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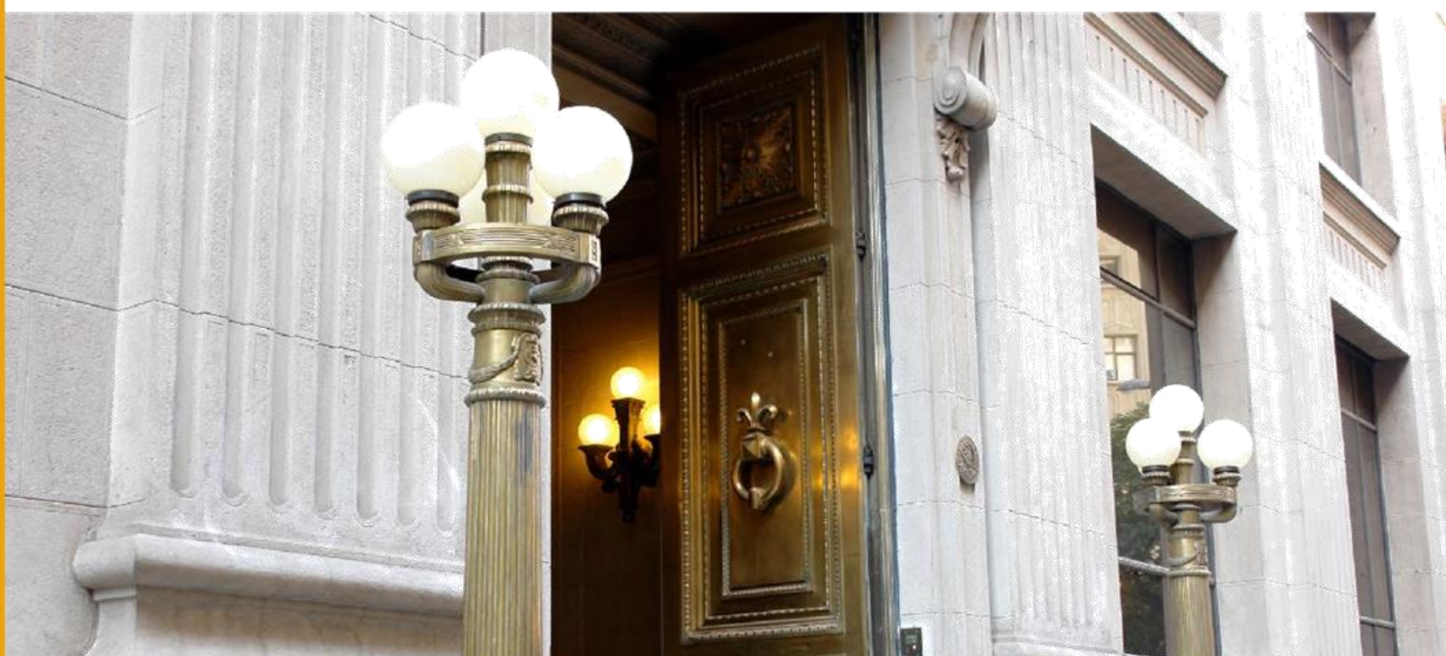

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A Preliminary Assessment of the Economic Effects of Climate Change in Chile*

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Abstract

The study of energy and climate has become of primary relevance for policymakers in central banks and other institutions. Current analyses for Chile suggest medium to strong direct physical effects, with some studies pointing to relatively higher impacts in the northern and central regions. Also, indirect effects, such as those originating from green transitions around the world, are likely to be significant. This paper provides a brief review of the effects that climate change may have on the economy and describes efforts made by the Central Bank of Chile to gain a better understanding of these effects. These efforts include: geo-referencing of assets and the primary physical risks they face, characterization of the transmission channels through which climate risks can propagate, a better estimation of the uncertainty of climatic events and the development of new general equilibrium models.

Resumen

El estudio del cambio climático y la energía ha cobrado gran relevancia tanto para formuladores de política de bancos centrales, así como de otras instituciones. En cuanto a efectos asociados a riesgos físicos, la evidencia reciente para Chile sugiere impactos directos de medianos a fuertes, y algunos estudios señalan efectos relativamente mayores en las regiones norte y central. Además, es probable que los efectos indirectos asociados al cambio climático sean significativos, como los que se derivan de las transiciones a energías verdes en todo el mundo. En este artículo se documenta una breve revisión de los impactos que el cambio climático puede tener en la economía y describe los esfuerzos realizados por el Banco Central de Chile para comprender mejor estos efectos. Estos esfuerzos incluyen: georreferenciación de de destinatarios del crédito y los principales riesgos físicos que enfrentan, caracterización de los canales de transmisión a través de los cuales se pueden propagar los riesgos climáticos, una mejor estimación de la incertidumbre de los eventos climáticos y el desarrollo de nuevos modelos de equilibrio general para cuantificar los shocks asociados al cambio climático.

