocated to energy sources, as illustrated in (section C.3), with a higher total investment cost (not the unit cost, but the cost of all installations to be deployed during the phase). This approach ensures that when a large amount is allocated for redistribution, it is effectively used. If the funds were distributed equally among all energy sources, those with lower total investment costs (either due to limited deployment potential or inherently low investment costs) could reach their minimum required investment (i.e., zero) before utilizing their entire allocated share. In such cases, any remaining funds would go unused, reducing the overall efficiency of the redistribution mechanism. In both the sensitivity analysis and the tax rate analysis, there is always a significant investment in hydro and wind energy. Therefore, the allocation will follow the specified distribution.

The amount **collected** during a phase will be available at the end of that phase. The first collection of the carbon tax takes place during the 2020 to 2025 phase and the **subsidy** begins in the 2025 to 2030 phase.



**Figure 4.20: Scheme of the implementation of the collection mechanism and subsidies for renewable energies**

Regarding GEMMES, Pierre Jacques had previously incorporated the carbon tax by only subtracting the portion associated with firms from the unit price. It was not explicitly present in the cost and revenue equations of the different sectors. This approach was acceptable because all the money paid was redistributed in the same proportions to those who paid it, whether firms, households, banks, or the government, allowing these terms to be omitted. The fundamental assumption now is that subsidies will be allocated to the firm sector, as the energy sector primarily consists of private companies. If the proportion of subsidies given to firms is not exactly equal, either smaller or larger, than the carbon tax collected, the difference in funds will come from the government in the form of a tax collection deficit. The previous version redistributed part of the collected money to banks, households and the government because they had also paid the tax, but this will no longer be the case here.

<sup>1</sup>Geothermal energy is excluded from redistribution due to its negligible contribution relative to other renewable energy sources.

In order to facilitate future work, redistribution has been implemented more generally in the coupling and GEMMES. Instead of directly redistributing solely to firms, four new variables have been created to redistribute to the four sectors: subsidies to firms, households, banks and government, respectively, denoted as  $rct_F$ ,  $rct_H$ ,  $rct_B$  and  $rct_G$ . This will also allow us to implement the case of household distribution more easily (section 4.4).

These variables will appear in various GEMMES equations. For banks and firms, the same approach is followed. The gross operating surplus is reduced by the carbon tax and the total financing needs are reduced by the subsidy allocated. Regarding households, household income is decreased by the carbon tax paid by households but increased by the subsidy granted to them. This will, of course, affect other variables accordingly. The modified GEMMES equations are in the Appendix C.

The choice of subsidies is arbitrary and is based on the revenues generated by the tax or independently. The following cases are studied:

- Constant subsidies
- Subsidies proportional to the carbon tax income

#### 4.3.2 Constant subsidies

Constant subsidies of: 0, 5, 10 and 15 GUSD<sub>2021</sub> (billions) correspond to 0, 18.73, 37.46 and 56.19 TCOP<sub>2021</sub><sup>1</sup>, respectively are considered.

From an energy systems perspective, no significant differences are observed between the scenarios. The variations in energy related outcomes are minimal, if not negligible. This is primarily because the total investment cost for technology, denoted as  $C_{inv}(\text{tech})$ , is reduced due to subsidies. However, this differs from a reduction in the technology specific investment cost,  $c_{inv}(\text{tech})$ , which represents the cost per gigawatt of installed capacity.

Across all scenarios, emission trajectories, energy systems configurations and all other related aspects in EnergyScope remain unchanged. The only variation lies in the total system costs, which decrease as subsidies increase, due to lower effective investment expenditures. The Figure 4.21a shows clearly that the ratio between tax expenditures and tax revenues remains constant, adjusted by a factor. Since the energy system remains unchanged, carbon prices remain the same and only the subsidies amounts vary.

From an economic modeling standpoint, particularly in the context of EnergyScope providing inputs to GEMMES, the investment costs are not directly reduced by the subsidies. Instead, the subsidies are applied to these costs, which is explicitly accounted for in the model formulation. Therefore, the total energy investment costs in GEMMES remain unchanged, as the subsidies do not diminish the actual investment amounts, they merely offset them. This distinction is crucial and is clearly reflected in the corresponding equations (Appendix C).

Expanding further on the economic dimension : total energy investments remain constant, as do the imports of energy and overall imports. Inflation is also consistent across all scenarios, as the carbon tax impacts unit costs uniformly. The primary differences are observed in the behavior and relationships between the government and non-financial cor-

<sup>1</sup>Amounts in constant 2021 US dollars (USD<sub>2021</sub>) were converted to constant 2021 Colombian Pesos (COP<sub>2021</sub>) using the average annual exchange rate for 2021, which was 1 USD = 3 745.94 COP, according to [Exc21]

porations (NFCs). The general dynamic is that when subsidies increase, the funding comes not only from the carbon tax but also from the government, if the carbon tax is insufficient. Larger subsidies therefore result in reduced government revenue but increased funds for energy firms (and firms in general). This is evident in Figure 4.21c and Figure 4.21d, where higher subsidies lead to more funds for firms. As firms receive more money, their investments increase (Figure 4.21e) and unemployment (Figure 4.21f) decreases with higher subsidies. Finally, GDP growth (Figure 4.21b) and GDP levels remain consistently higher with greater subsidies, due to the economic stimulus they generate. However, their impact diminishes over time as the economy gradually adapts to the policy. Nevertheless, the difference in GDP growth between the scenario without subsidies and the one with 15 GUSD in subsidies (the two extremes) remains below 0.1%, indicating a relatively limited overall effect.

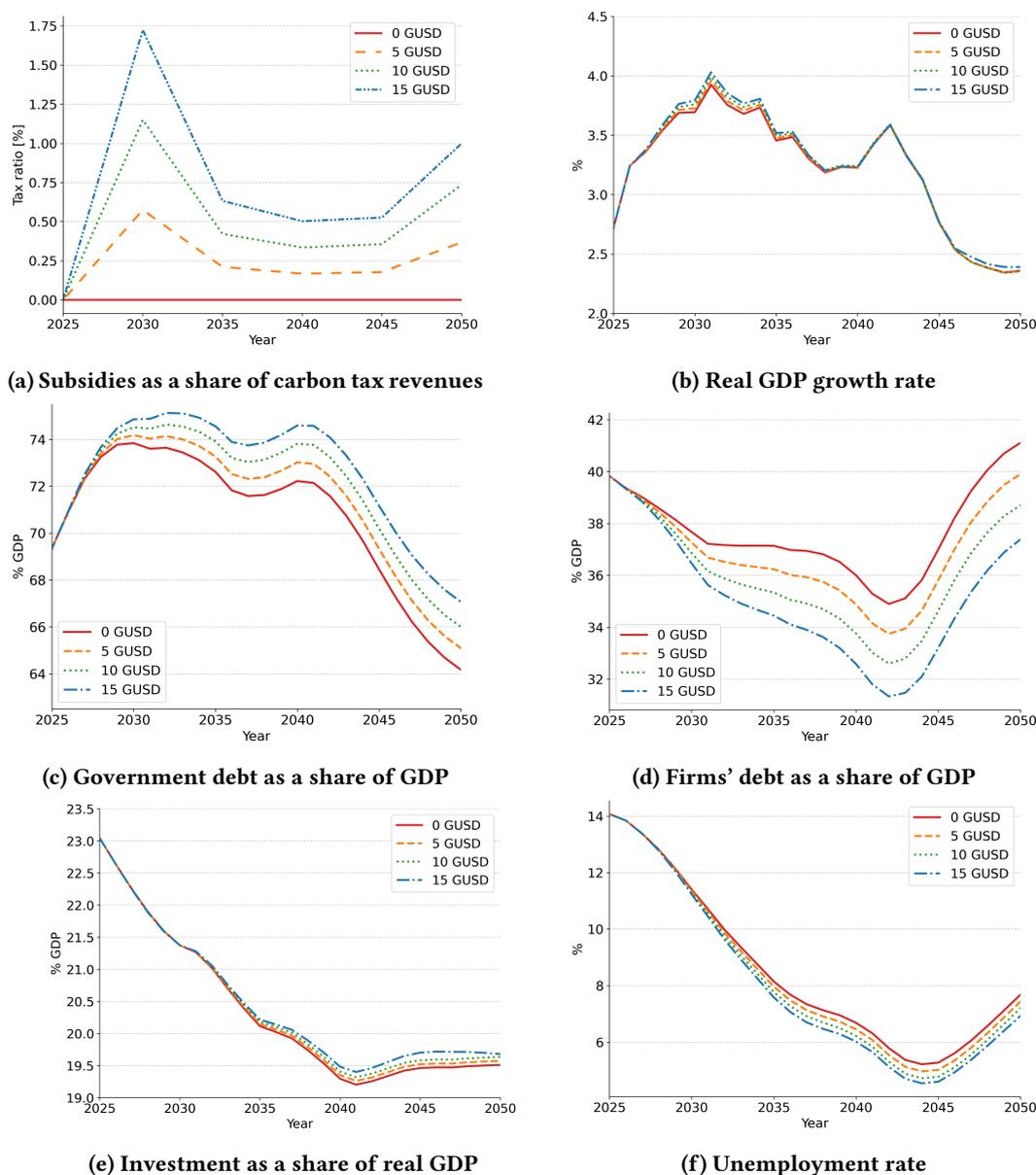


Figure 4.21: Macroeconomic dynamics of the four scenarios of constant subsidies

The question is: *can the government's debt be increased indefinitely to derive general benefits for the economy?*

Clearly, this is not a viable long-term approach. While the government can support subsidies through debt to some extent, excessive debt levels may necessitate higher interest rates to maintain fiscal credibility. Furthermore, if the additional debt is not matched by sufficient gains from firms, inflationary pressures are likely to arise.

Although moderate, debt financed subsidies can generate macroeconomic benefits, relying on increasing public debt indefinitely is not a sustainable strategy. In the specific case of Colombia, recent economic developments highlight this risk: in 2023, interest rates had to be raised to contain inflation. Such experiences underscore the importance of maintaining fiscal prudence.

### 4.3.3 Subsidies proportional to the carbon tax income

The baseline scenario corresponds to the case where no subsidies are applied. The cases labeled as  $\times 0.25$ ,  $\times 0.5$ ,  $\times 0.75$  and  $\times 1$  represent the multiplication factors applied to the carbon tax revenues.

In the context of the energy transition, emissions are expected to peak around 2030, followed by a quasi-steady decline to net-zero by 2050. Since revenues are directly linked to emissions through the *GWP cost factor*, they will increase until peaking between 2035 and 2040, before gradually decreasing to near-zero levels (Figure 4.24).

It is anticipated that the overall system behavior will remain similar to the case of constant subsidies. From an energy perspective, the differences are still negligible. However, as previously observed (subsection 4.3.2), some variations in the total cost of the energy system are still occurring, just because the total costs is reduced by subsidies. These changes are expected to be mainly economic.

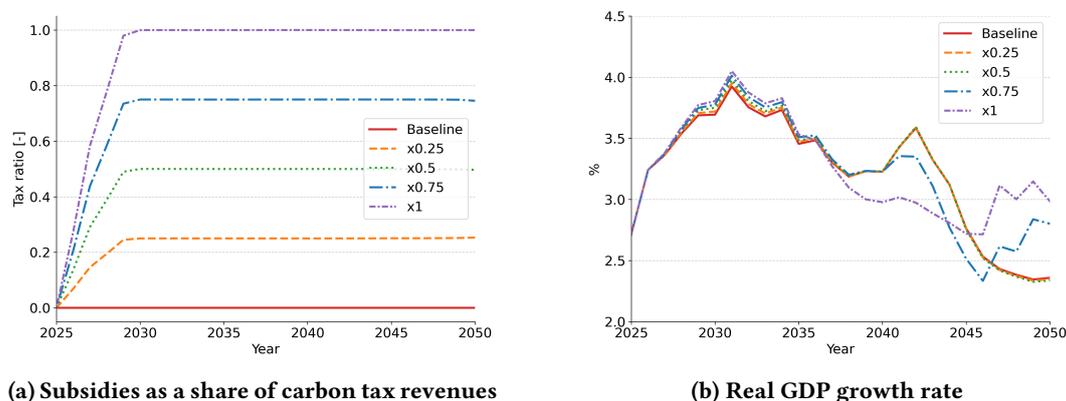
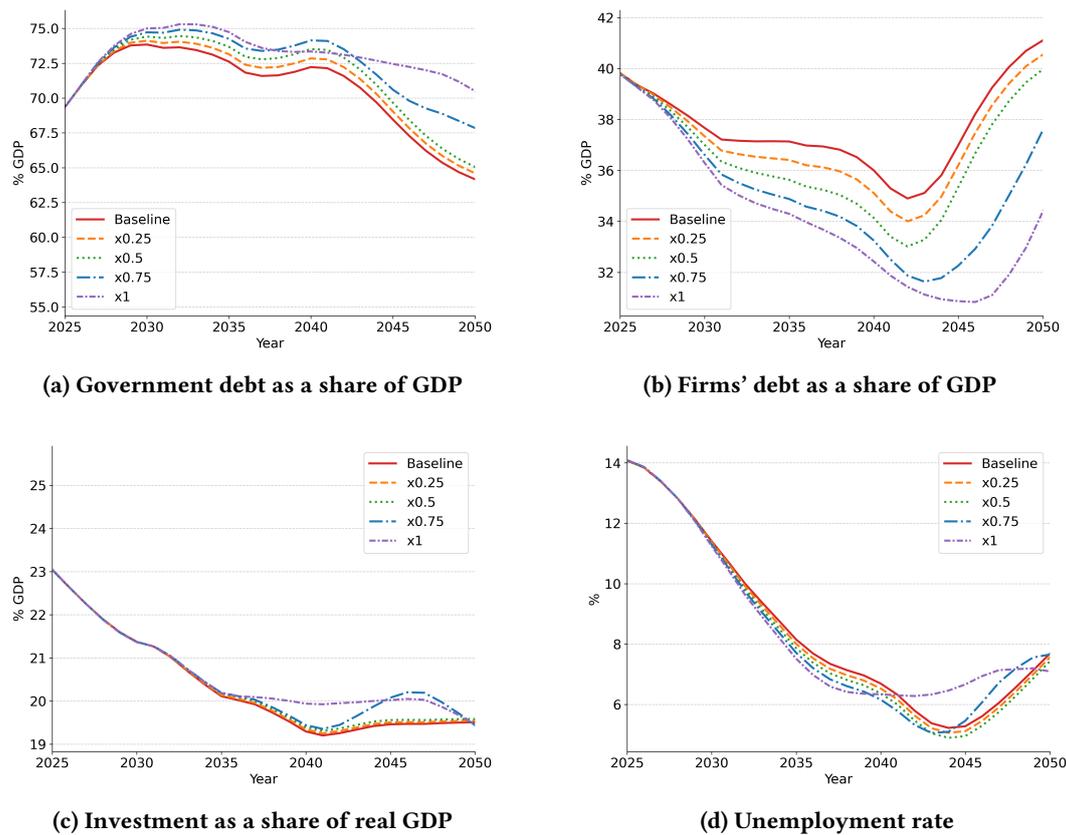
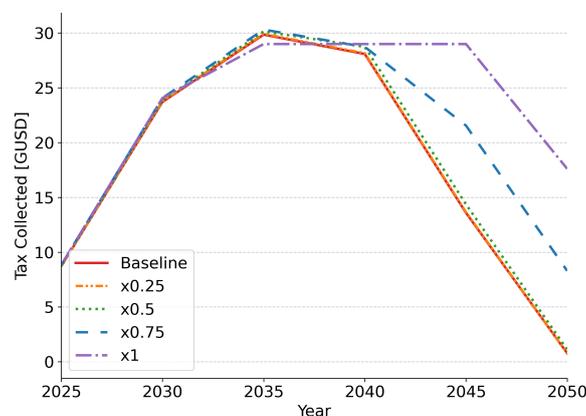


Figure 4.22: Macroeconomic dynamics of the four scenarios of proportional subsidies to the carbon tax income (1/2)



**Figure 4.23: Macroeconomic dynamics of the four scenarios of proportionnal subsidies to the carbon tax income (2/2)**

The results (Figure 4.23) confirm that the system’s general behavior remains consistent with previous findings. However, certain anomalies appear at subsidy levels of 0.75 and 1.0 (Figure 4.24). These irregularities arise from limitations within the EnergyScope model, where high subsidy levels can lead to unrealistically low investment costs. Consequently, investigating higher carbon revenue multiplication factors using the coupled models becomes less meaningful under these modeling constraints. However, when focusing solely on the GEMMES model, thus bypassing the limitations of EnergyScope, the deviations from the baseline scenario become more significant.



**Figure 4.24: Tax collected for subsidies proportional to the carbon tax income**

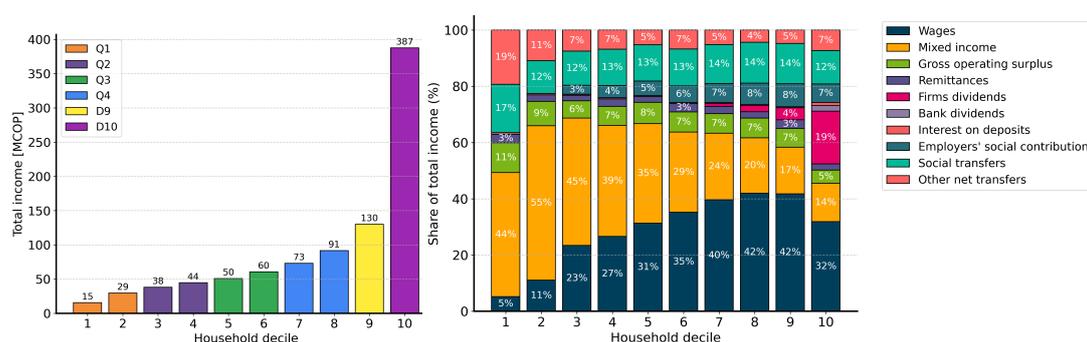
## 4.4 Redistribution to Households Scenario

People with a lower income tend to spend a larger fraction of their income on electricity, heating and public transportation. By extension, these are the main emitting sectors, which means that a larger portion of their income is taxed by the carbon tax [Mar24]. It has also been proven that they are the most vulnerable to climate change while emitting the least emissions globally. Therefore, it is important to analyze not just households as a whole, but differentiated by income level, in order to get an overview of the impact of the transition on them and to implement mitigation mechanisms. Considering households separately is a feature typical of microeconomic models such as the MSM model used in Romero's article [Rom+18] but here, this approach is effectively integrated into a macroeconomic framework. This section will examine various types of redistribution shares across different household categories.

### 4.4.1 Model

The revenue generated from the carbon tax will be redistributed to households, which are categorized into six groups based on their total income. This total income includes wages, mixed income<sup>1</sup>, remittances, firms and bank dividends, interest on deposits, employer social contributions, social transfers and other net transfers. The categories of households are defined as follows: Q1, Q2, Q3 and Q4 represent the first four quintiles of total income and D9 and D10 the last two deciles, meaning the population is divided into six income groups, with Q1 corresponding to the poorest 20% of households, Q2 to the next 20% and so on up to Q4. The D9 and D10 categories, by contrast, represent the top 10% of households, divided into two distinct subgroups.

The original data ([Dep24a; Dep24b]) was structured by deciles, representing ten distinct household income groups. For this analysis, the first eight deciles were grouped in pairs (i.e., D1–D2, D3–D4, etc.) due to their high similarity in both total income levels (Figure 4.25) and income composition (Figure 4.26). Consequently, retaining all ten individual categories was not necessary. In contrast, the ninth and tenth deciles displayed markedly different income profiles, warranting their separate treatment. This classification enables a more targeted redistribution strategy, particularly aimed at mitigating the regressive effects of the carbon tax on lower-income households.



**Figure 4.25: Total income by decile, with the grouping of deciles into quintile highlighted** **Figure 4.26: Share of total income based on income categories for each income decile**

<sup>1</sup>Mixed income refers to the combined earnings from both labor and capital for self-employed individuals or unincorporated businesses.

The required implementation consists of disaggregating households in GEMMES. This modification is not limited to the case of the carbon tax but more broadly allows for the simulation of new economic scenarios that take different social groups into account in greater detail, which could benefit the AFD. Jhan Jhailer, from AFD, has already performed the household disaggregation in GEMMES, but it has not yet been integrated into the coupling. In this master's thesis, this disaggregation will be implemented in the GEMMES version used for the coupling (which differs slightly from the standard version) as well as in the coupling itself. One of the major changes is the sixfold increase in the number of household related variables. For instance, each household category will have its own variable for disposable income and its evolution over time. The same will apply to savings, investment, taxes, income and so on. To properly calibrate the model, it is essential to have accurate data from 2019. For this purpose, Jhan Jhailer relies on official data from the Colombian government obtained through surveys [Dep24a; Dep24b].

Moreover, the distribution of the carbon tax revenues among households still needs to be implemented, as well as the allocation of costs from EnergyScope to GEMMES (CAPEX and OPEX). To achieve this, the same Colombian government survey data [Dep24a; Dep24b] will be used alongside several assumptions to establish a detailed allocation. The resulting distributions are presented in Appendix D.

The model with and without household disaggregation initiates from the same baseline in 2019, confirming the accuracy of the calibration data. While the general trends align, some discrepancies are observed originating from the differentiation of household behaviors. Further refinement of the GEMMES calibration would be advantageous in future analyses, though the current approach will be retained for the present study.

For simplicity, a redistribution of a constant amount is considered, with a sufficiently high value to observe significant effects: 15 TCOP, equivalent to 3.53 GUSD (billions). This amount is greater than the carbon tax collected, therefore the additional funding is provided by the government.

#### 4.4.2 Cases

Different cases will be studied. The baseline HD (household disaggregation) refers to the case where the GEMMES model with disaggregation is used with a carbon tax, but without any redistribution. The first, the simplest, assumes that the money is redistributed equally. This case is similar to what has already been simulated. The second case is based on the hypothesis that lower-income households are the most impacted, so the redistribution will be exclusively directed to Q1 to counterbalance the negative effects.

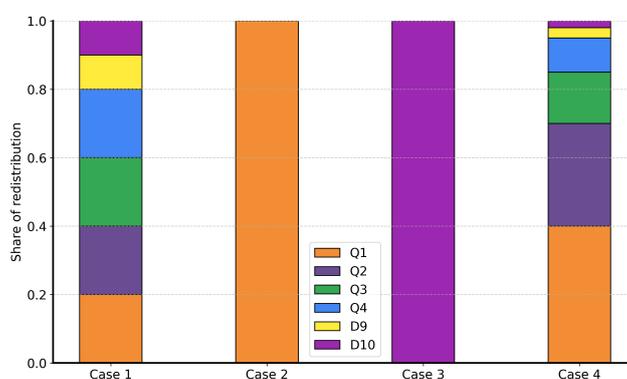


Figure 4.27: Case presentation: Distribution of redistribution across household categories

To study the opposite behavior and assess whether the situation deteriorates, a simulation will also be carried out in which all the money is allocated to the wealthiest (D10). Finally, a progressive case with an increasing share of tax revenue distributed to lower incomes will be examined. All the cases <sup>1</sup> are represented on Figure 4.27 (preceding page).

### 4.4.3 Analysis

#### 4.4.3.1 Macroeconomic effects

The analysis first focuses on macroeconomic results, although this is not where inequalities are most evident. The EnergyScope outcomes remain unchanged, indicating that energy investments are similar across scenarios (as in the case with subsidies). The main difference arises from changes in households' disposable income (Figure 4.28e). Higher income levels lead to increased demand, thereby stimulating economic activity. This effect is visible through the lower unemployment rates observed in the redistribution scenarios (Figure 4.28c). The currency depreciates more under redistribution, as higher demand drives up imports (Figure 4.28a). This results in greater demand for foreign currencies to finance these imports, leading to a depreciation of the national currency. Inflation remains largely unchanged across all scenarios. Government debt increases in the redistribution cases, as the redistributed funds come from both carbon tax revenues and additional government resources (Figure 4.28d). The D10 scenario exhibits slight deviations from the others, which can be attributed to a higher total level of household disposable income in this case. This results from a redistribution strategy that favors wealthier households, who tend to have a greater economic effect. Overall, only minor differences appear across the different redistribution cases, as the total disposable income of households remains similar in each scenario.

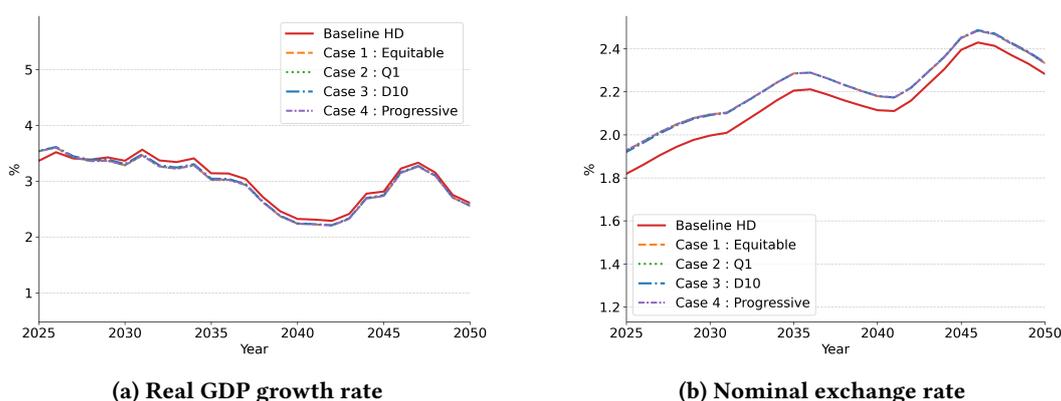


Figure 4.28: Macroeconomic dynamics of the five cases of households redistribution (1/2)

<sup>1</sup>Q1, Q2, Q3 and Q4 each represent 20% of households, while D9 and D10 represent only 10% each. If the same total amount is redistributed to each group, households in D9 and D10 would receive twice as much per household. This is why, in the first scenario, D9 and D10 appear to receive half as much, reflecting an adjustment for group size.

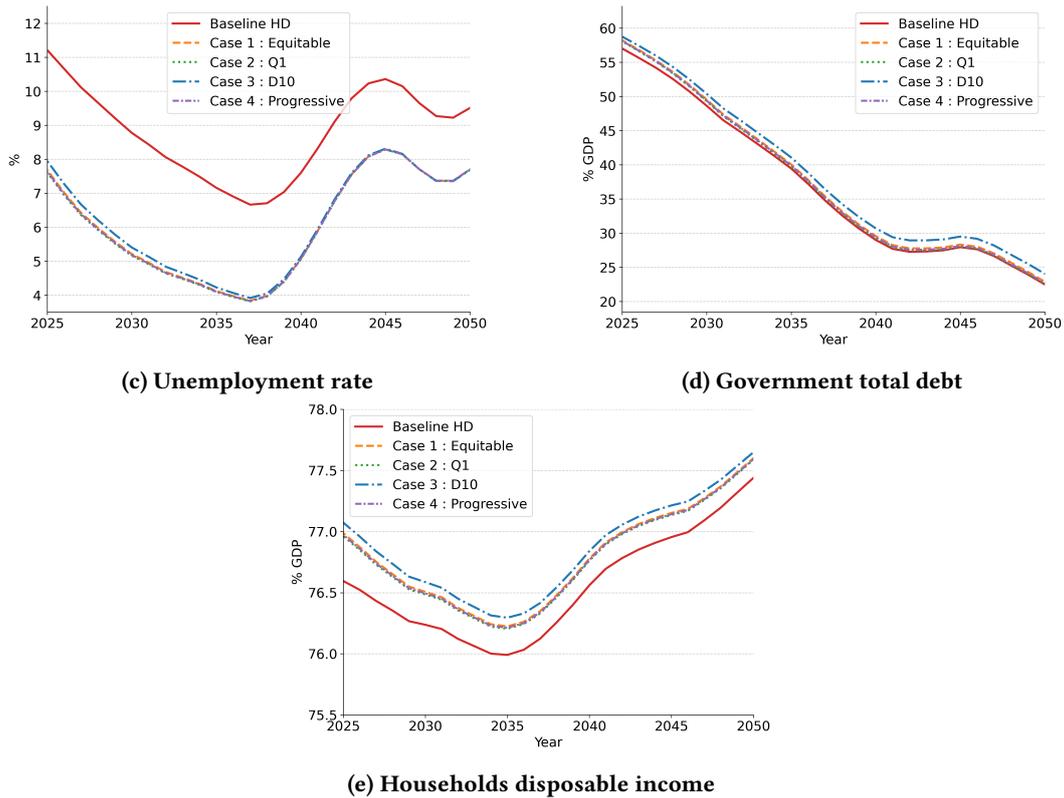
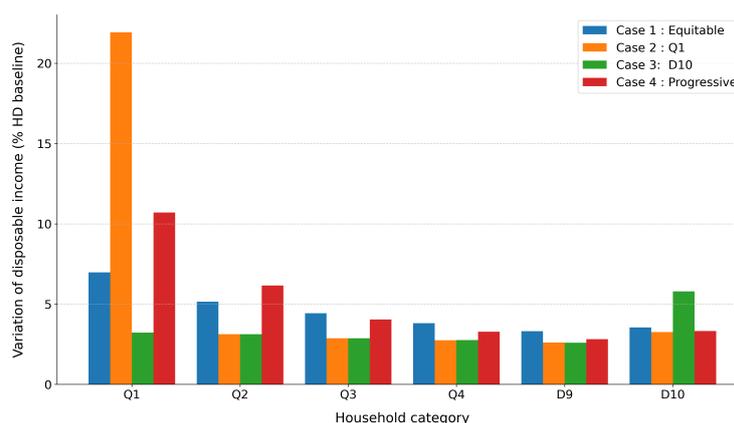


Figure 4.28: Macroeconomic dynamics of the five cases of households redistribution (2/2)

#### 4.4.3.2 Households effects

Focusing on the behavior of each household reveals shifts in income, which in turn influence savings and investments. By analyzing the temporal variation from 2025 to 2050, a marked increase in the disposable income for Q1 is observed in Case 2, where full redistribution is applied to the household. In case 4, the progressive redistribution scenario, the variation decreases as wealthier households are reached, since progressively less money is redistributed, bringing it closer to the baseline scenario with no redistribution. Redistribution applied equally still results in higher variations for the poorest households. This is due to the lower disposable income of these households, meaning that a constant subsidy proportionally increases their income more significantly compared to wealthier households, where the impact is much smaller. This trend is evident, as case 3 represents total redistribution for D10, yielding a 5.79% variation, while case 2 represents total redistribution for Q1, with a 21.93% variation. Finally, categories Q2, Q3, Q4 and D9 experience greater variations in cases 1 and 4, as these are the only scenarios incorporating redistribution for these household categories. Although these households do not receive direct transfers in Cases 2 and 3, their disposable income is still slightly higher than in the baseline scenario. This outcome is driven by macroeconomic effects, as the overall economy experiences a stimulus.



**Figure 4.29: Variation in disposable income (mean between 2025 and 2050) compared to the baseline HD (household disaggregation), for different cases grouped by household categories**

Investments and savings are closely linked to household disposable income, investment decisions primarily depend on disposable income, while savings are determined as the residual between disposable income and consumption. The effects of redistribution policies on these variables are generally modest, with variations of less than 5% relative to the Baseline HD scenario across most households. However, the first income quintile (Q1) stands out as an exception. In this group, redistribution leads to significantly higher investment and saving rates. Specifically, average investment levels for Q1 increase by +22.54% under Case 2 (Q1 redistribution), compared to +7.16% in Case 1 (Equitable), +11.01% in Case 4 (Progressive) and only +3.30% in Case 3 (D10), increased related with amount redistributed to Q1. Similarly, savings for Q1 rise by +27.88% in Case 2, compared to +7.45%, +12.54% and +2.45% in the other respective scenarios. This pronounced effect can be attributed to the initially low disposable income of Q1 households, which restricts their consumption and consequently limits both their investment and saving capacities. Redistribution effectively alleviates this constraint, allowing for substantial increases in both variables.

#### 4.4.3.3 Inequality

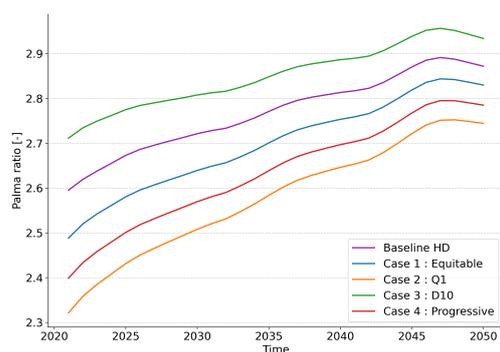
Several metrics are available to quantify income inequality, this study concentrates on two widely-used measures: the Palma ratio and the Gini index. The Palma ratio allows us to assess inequality by dividing the income share of the richest 10% (D10) by that of the poorest 40% (Q1 and Q2). On the other hand, the Gini index<sup>1</sup> captures how far the Lorenz curve deviates from the "line of equality", with the Lorenz curve representing the cumulative share of income by the population. The Palma ratio emphasizes disparities at the extremes of the income distribution, while the Gini index provides a more general overview of inequality.

In 2023, Colombia exhibited one of the highest levels of income inequality globally, with a Palma ratio of 18.2 and a Gini index of 0.515 [Dat24]. By contrast, in all the scenarios presented in Figure 4.30, the simulated Palma ratios range from 2 to 3, while the Gini index values fall between 0.30 and 0.35. These values appear relatively low compared to those reported in other datasets. A report by AFD [Mon+22] also reported relatively low figures, with a Palma ratio of 4.2 in 2020 (see detailed data in Appendix F), though the Gini index reached 0.54, closer to external sources like "Our World in Data". These

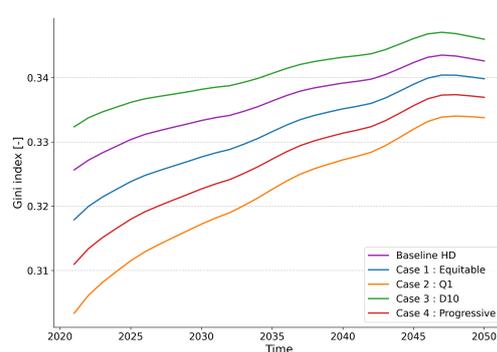
<sup>1</sup>The Gini index ranges from 0 (perfect equality) to 1 (maximum inequality).

discrepancies may be attributed to methodological differences, particularly regarding the use of pre-tax versus post-tax income, as well as the precision and scope of the underlying data. Additionally, it is important to note that the data used in this study are derived from official government sources, which primarily cover formal employment. Given Colombia's high level of informal labor, this likely results in an underestimation of income inequality and may partially explain the deviation from other reported figures.

As shown on Figure 4.30 and Figure 4.31, all cases improve inequalities compared to the case without redistribution (Baseline HD), except for D10. D10 exacerbates inequalities because it increases the income of the D10 group, richer group. The best case is when the redistribution is fully allocated to Q1, followed by the progressive case and finally the equitable case.



**Figure 4.30: Evolution of the Palma ratio of different redistribution households cases**



**Figure 4.31: Evolution of the Gini index of different redistribution households cases**

Inequalities increase over time, but the difference between the cases decreases because the higher the Palma ratio and Gini index initially, the smaller the increase will be. The higher-income households have much greater growth (in Appendix E evolution over time of disposable income by households) than the lower-income households because they can invest more and have savings; this is a well-known phenomenon:

*"The rich get richer and the poor get poorer."* from Percy Bysshe Shelley in A Defence of Poetry [She21]

The findings in "Climate Change Policies and Income Inequality" [Bet+24] similarly show an increase in income inequality following the implementation of climate change policies, with short-term impacts assessed using measures such as the Palma ratio and the Gini index after a policy induced climate shock.

#### 4.4.3.4 Final reflections

If the only criterion were to reduce inequality, the optimal strategy would be to redistribute exclusively to the poorest households. However, this raises important questions of fairness. Why should support be cut off abruptly for a household just above the eligibility threshold. For example, at the 21st percentile while the bottom 20 percent receive benefits? The boundary of fairness is ambiguous and open to interpretation.

In particular, public acceptance of redistributive policies depends not only on their outcomes but also on how they are implemented. As McCaffery and Baron [MB05] highlight, factors such as tax transparency and the visibility of public goods influence support. These insights are also relevant for all types of redistribution, as renewable energies investments.

In this regard, a progressive redistribution scheme appears to be a reasonable compromise, since all households receive support just not the same amount. Nevertheless, its legitimacy relies on how progressivity is structured, potentially through a weighting system linked to income levels.

There is no clear public consensus in favor of either a flat or a progressive tax system. Although the current discussion focuses on redistribution, most empirical studies examine taxation, as it is more common to levy taxes than to redistribute directly; yet, the two remain closely intertwined. In the study by Roberts [RH94], three distinct groups are identified: those who support strong progressivity, those who prefer moderate progressivity and those in favor of a flat tax rate. Despite these differences, progressivity remains broadly accepted by the public [RH94; Tar20], provided it is implemented transparently. However, many citizens note that even within a progressive system, wealthier taxpayers often manage to circumvent the rules, through loopholes or tax evasion which fuels a perception of unfairness.

It is essential to acknowledge that no definitive solution has been established to guarantee a reduction in inequalities or even to ensure that they do not worsen over time. Additional strategies such as social expenditure and tax progressivity can be implemented, though the latter tends to be less effective due to behavioral responses [DP14]. Reducing inequalities remains a key challenge in the design of fair and effective redistribution mechanisms.

This research provided further insights into the energy, economic and social related behaviors associated with a carbon tax in Colombia. The complexity of the issue is apparent, as it involve multidisciplinary component all interconnected, not to mention the political dynamics that may arise and alter the landscape at both the local and global levels.

## 5.1 Summary

After refining certain parameters and making some adjustments to the coupling, three distinct aspects of a carbon tax in Colombia have been implemented in this master's thesis: tax rates, subsidies for renewable resources and redistribution to households. This leads to the following conclusions:

The general pattern of an energy transition shows that the higher the carbon tax, the faster the shift toward renewable energy sources. Emissions are primarily driven by fossil fuel use, particularly liquid fossil fuels (LFO). However, such accelerated transitions come at the cost of higher cumulative transition costs. Macroeconomic dynamics are largely influenced by the carbon tax level and the massive energy investments. A two-phase trajectory emerges: initially, GDP growth rate rises due to investment-led stimulus, followed by a contraction phase as the economy adjusts to structural changes.

The exploration of tax rate levels and their trajectories highlights that, from an emissions standpoint, rapid action (*Sigmoid Quick*) is preferable. Yet, this approach results in severe economic shocks and a significantly higher total cost of transition. On the other hand, delayed action (*Sigmoid Late*) tends to better preserve economic stability, but delays climate benefits and leads to much higher cumulative emissions. A *Linear* path offers a balanced compromise without clear dominance in either climate or economic outcomes.

A carbon tax set at 50% of the baseline rate fails to complete the transition in all scenarios. The higher the tax rate, the faster the transition but also the stronger the economic impacts. Ultimately, applying the SOS (Safe Operational Space) framework revealed that none of the transition scenarios met the established macroeconomic stability thresholds. To prevent destabilizing outcomes, transition policies must be accompanied by well-designed economic adjustment mechanisms.

The second aspect examined concerns subsidies: whether implemented as proportional or constant transfers, they yield similar results. There is no significant impact on the energy transition itself, but at the macroeconomic level, the subsidies introduce a redistribution dynamic between the government and firms: higher subsidies shift more funds toward firms, stimulating investment and slightly boosting GDP growth, albeit with a marginal rise in unemployment. Importantly, subsidies financed through government spending increase public debt, particularly when they exceed tax revenues. While such debt-financed measures can support short-term economic activity, they are not a sustainable long-term strategy. Excessive public borrowing risks undermining fiscal stability and triggering in-

flationary pressures, as illustrated by Colombia's recent monetary tightening to counter rising inflation. Nevertheless, in all modeled scenarios, public debt ultimately trends downward by 2050, suggesting that moderate use of subsidies may be fiscally manageable within a carefully designed policy framework.

Finally, from a social perspective, the overall macroeconomic behavior differs between a case with no redistribution and redistribution between households, but not between the different social redistribution cases. This is due to the cumulative variables of households being very similar between the redistribution cases, with changes occurring at the level of different households. Our results show that targeted redistribution to the poorest households (Q1) not only produces the greatest relative gains in disposable income but also yields the most substantial reduction in inequality, as measured by the Palma ratio and Gini index. Progressive redistribution also improves equity, particularly for lower-middle-income groups, while equal redistribution offers more modest benefits. Conversely, scenarios favoring high-income households (D10) exacerbate disparities, underlining the importance of redistribution design. Despite improvements, structural inequalities persist and tend to grow over time, driven by the disproportionate capacity of wealthier households to accumulate savings and capital. These findings emphasize that without carefully designed fiscal policies, the transition to a sustainable economy risks reinforcing existing socio-economic divides. Integrating equity considerations into climate policy is therefore essential to ensure both environmental and social sustainability.

## 5.2 Research perspectives

This work closes with suggestions for future research directions, beginning with a part on improvements of the models and tools employed<sup>1</sup>, followed by a discussion on potential avenues for extending this work.

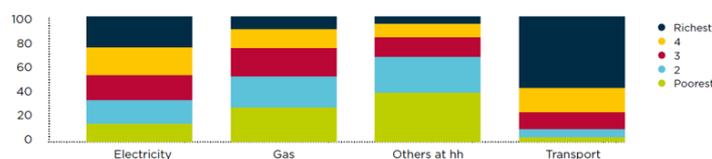
- A first general remark on the implementation of the coupling is that it is not user-friendly. It does not work on Windows without major modifications and if the daily time resolution version of EnergyScope is used, it takes several hours while monopolizing computer system resources. Additionally, complexity has been added by using Python, C and R, whereas standardizing everything into a single language could have removed a layer of complexity, even if it would have required more time to implement. Given that this coupling is intended for modeling trajectories for the Colombian government, this level of complexity requires users who are sufficiently trained, with knowledge in economics, energy and coding. Moreover, no documentation has been created on how it functions, which is unfortunate, as such a code was developed but not made accessible.
- In the coupling, the influence of energy transition prices on energy demand is currently underrepresented, as there is no feedback mechanism from prices to consumption. This limitation could be addressed by incorporating demand elasticity functions to better reflect how consumers adjust their behavior in response to price changes.
- Also, the propagation of energy costs through general price levels is not fully captured, limiting the ability to assess inflationary effects and feedbacks on real income

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<sup>1</sup>A small aside: improvements can always be made to models because a model is only a representation of reality. There will always be a desire to improve it in order to better approximate reality. However, it is important not to forget that models are also used for computational efficiency. Therefore, specific elements should only be included when their added value has been carefully evaluated in advance.

and investment. In addition, the current structure of GEMMES treats energy costs as distributed across all sectors, rather than modeling energy producing firms as a distinct category. Introducing a dedicated sector for energy firms would allow for a more realistic representation of pricing mechanisms, investment decisions and profit dynamics within the energy sector.

- Although now that GEMMES now includes disaggregated household types, it is also possible to disaggregate EnergyScope. The following graph, Figure 5.1, shows the energy-related expenditures in Colombia, broken down by household income quintile<sup>1</sup>. It is very noticeable that the composition varies significantly depending on wealth. This would strengthen the segmentation, as assumptions about energy distribution had to be made.



**Figure 5.1: Distribution of household energy-related expenditures by income quintile, at the national level [MY20]**

- If more interest is given to the data, it would be important to find data on transportation because, as explained in the section 3.1, the transportation data is from Belgium, which is absolutely not comparable.

Focusing on the tracks related to carbon taxation in Colombia, it will be possible to further investigate tax rates, with a greater emphasis on mitigating policies, as this is the main point of improvement as well as subsidies and household impacts.

- The conclusion regarding tax rates is that, in all cases, they do not adhere to the SOS and therefore, it would be necessary to use either monetary tools or fiscal policies to reduce the impact. It would be interesting to explore other options, such as an energy price cap as a fiscal policy or the implementation of measures by the central bank to help maintain economic stability within the SOS.
- As highlighted in the study, subsidies in renewable energy are beneficial for the economy but increase public debt. Exploring mechanisms that help contain debt levels while also identifying what the acceptable limits for debt are, can support the design of more feasible carbon tax. One possible option is to consider financing subsidies through international donors or by leveraging loans with lower interest rates, rather than relying exclusively on government resources.
- For households, since the model has just been implemented, it should continue to be calibrated with more data. Currently, the model with and without households does not give exactly the same values. Moreover, the dynamics of the Palma ratio, which tends to increase over time in the scenarios studied, deserves particular attention: it would be useful to identify corrective mechanisms to contain or reduce inter-quintile inequalities. Finally, better integration of the households with the other components of the model could allow for a more accurate capture of the full distributive effects of carbon taxation and anticipate more realistic adjustment policies. As mentioned earlier, disaggregation in EnergyScope would provide even more possibilities.

<sup>1</sup>"Others at hh" refers to other types of energy expenditures of the household



# **Appendix**



# Sigmoid Quick Action

## A

The results, energetic and macroeconomic are showed in this section for the specific scenario : Sigmoid Quick Action.

### A.1 Energy

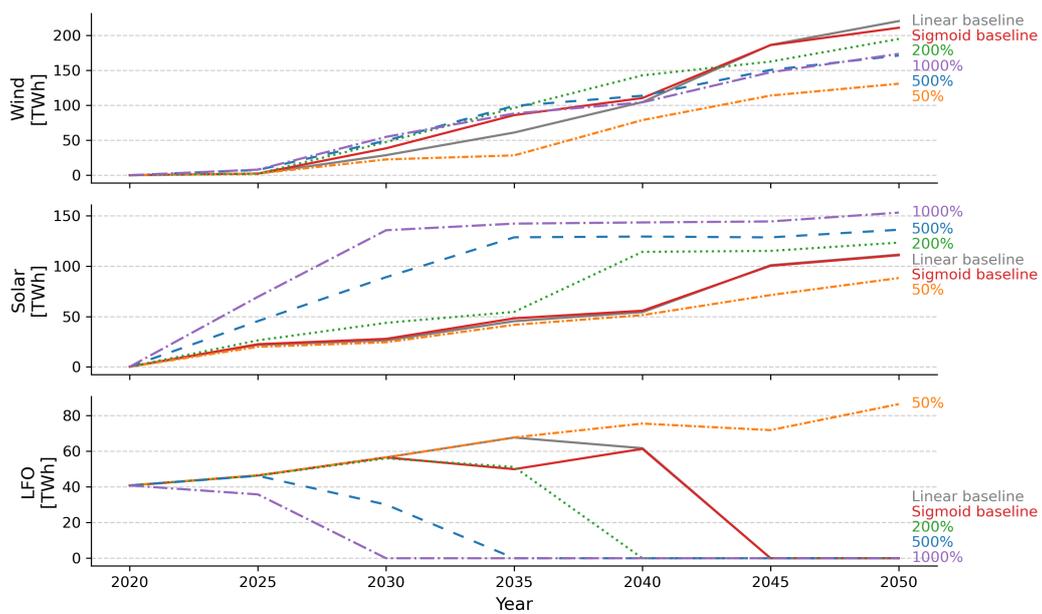
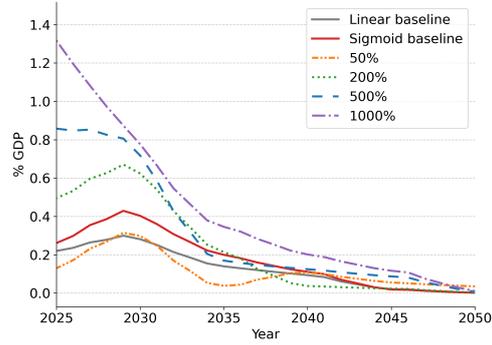
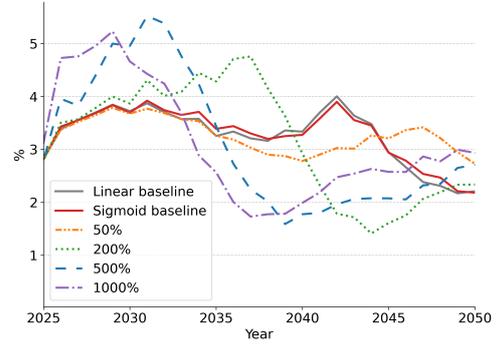


Figure A.1: Evolution of energy consumption: Wind, solar and LFO with varying cases of tax rates quick action case

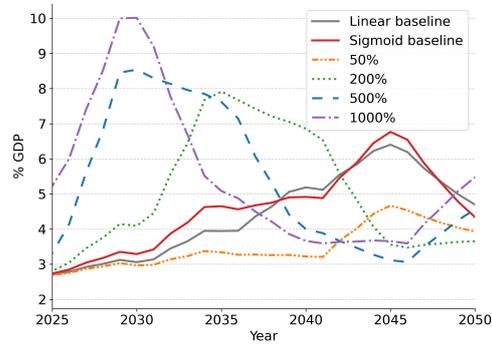
**A.2 Macroeconomic effects**



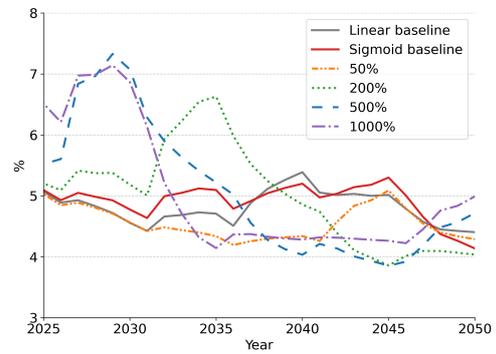
**(a) Carbon tax as a share of GDP**



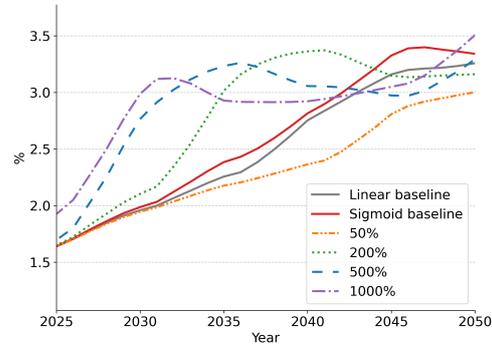
**(b) Real GDP growth rate**



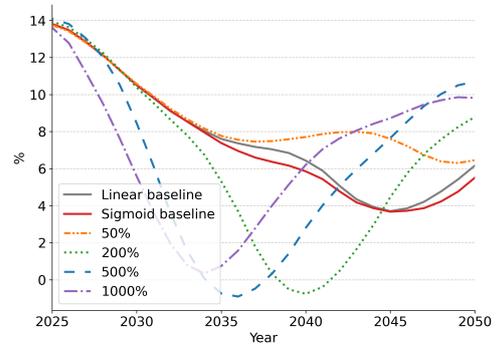
**(c) Total energy investment as a share of GDP**



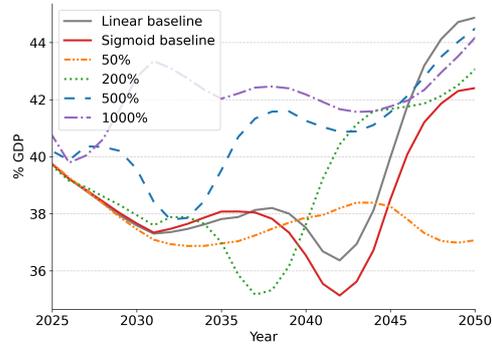
**(d) Consumer inflation rate**



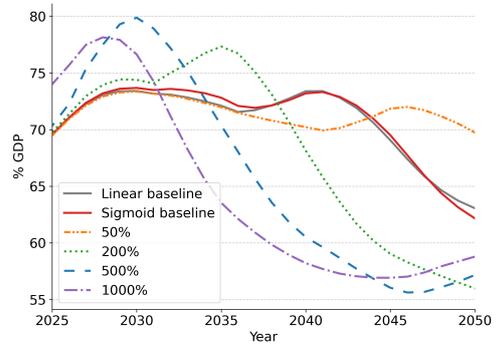
**(e) Nominal exchange rate**



**(f) Unemployment rate**



**(g) NFCs total debt**



**(h) Government total debt**

**Figure A.2: Macroeconomic dynamics of the four scenarios of sigmoid quick action tax rates**

# Safe Operating Space of Colombia Economy

B

Variable	Lower Bound	Higher Bound
Per-Capita GDP Growth (%)	0	0.2
Inflation (%)	1	4.0
Reserve Ratio (%GDP)	0	18.0
Foreign Debt (%GDP)	0	40.0
Private Debt (%GDP)	0	90.0
Public Debt (%GDP)	0	63.0
Fiscal Deficit (%GDP)	0	3.5
Households Fragility Index <sup>a</sup> (%)	0	45.0
Firm Fragility Index <sup>b</sup> (%)	0	26.0
Unemployment <sup>c</sup> (%)	-1	12.0
Current Account Deficit (%)	0	5.0

Table B.1: Safe Operating Space (SOS) of Colombia economy



# Redistribution to Renewable Energies Equations



## C.1 EnergyScope

New variables have been created in EnergyScope. First, in the files for initializing a case "PES\_Dat\_related\_...", a variable *sub\_ren* has been added. This variable defines the subsidy that will be granted every 5 years.

Next, in the EnergyScope model, *tax\_spent* and *tax\_collect* have been added. *tax\_spent* is set to the value of *sub\_ren*. This *tax\_spent* variable is redundant in this case, but if the subsidy is not fixed in the case file, it will be useful.

$$\text{tax\_collect}_{\text{collect}} = t_{\text{phase}} \times \frac{\left( \text{TotalGWP}_{y_{\text{start}}} \times \text{gwp\_cost}_{y_{\text{start}}} + \text{TotalGWP}_{y_{\text{stop}}} \times \text{gwp\_cost}_{y_{\text{stop}}} \right)}{2} \quad (\text{C.1})$$

The technologies have been divided into renewable and non-renewable, which also allows splitting all the investment costs *c\_inv* (by phase, by technology, phase-only, annualized or not) into renewable or non-renewable categories. The investment costs will be reduced by *tax\_spent* divided by 5, depending on whether the cost considered is per technology or a total value.

In order to avoid biasing GEMMES, the investment cost used as input in GEMMES cannot be the one reduced by the tax, as that would imply a lower investment, which is not the case. Therefore, care must be taken to use the investment cost without the reduction due to subsidies, as the subsidy will be incorporated into GEMMES.

## C.2 GEMMES

Figure C.1 presents the new variable introduced into the GEMMES equations.

	NFC	FC	G	H
Carbon tax	$ct_F$	$ct_B$	$ct_G$	$ct_H$
Reinvestment in Renewable Energies	$rct_F$	$rct_B$	$rct_G$	$rct_H$
Subsids in technologies	$se_F$	$se_B$	$se_G$	$se_H$

**Figure C.1: Exogenous variables contained in *Energy\_system\_costs.csv*. "NFC"=Non-Financial Corporations, "FC"=Financial Corporations, "G"=Government, "H"=Households.**

New definitions:

$$T_c = \sum c_{ti} \cdot p - \sum rct_{ti} \cdot p \quad (C.2)$$

$$ct = \sum ct_i \quad (C.3)$$

$$rct = \sum rct_i \quad (C.4)$$

$$se = \sum se_i \quad (C.5)$$

The new modifications are indicated in blue within the existing definitions:

$$T_t = T_i + T_m + T_{vat} + T_p + T_{gr} + T_y + T_c \quad (C.6)$$

$$G_p = C_G + (1 + \tau_{W,G}) \cdot w_G \cdot L_G + p^{IC} \cdot IC_G + p_K \cdot I_G + ST_G \\ + (ct_G - rct_G) \cdot p - (se_F \cdot p_{KF}^E + se_B \cdot p_{KB}^E + se_H \cdot p_{KH}^E) \quad (C.7)$$

$$GOS_F = Y^D - IM - T^P - T^M - T^V - \tau^{Y,F} \cdot Y^{P,D} - p^{IC} \cdot IC_F \\ + p_F^{ICE} \cdot ICE_F - INS_F - Com_F - (1 + \tau_{W,F}) \cdot W_F \cdot L_F - ct_F \cdot p \quad (C.8)$$

$$TFN_F = p^K \cdot I_K^F + p_F^{KE} \cdot I_F^{KE} - REF - rct_F \cdot p - se_F \cdot p_{KF}^E \quad (C.9)$$

$$GOS_B = Y^B - p^{IC} \cdot IC_B - p_B^{ICE} \cdot ICE_B - \tau_Y^B \cdot Y^B \\ - (1 + \tau_{W,B}) \cdot W_B \cdot L_B - ct_B \cdot p \quad (C.10)$$

$$TFN_B = \left[ \dot{L}d + \dot{B}g_B + \dot{R}d + I_B + I_B^{KE} \cdot p_B^{KE} \right] \\ - \left[ (1 + lr) \cdot \dot{D}d + \dot{O}F_B + FD_{IB} + \dot{T}IRH \right] \cdot p \\ + \left[ \dot{D}_B^{FX} \cdot e^N + \dot{L}_F^{FX,B} \cdot e^N + \dot{R}_B^{FX} \cdot e^N - \dot{L}_B^{FX,W} \cdot e^N \right] - rct_B \cdot p - se_B \cdot p_{KB}^E \quad (C.11)$$

$$YD_H = (1 - \tau_w)WL + MI_h + ESC + ST - WSC - i_{lh}L_{dh} + i_{dep}(1 - m_{dh})D_h \\ + DIV_{fh} + DIV_{bh} + Rem \cdot en + GOSH - Insh - Comh + Othhh + rct_H \cdot p - ct_H \cdot p \quad (C.12)$$

### C.3 Distribution of investments to renewable energy

As explained in subsection 4.3.1, investment costs cannot realistically reach zero. Applying subsidies imposes an upper bound on the reduction of total investment costs. The subsidy amount is deducted from the total investment cost of renewable energy technologies and allocated across technologies in a way that avoids pushing any individual investment cost too close to zero. The investment cost per deployment phase varies significantly by technology. For example, in the linear baseline (Figure C.2), offshore wind, which has particularly high investment costs in the 2040–2045 period, experiences a sharp decrease in the following phase. Allocating a large share of the subsidy to offshore wind could result in an unrealistically low investment cost for the 2045–2050 period. To prevent such outcomes, subsidy allocation is made dynamic across technologies and over time, ensuring that the costs remain within realistic limits, as shown on Figure C.3.

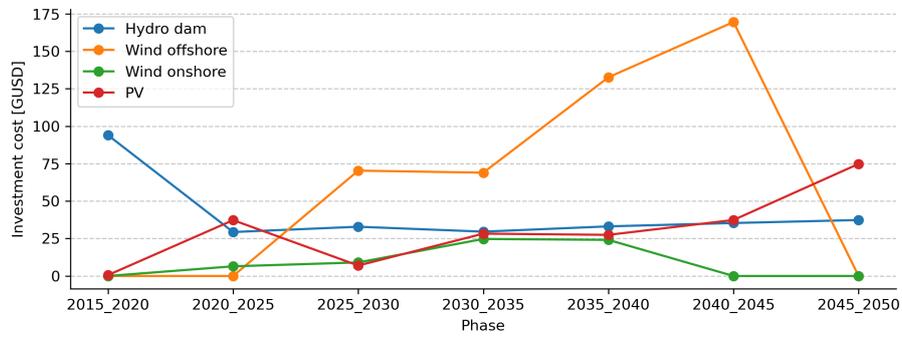


Figure C.2: Total investment costs non annualized (based on newly installed capacity) for each technology subsidy

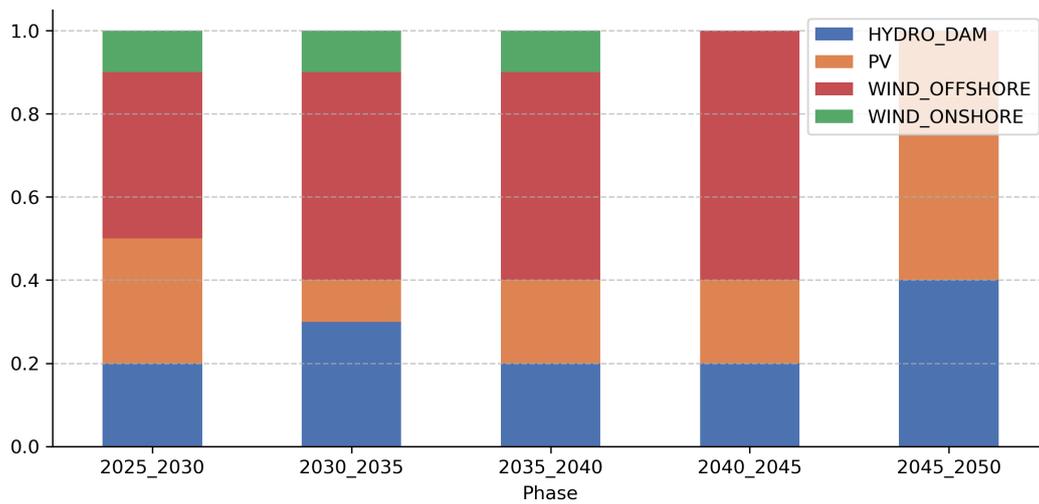


Figure C.3: Share of total subsidies allocation between renewable energies



# Distribution of the carbon tax and energy costs among households

This approach aims to allocate CAPEX, OPEX and the carbon tax across various household categories, thereby enabling a disaggregated representation of households within the coupling framework.

To begin with, the study [Dep24a; Dep24b] considers four categories: poor, vulnerable, middle class and high income, based on income levels. These categories are matched to our percentiles and deciles based on the share of the population. The following assumptions were made to determine a distribution using the accessible data:

- **CAPEX:** The major investments made by households in the energy sector are vehicles, so we will use the vehicle purchase share as a proxy.
- **OPEX:** The operational costs mainly consist of cooking, heating and fuels for households. Therefore, natural gas and fuel will be considered here.
- **Carbon Tax:** The carbon tax is applied to both OPEX items, specifically gas and fuels.

Finally, for the household distribution used in this master's thesis, the final percentages for the three categories are provided in Table D.1.

Category	Q1	Q2	Q3	Q4	D9	D10
CAPEX	0.5188%	1.3859%	4.1766%	17.0568%	16.4872%	60.3746%
OPEX	3.9316%	7.3126%	12.0068%	19.0474%	14.5852%	43.1164%
Carbon tax base	5.0993%	9.3696%	14.8651%	19.8400%	13.9632%	36.8627%

**Table D.1: Repartition of CAPEX, OPEX and carbon tax between the five categories of households.**



# Disposable income of households

E

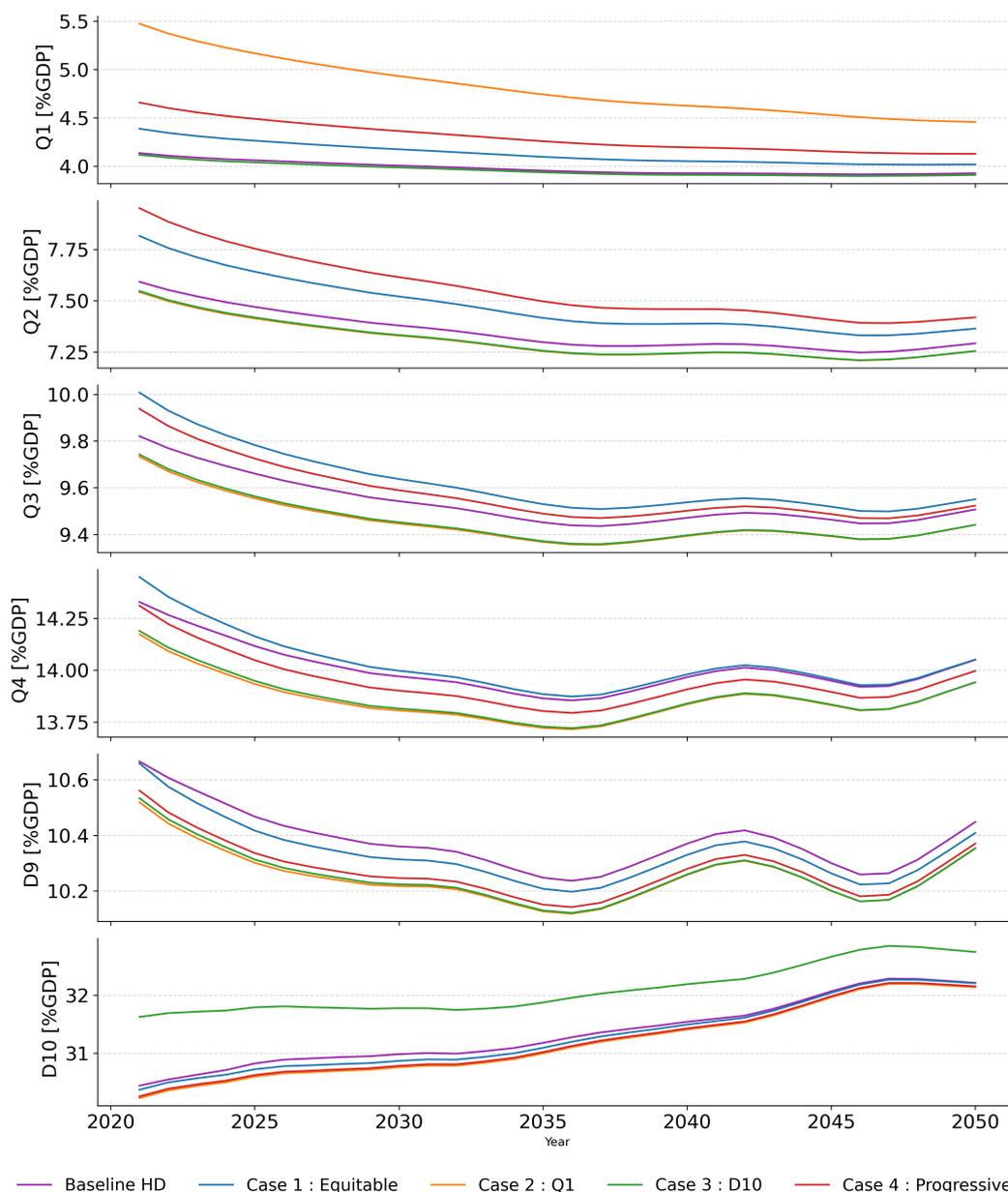


Figure E.1: Evolution of disposable income of households for each household's categories for varying cases of household redistribution



# Palma ratio data



Tabla 8. Desigualdad por zonas geográficas

Subgrupo poblacional	Año	Gini	Índice de Theil	Índices de Atkinson		Razón percentiles (90/10)	Ratio Palma
				A (1)	A (2)		
Total urbano	2002	0,55	0,61	0,41	0,65	10,8	4,2
	2010	0,53	0,57	0,40	0,64	10,6	4,0
	2017	0,49	0,46	0,34	0,58	8,4	3,3
	2020	0,53	0,55	0,41	0,69	11,6	4,0
Total rural	2002	0,51	0,58	0,38	0,61	9,5	3,5
	2010	0,47	0,43	0,33	0,56	8,6	2,7
	2017	0,46	0,41	0,31	0,53	7,3	2,5
	2020	0,46	0,41	0,31	0,53	7,6	2,5
13 Ciudades y A.M.	2002	0,54	0,59	0,40	0,64	10,5	4,1
	2010	0,52	0,56	0,39	0,63	9,9	3,7
	2017	0,48	0,38	0,29	0,52	6,7	2,8
	2020	0,54	0,55	0,41	0,72	11,7	4,1
Total Nacional	2002	0,57	0,67	0,45	0,69	12,9	4,9
	2010	0,56	0,63	0,44	0,68	12,7	4,6
	2017	0,50	0,50	0,37	0,61	9,7	3,4
	2020	0,54	0,57	0,41	0,68	11,9	4,2

Fuente: Elaboración propia con base en la GEIH

Figure F.1: Inequality metrics by geographic region from "Diagnóstico Multidimensional sobre las desigualdades en Colombia." [Mon+22]



# Bibliography

- [AE09] M. S. Andersen and P. ( Ekins. *Carbon Energy Taxation: Lessons from Europe*. Oxford: Oxford University Press, 2009.
- [AGO23] E. Angel-Sanint, S. García-Orrego, and S. Ortega. “Refining wind and solar potential maps through spatial multicriteria assessment. Case study: Colombia”. In: *Energy for Sustainable Development* 73 (2023), pp. 152–164.
- [Ame25] America Economía. *Colombia’s Energy Crisis Deepens Due to El Niño’s Impact on Hydropower*. Accessed: 2025-02-17. 2025.
- [Ban24] W. Bank. *State and Trends of Carbon Pricing 2024*. Tech. rep. License: CC BY 3.0 IGO. World Bank, 2024.
- [Bet+24] L. Bettarelli, D. Furceri, P. Pizzuto, and N. Shakoor. “Climate Change Policies and Income Inequality”. In: *Energy Policy* 191 (2024), p. 114176. DOI: 10 . 1016/j . enpol . 2024 . 114176.
- [Bla24] M. Blanquer. *Gustavo Petro, the president who is ushering in an ecological revolution in Colombia*. Accessed: 2025-04-22. Energy News Pro. June 2024. URL: <https://energynews.pro/en/gustavo-petro-the-president-who-is-usher-ing-in-an-ecological-revolution-in-colombia/>.
- [BO71] W. J. Baumol and W. E. Oates. *The Use of Standards and Prices for Protection of the Environment*. Vol. 73. Swedish Journal of Economics, 1971, pp. 42–54.
- [Cal+16] S. Calderón, A. C. Alvarez, A. M. Loboguerrero, S. Arango, K. Calvin, T. Kober, K. Daenzer, and K. Fisher-Vanden. “Achieving CO2 reductions in Colombia: Effects of carbon taxes and abatement targets”. In: *Energy Economics* 56 (May 2016), pp. 575–586. DOI: 10 . 1016/j . eneco . 2015 . 05 . 010.
- [Car19] Carbon Pricing Leadership Coalition. *Distributional Impacts of Carbon Pricing on Households*. Tech. rep. Accessed: 2025-04-17. World Bank, 2019.
- [Cas22] C. Castiblanco-Rozoa. “El papel del impuesto al carbono en la transición energética: una revisión de su aplicación en Colombia”. The role of the carbon tax in the energy transition: A review of its application in Colombia. In: *Gestión y Ambiente* 25.1 (2022). Accessed: 2025-04-22. DOI: 10 . 15446/ga . v25n1 . 102263.
- [CEI18] Carbon Trust, Environmental Defense Fund, and International Emissions Trading Association. *COLOMBIA: An Emissions Trading Case Study*. Tech. rep. Carbon Trust, EDF, and IETA, 2018.
- [Cel22] Celsia S.A. *Celsia intensifies the construction of solar farms, with 17 new plants amounting to 260 MW of capacity and COP 1 trillion in investments*. Accessed: 2025-03-25. May 2022. URL: <https://www.celsia.com/en/noticias/celsia-intensifies-the-construction-of-solar-farms-with-17-new-plants-amounting-to-260-mw-of-capacity-and-cop-1-trillion-in-investments/>.

- [Chu04] M. Chupka. “Carbon Taxes and Climate Change”. In: *Encyclopedia of Energy*. Ed. by C. J. Cleveland. Elsevier, 2004, pp. 299–306. DOI: 10.1016/B0-12-176480-X/00495-2.
- [Con+17] D. Conway, K. Richards, S. Richards, P. Keenlyside, S. Mikolajczyk, C. Streck, J. Ross, A. A. Liu, and A. Tran. *Carbon Tax Guide: A Handbook for Policy Makers*. Vol. 1. PMR Carbon Tax Guide - Translations. Available in English. Licensed under Creative Commons Attribution 3.0 IGO. Washington, D.C.: World Bank Group, 2017.
- [CR17] J. C. Carbone and N. Rivers. “The Impacts of Unilateral Climate Policy on Competitiveness: Evidence from Computable General Equilibrium Models”. In: *Review of Environmental Economics and Policy* 11.1 (2017), pp. 24–42. DOI: 10.1093/reep/rew025.
- [CR25] S. Coccia and A. Russo. “Inflation, Inequality and Financial Vulnerability: Monetary vs. Fiscal Policy in the Face of an Energy Shock”. In: *Energy Economics* 108 (2025), p. 108222. DOI: 10.1016/j.eneco.2025.108222.
- [Dan24] J. Daniels. “Colombia battles to diversify economy away from oil and gas”. In: *Financial Times* (2024). Accessed: 2025-02-17.
- [Dat24] O. W. in Data. *Palma Ratio (S90/S40) - Colombia*. Accessed via Our World in Data. Global Change Data Lab. 2024. URL: <https://ourworldindata.org/grapher/palma-ratio-s90s40-ratio?tab=chart&country=~COL> (visited on 04/28/2025).
- [Dep24a] Departamento Administrativo Nacional de Estadística (DANE). *Gran Encuesta Integrada de Hogares 2019*. Accessed: 2025-04-25. 2024. URL: <https://microdatos.dane.gov.co/index.php/catalog/599>.
- [Dep24b] Departamento Administrativo Nacional de Estadística (DANE). *Matriz de Contabilidad Social 2019*. Accessed: 2025-04-25. 2024. URL: <https://www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-anuales/matrices-complementarias#matriz-de-contabilidad-social>.
- [Dévnd] A. F. de Développement (AFD). *GEMMES: Un nouvel outil de modélisation qui intègre la transition énergétique*. Accessed: 2024-03-06. n.d.
- [DF23] A. Dobbins and U. Fahl. “Effects of Carbon Tax Redistribution Schemes on Energy Welfare of Households in Germany”. In: *Vulnerable Households in the Energy Transition*. Ed. by R. Bardazzi and M. G. Paziienza. Studies in Energy, Resource and Environmental Economics. Open Access under CC BY 4.0. Springer, Cham, 2023, pp. 139–171. ISBN: 978-3-031-35683-4. DOI: 10.1007/978-3-031-35684-1\_7.
- [Dir24] Direction générale du Trésor. *Colombie – Situation économique et financière (juillet 2024)*. Tech. rep. Accessed: 2025-04-22. Ministère de l’Économie, des Finances et de la Souveraineté industrielle et numérique, July 2024.
- [DP14] P. Dörrenberg and A. Peichl. “The impact of redistributive policies on inequality in OECD countries”. In: *Applied Economics* 46.17 (2014). Originally published on Social Science Research Network, 2012, pp. 2140–2150. DOI: 10.1080/00036846.2014.892202.
- [Eco25] Ecopetrol S.A. *About Ecopetrol*. Accessed: 2025-02-17. 2025.
- [Ene23] EnergyScope Project. *Input Data – Colombia*. Accessed: 2025-03-25. 2023.

- [Ene25] Energyscope. *Input Data - Colombia*. Accessed: 2025-01-07. 2025.
- [ENV19] J. Ellis, D. Nachtigall, and F. Venmans. “Carbon Pricing and Competitiveness: Are They at Odds?” In: *OECD Environment Working Papers* 152 (2019). doi: 10.1787/f79a75ab-en.
- [ERM22] W. B. G. ( R. C. G. bibinitperiod ERM). *Offshore Wind Roadmap for Colombia*. Tech. rep. Consultado el 22 de abril de 2025. Ministerio de Minas y Energía de Colombia, 2022.
- [Eur21a] European Central Bank. *Euro foreign exchange reference rates*. Accessed: 2025-04-15. 2021. URL: [https://www.ecb.europa.eu/stats/policy\\_and\\_exchange\\_rates/euro\\_reference\\_exchange\\_rates/html/index.en.html](https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/index.en.html).
- [Eur21b] Eurostat. *Consumer prices - inflation*. Accessed: 2025-04-15. 2021. URL: [https://ec.europa.eu/eurostat/statistics-explained/index.php/Consumer\\_prices\\_-\\_inflation](https://ec.europa.eu/eurostat/statistics-explained/index.php/Consumer_prices_-_inflation).
- [Exc21] Exchange-Rates.org. *USD to COP Exchange Rate History for 2021*. Accessed: 2025-04-15. 2021. URL: <https://www.exchange-rates.org/exchange-rate-history/usd-cop-2021>.
- [Fat+23] A. Fattahi, F. Reynès, B. van der Zwaan, J. Sijm, and A. Faaij. “Soft-linking a national computable general equilibrium model (ThreeME) with a detailed energy system model (IESA-Opt)”. In: *Energy Economics* 123 (2023), p. 106750. doi: 10.1016/j.eneco.2023.106750.
- [Fen+10] K. Feng, K. Hubacek, D. Guan, M. Contestabile, J. Minx, and J. Barrett. “Distributional Effects of Climate Change Taxation: The Case of the UK”. In: *Environmental Science & Technology* 44.10 (2010), pp. 3670–3676. doi: 10.1021/es902974g.
- [Fin24] Financial Times. *Colombia Battles to Diversify Economy Away from Oil and Gas*. Accessed: 2025-02-17. 2024. URL: <https://www.ft.com/content/95be32c9-e292-485c-8103-505c564daf13>.
- [Fun22] D. A. de la Función Pública. *Ley 2277 de 2022*. Accessed: 2025-04-22. 2022.
- [Gau15] P. Gauthier-Maradei. “Status of Biofuels in Colombia”. In: *Bioenergy and Latin America: A Multi-Country Perspective*. Accessed: 2025-04-22. European Union, 2015, p. 115.
- [GDM24a] A. Godin, Y. Devrim, and A. Moreau-Santos. *Modelling low-carbon transitions in Colombia: macrofinancial opportunities and risks*. Tech. rep. Report commissioned by the Agence Française de Développement to explore the macrofinancial implications of low-carbon transitions in Colombia. Paris, France: Agence Française de Développement, 2024.
- [GDM24b] A. Godin, Y. Devrim, and A. Moreau-Santos. *Modelling Low-Carbon Transitions in Colombia: Macrofinancial Opportunities and Risks*. 1st ed. Paris, France: Agence Française de Développement, 2024.
- [Glo25a] Global Solar Atlas. *Global Solar Atlas - Colombia*. Accessed: 2025-02-17. 2025.
- [Glo25b] Global Wind Atlas. *Global Wind Atlas - Colombia*. Accessed: 2025-02-17. 2025.

- [Gon+23] T. González, R. Delgado, C. Herrera, Á. Cadena, D. Hidalgo, and G. Mejía. *Estudio para la Hoja de Ruta de la Transición Energética Colombia 2050*. Available at: [https://colombiainteligente.org/es\\_co/tendencias/estudio-para-la-hoja-de-ruta-de-la-transicion-energetica-colombia-2050/](https://colombiainteligente.org/es_co/tendencias/estudio-para-la-hoja-de-ruta-de-la-transicion-energetica-colombia-2050/). Energía que transforma, Tendencias. May 2023.
- [Gou95] L. H. Goulder. “Environmental taxation and the double dividend: A reader’s guide”. In: *International Tax and Public Finance* 2 (1995), pp. 157–183. doi: 10.1007/BF00877495.
- [Gov23] Government of Sweden. *Sweden’s Carbon Tax*. Accessed: 2025-02-20. 2023.
- [GP21] M. A. Gonzalez-Salazar and W.-R. Poganietz. *Mitigating the impact of El Niño Southern Oscillation on hydropower by complementing it with solar-and wind-power in Latin America*. Conference Paper, November 2021. 2021.
- [Gro+24] J. Grosjean, O. Cuny, C. Gianella, and P. Reyl. “La tarification du carbone dans les pays nordiques”. In: *Trésor-Éco* 346 (July 2024).
- [GW24] C. Glocker and P. Wegmüller. “Energy Price Surges and Inflation: Fiscal Policy to the Rescue?” In: *Journal of International Money and Finance* 103 (2024), p. 103201. doi: 10.1016/j.jimonfin.2024.103201.
- [HMM09] K. A. Hassett, A. Mathur, and G. E. Metcalf. “The Incidence of a U.S. Carbon Tax: A Lifetime and Regional Analysis”. In: *The Energy Journal* 30.2 (2009), pp. 155–178. doi: 10.5547/ISSN0195-6574-EJ-Vol30-No2-7.
- [IEA24] I. E. A. (IEA). *Nationally Determined Contribution (NDC) to the Paris Agreement: Colombia*. Accessed: 2024-12-17. 2024.
- [Ini25] L. Ini. *Colombia Approaches 2 GW Solar Capacity Milestone*. Accessed: 2025-03-25. pv magazine. Apr. 2025. URL: <https://www.pv-magazine.com/2025/04/30/colombia-approaches-2-gw-solar-capacity-milestone/>.
- [Int23a] International Chamber of Commerce. *ICC Proposals for Effective Carbon Pricing: Leakage and Linkage Considerations*. Tech. rep. Accessed: 2025-04-17. International Chamber of Commerce, 2023.
- [Int23b] International Energy Agency. *Colombia - Countries & Regions*. International Energy Agency. 2023. URL: <https://www.iea.org/countries/colombia> (visited on 01/07/2025).
- [Jac25] P. Jacques. “Coupling models to understand the interactions between energy transition and macroeconomic dynamics”. Doctoral Thesis. Louvain-la-Neuve: UCLouvain, 2025.
- [KS22] A. Köppl and M. Schratzenstaller. “Carbon taxation: A review of the empirical literature”. In: *Journal of Economic Surveys* 37.4 (2022). Open Access, pp. 1353–1388. doi: 10.1111/joes.12531.
- [KSH96] A. Köppl, K. W. Steininger, and H. K. Huber. “Carbon taxation in Austria: Employment and distributional effects”. In: *Energy Policy* 24.4 (1996), pp. 355–367. doi: 10.1016/0301-4215(96)00009-6.
- [Lim+19] G. Limpens, S. Moret, H. Jeanmart, and F. Maréchal. “EnergyScope TD: A novel open-source model for regional energy systems and its application to the case of Switzerland”. In: *Applied Energy* 255 (2019), p. 113729. doi: 10.1016/j.apenergy.2019.113729.

- [Lim+24] G. Limpens, X. Rixhon, F. Contino, and H. Jeanmart. “EnergyScope Pathway: An open-source model to optimise the energy transition pathways of a regional whole-energy system”. In: *Applied Energy* 358 (2024), p. 122501. ISSN: 0306-2619. DOI: <https://doi.org/10.1016/j.apenergy.2023.122501>.
- [LLL17] X. Labandeira, J. M. Labeaga, and X. López-Otero. “A meta-analysis on the price elasticity of energy demand”. In: *Energy Policy* 102 (2017), pp. 549–568. ISSN: 0301-4215. DOI: <https://doi.org/10.1016/j.enpol.2017.01.002>.
- [Mar24] C. Mardones. “Improving the estimation of the distributional impacts of carbon pricing and targeted transfers to reduce its regressivity in Latin American countries”. In: *Ecological Economics* 225 (2024), p. 108336. DOI: [10.1016/j.ecolecon.2024.108336](https://doi.org/10.1016/j.ecolecon.2024.108336).
- [MB05] E. J. McCaffery and J. Baron. “The Political Psychology of Redistribution”. In: *Political Psychology* 26.6 (2005), pp. 881–920. DOI: <https://doi.org/10.2139/ssrn.695305>.
- [Mig+25a] C. de Miguel, S. Lorenzo, J. Ferrer, J. J. Gómez, and J. E. Alatorre. *Economic Policy and Climate Change: Carbon Pricing in Latin America and the Caribbean*. Project Document LC/TS.2024/58. Santiago, Chile: Economic Commission for Latin America and the Caribbean (ECLAC), 2025.
- [Mig+25b] C. de Miguel, S. Lorenzo, J. Ferrer, J. J. Gómez, and J. E. Alatorre. *Economic policy and climate change: Carbon pricing in Latin America and the Caribbean*. United Nations publication. Version LC/TS.2024/58. Santiago, 2025.
- [MIN21] MINENERGÍA. *Hoja de ruta del hidrógeno en Colombia*. Technical Report. Accessed: 2025-04-22. Ministerio de Minas y Energía and Banco Interamericano de Desarrollo, 2021.
- [Min23] Ministerio de Minas y Energía. *Potencial energético subnacional y oportunidades de descarbonización en usos de energía final*. Technical Report. Accessed: 2025-02-21. Ministerio de Minas y Energía, 2023.
- [Mog20] J. S. Mogollón. *Carbon Tax in Colombia*. Webinar presentation: Sustainable Financing of Protected Areas – Earmarking Fund from Carbon Taxes, Colombia. Corporate Environmental Manager. Bogotá, Colombia, May 2020.
- [Mon+22] J. M. Monroy, J. Núñez Méndez, J. D. Ramírez, and D. N. Lasso. *Diagnóstico Multidimensional sobre las desigualdades en Colombia*. Documento de trabajo. Extensión de la Facilidad de investigación UE-AFD sobre las desigualdades. Coordinadores: Felipe Corrales (AFD), Jairo Núñez Méndez (Fedesarrollo). Bogotá D.C.: Fedesarrollo and Agence Française de Développement (AFD), Oct. 2022.
- [MR15] B. C. Murray and N. Rivers. “British Columbia’s Revenue-Neutral Carbon Tax: A Review of the Latest “Grand Experiment” in Environmental Policy”. In: *Energy Policy* 86 (2015), pp. 674–683. DOI: [10.1016/j.enpol.2015.08.011](https://doi.org/10.1016/j.enpol.2015.08.011).
- [MW21] F. Misch and P. Wingender. *Revisiting Carbon Leakage*. IMF Working Paper WP/21/207. Authorized for distribution by Peter Dohlman. International Monetary Fund, Aug. 2021.

- [MY20] R. J. Mori and A. Yépez-García. *How Do Households Consume Energy? Evidence from Latin America and the Caribbean*. Technical Report. Cataloging-in-Publication data provided by the Inter-American Development Bank, Felipe Herrera Library. Washington, D.C.: Inter-American Development Bank, 2020.
- [Nat15] U. Nations. *Paris Agreement*. Tech. rep. FCCC/CP/2015/L.9/Rev.1. Accessed: 2025-03-05. United Nations Framework Convention on Climate Change (UNFCCC), 2015.
- [Nat24] U. Nations. *Sustainable Development Goals*. Accessed: 2024-12-17. 2024.
- [OEC16] OECD. *Effective Carbon Rates: Pricing CO through Taxes and Emissions Trading Systems*. OECD Series on Carbon Pricing and Energy Taxation. Paris: OECD Publishing, 2016. DOI: 10.1787/9789264260115-en.
- [OEC23a] OECD. “Colombia”. In: *OECD Economic Outlook*. Vol. 2023. 2. Accessed: 2025-04-22. Paris: OECD Publishing, 2023. DOI: 10.1787/e2f39dc4-en.
- [OEC23b] OECD. *Effective Carbon Rates 2023: Pricing Greenhouse Gas Emissions through Taxes and Emissions Trading*. OECD Series on Carbon Pricing and Energy Taxation. Paris: OECD Publishing, 2023. DOI: 10.1787/b84d5b36-en.
- [OEC24] OECD. *Colombia: Economic Snapshot – 2024*. Country Economic Snapshot. Accessed: 2025-04-18. Organisation for Economic Co-operation and Development, 2024.
- [OS24] A. M. O. and J. D. Sarm. *La dependencia del país y de los territorios de los hidrocarburos y el carbón en Colombia y la necesidad de la diversificación de las exportaciones y de la producción ante la transición energética*. Documentos de antecedentes del Informe Nacional de Desarrollo Humano 2024. 2024.
- [Par+25] J. F. Parra, J. Arias-Gaviria, Y. Olaya Morales, E. Larsen, and S. Arango-Aramburo. *Quantifying the 2050 Scenarios for Colombia’s Electricity Sector Transition*. Available at SSRN: <https://ssrn.com/abstract=4916280>. 2025.
- [Pav+22] M. Pavičević, P. Thiran, G. Limpens, F. Contino, H. Jeanmart, and S. Quoilin. “Bi-directional soft-linking between a whole energy system model and a power systems model”. In: *2022 IEEE PES/IAS PowerAfrica*. IEEE, 2022, pp. 1–5. DOI: 10.1109/PowerAfrica53997.2022.9905392.
- [PAV21] C. Peñasco, L. D. Anadón, and E. Verdolini. “Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments”. In: *Nature Climate Change* 11.3 (2021), pp. 257–265. DOI: 10.1038/s41558-020-00971-x.
- [PB99] I. W. Parry and A. M. Bento. *Tax Deductible Spending, Environmental Policy, and the “Double Dividend” Hypothesis*. Tech. rep. 2119. World Bank, Development Research Group, Infrastructure and Environment, 1999. DOI: 10.1596/1813-9450-2119.
- [Pea91] D. W. Pearce. “The Role of Carbon Taxes in Adjusting to Global Warming”. In: *The Economic Journal* 101.407 (1991), pp. 938–948. DOI: 10.2307/2233863.
- [Pla] D. N. de Planeación. *Departamento Nacional de Planeación - DNP*. Accessed: 2024-12-01.
- [Pow24] Power Technology. *Top 5 hydro power plants in development in Colombia*. Accessed: 2024-01-24. 2024. URL: <https://www.power-technology.com/data-insights/top-5-hydro-power-plants-in-development-in-colombia/?cf-view>.

- [PRT09] A. Pinilla, L. Rodriguez, and R. Trujillo. "Performance evaluation of Jepirachi Wind Park". In: *Renewable Energy* 34 (2009), pp. 48–52. DOI: 10.1016/j.renene.2008.04.015.
- [PT90] D. W. Pearce and R. K. Turner. *Economics of Natural Resources and the Environment*. Johns Hopkins University Press, 1990.
- [Qa19] A. Quinet and al. *La valeur de l'action pour le climat : Une valeur tutélaire du carbone pour évaluer les investissements et les politiques publiques*. France Stratégie, 2019.
- [QC24] H. F. T. Quintero and J. J. L. Cubillos. "Conflict and resistance: Unveiling the hidden costs of small hydropower in an armed conflict-affected region of Antioquia, Colombia". In: *Energy Research & Social Science* 118 (2024), p. 103792. DOI: 10.1016/j.erss.2024.103792.
- [Ren22] Renewable Energy World. *Colombia's Ituango Hydropower Plant Launches Commercial Operations*. Accessed: 2024-01-24. 2022. URL: <https://www.renewableenergyworld.com/energy-business/new-project-development/colombias-ituango-hydropower-plant-launches-commercial-operations/>.
- [Rep16] C. de la República de Colombia. *Ley 30030265 de 2016*. Accessed: 2025-04-22. 2016.
- [Rep17] P. de la República de Colombia. *Decreto 2190 de 2017*. Disponible sur le site SUIN-Juriscol. Accessed: 2025-04-22. 2017.
- [Rep20] República de Colombia. *Actualización de la Contribución Determinada a Nivel Nacional de Colombia (NDC)*. Tech. rep. Documento presentado ante la CM-NUCC. Ministerio de Ambiente y Desarrollo Sostenible, Dec. 2020.
- [RH94] M. L. Roberts and P. A. Hite. "Progressive Taxation, Fairness, and Compliance". In: *Law & Policy* 16.1 (1994), pp. 27–48. DOI: 10.1111/j.1467-9930.1994.tb00115.x.
- [Rix25] X. Rixhon. "Exploration of uncertainty-aware energy transition pathways: reinforcement learning and principal component analysis-based methods". Promoters: Hervé Jeanmart, Francesco Contino. PhD thesis. 2025.
- [Rom+18] G. Romero, A. Álvarez-Espinosa, S. Calderón, and A. Ordóñez. "Impactos distributivos de un impuesto al carbono en Colombia: vínculo entre modelos de microsimulaciones y equilibrio general". In: *Lecturas de Economía* 89 (July 2018). julio-diciembre, pp. 163–198.
- [RR22] H. Ritchie and P. Rosado. "Which countries have put a price on carbon?" In: *Our World in Data* (2022). <https://ourworldindata.org/carbon-pricing>.
- [Sal+14] M. A. G. Salazar, M. Venturini, W.-R. Poganietz, M. Finkenrath, T. Kirsten, and H. Acevedo. *Bioenergy Technology Roadmap for Colombia*. Technical Report. Copyright © 2014 by the authors. All rights reserved. Please cite this document as: Gonzalez-Salazar, M.A., Venturini, M., Poganietz, W.R., Finkenrath, M., Kirsten, T., Acevedo, H., Bioenergy technology roadmap for Colombia, Università degli Studi di Ferrara, 2014. Università degli Studi di Ferrara, 2014.
- [She21] P. B. Shelley. *A Defence of Poetry*. Posthumously published, 1821.
- [Sma+18] F. R. Smail, T. S. Gspann, A. M. Boies, and N. A. Fleck. "The mechanical and electrical properties of direct-spun carbon nanotube mats". In: *Extreme Mechanics Letters* 21 (2018). Accessed: 2025-02-17, pp. 65–75. DOI: 10.1016/j.eml.2018.03.003.

- [SMM06] S. Speck, J. McNicholas, and J. Mulder. *The Use of Economic Instruments in Environmental Policy: Opportunities and Challenges*. Springer, 2006.
- [Sti+17] J. Stiglitz, N. Stern, M. Duan, O. Edenhofer, G. Giraud, G. Heal, E. La Rovere, M. Elisabeth, M. Pangestu, P. Shukla, Y. Sokona, and H. Winkler. *Report of the High-Level Commission on Carbon Prices*. Tech. rep. World Bank Group, May 2017.
- [Tar20] B. Tarrow. *The value of tax progressivity: Evidence from survey experiments*. GATE UMR 5824, F-69130 Ecully, France, 2020.
- [TG23] J. Thema and M. C. R. García. *The Energy Transition in Colombia: Current Situation, Projections, Challenges, Narratives and Public Policies – in Relation to the Energy Transition in Germany*. Wuppertal Paper No. 200. Wuppertal Institute, June 2023.
- [Uni03] E. Union. *Directive 2003/87/EC of the European Parliament and of the Council establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC*. Accessed: 2024-03-06. 2003.
- [Uni24] United Nations Environment Programme (UNEP). *Emissions Gap Report 2024*. Technical Report. United Nations Environment Programme, 2024.
- [VC14] M. J. Valencia and C. A. Cardona. “The Colombian biofuel supply chains: The assessment of current and promising scenarios based on environmental goals”. In: *Energy Policy* 67 (2014), pp. 876–887. doi: 10.1016/j.enpol.2013.12.021.
- [Wie+05] M. Wier, K. Birr-Pedersen, H. K. Jacobsen, and J. Klok. “Are CO<sub>2</sub> Taxes Regressive? Evidence from the Danish Experience”. In: *Ecological Economics* 52.2 (2005), pp. 239–251. doi: 10.1016/j.ecolecon.2004.07.016.
- [Wor23] World Bank. *Country Climate and Development Report: Colombia*. Technical Report. Latin America and Caribbean Region. © 2023 The World Bank Group. Accessed: 2025-04-22. Washington, DC: World Bank Group, July 2023.
- [Wor24] World Bank. *Consumer Price Index (annual % change) - Colombia*. Accessed: 2025-04-16. World Bank. 2024. URL: <https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG?locations=CO>.
- [Yam17] A. Yamazaki. “Jobs and Climate Policy: Evidence from British Columbia’s Revenue-Neutral Carbon Tax”. In: *Journal of Environmental Economics and Management* 83 (2017), pp. 197–216. doi: 10.1016/j.jeem.2017.03.003.
- [Yel19] A. E. Yeldan. “Economic Instruments of Greening”. In: *Handbook of Green Economics*. Ed. by S. Acar and E. Yeldan. Academic Press, 2019, pp. 153–162. ISBN: 9780128166352.
- [Yil+23] S. D. Yilmaz, S. Ben-Nasr, A. Mantes, N. Ben-Khalifa, and I. Daghari. *Climate Change, Loss of Agricultural Output and the Macro-Economy: The Case of Tunisia*. AFD Working Paper 286. Agence Française de Développement (AFD), 2023.

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