*The analysis and conclusions set forth are those of the authors and do not necessarily represent the views of the Central Bank of Chile or its Board members. We thank Elías Albagli, Lissette Briones, Benjamín García and the Macroeconomic Modeling team for helpful comments. Corresponding author: mgonzalezf@bcentral.cl

1 Introduction

The study of energy and climate has become of primary relevance for policymakers in central banks and other institutions. This heightened attention is partly due to the impact of extreme weather events, such as fire hazards, droughts, and water stress, on economic activity. Additionally, it is due to the effects of air pollution, biodiversity loss, ecosystem damage, and human migrations. Aside from direct physical effects, the adoption of transition paths associated with net-zero objectives also creates new challenges and opportunities (see Ocampo and Khor (2011) and Bernai (2013)). Given the uncertainty surrounding climate impacts and the multitude of associated challenges, the Central Bank of Chile has embarked on a work agenda that includes the creation of methodological tools to support the study of such risks (such as the production of new datasets, statistics, and modeling frameworks).

In order to analyze the economic impacts of climate change, the literature generally distinguishes between physical risks (those related to the physical impact of higher temperatures or extreme weather events) and transition risks (those related to the shift toward a low-carbon economy). Concerning physical risks, Córdova et al. (2022) suggest that exposure is region-dependent, with a concentration of risks in the northern and central regions of Chile. The authors distinguish among risks associated with the availability of water resources, resilience of the electrical network to climate shocks, changes in average regional temperatures, and impacts on labor productivity. Using data from the Climate Risk Atlas database (ARCLIM) from the Chilean Ministry of the Environment and the Climate Impact Explorer (CIE) database, the authors then assess the degree of exposure of each geographical region. They point out that the greatest threats arise in relation to the availability of water resources. Other indicators also show high or medium levels of risks, with the exception of labor productivity, which displays only a mild deterioration going forward.

In terms of transition risks, Chile is poised to face significant challenges and opportunities. Specifically, the country stands to benefit from climate transition plans being implemented at both the national and international levels. In this regard, Chile is already adapting its production structure to reduce the carbon footprint of some of its industries, including the electric and mining sectors (Avilés-Lucero et al. (2017)). Furthermore, Chile possesses some of the largest deposits of minerals required for the green transition, such as copper and lithium.

This policy note provides a brief overview of the characteristics surrounding the impact of climate change in Chile. It emphasizes both aggregate and sectoral effects, including a review of the limitations of current studies. Additionally, the note presents an initial assessment of the impact of energy price shocks within a standard Dynamic Stochastic General Equilibrium (DSGE) framework that has been extended to account for the diversity of energy sources used in production.

2 Recent Developments and Main Challenges for the Chilean Economy

2.1 Macroeconomic Effects of Climate Change

Physical Risks: A growing body of literature examines the macroeconomic effects, particularly in terms of GDP losses resulting from climate change, using various methodologies, as summarized in Madeira (2022). While some of the literature predicts that Chile will experience moderate effects from higher temperatures, other studies suggest significant damages in terms of GDP losses. Overall, the variability in projections reflects the uncertainty associated with estimating the long term effects of climate change in the economy.

Empirical papers estimating mild effects include, among others, Roson and Sartori (2016) suggesting marginal losses equivalent to 0.3% of GDP by 2062, Kalkuhl and Wenz (2020) finding losses around 4.8% of GDP by 2100 using panel regressions, and Kahn et al. (2021) estimating GDP losses ranging from 0.5%, 1.7%, to 5.2% in 2030, 2050, and 2100, respectively, to 1.2%, 4% and 11.1%, depending on the scenario considered. Papers using structural methods to estimate the effects of climate change in Chile include OECD (2015), finding a negative impact between 0.3% and 0.6% of GDP by 2060, Cruz and Rossi-Hansberg (2021) estimating a fall equal to 1.9% of GDP per capita by 2200 and Guo et al. (2021) forecasting a GDP decline between 0.9% and 3% by 2050.

However, these findings could be considered as representing lower bound predictions. This is because they fail to fully incorporate the complexity of the economic impact of climate change. They either focus on narrowly defined variables, such as labor productivity, do not account for the spillover effects of productivity losses among productive units, consider only linear dynamics between temperatures and productivity, or do not take into account other relevant dimensions, such as the impact that atmospheric changes can have on the availability of essential resources needed for both production and livelihood.

In this respect, the IPCC WGI Interactive Atlas (Gutiérrez et al. (2021)) offers a complementary assessment by summarizing the predictions from a range of models presented in the IPCC reports on the impact of changes in key atmospheric and oceanic variables. As an example, the atlas shows that there is a high level of confidence across models that ocean acidity will increase (see Figure 1). This phenomenon poses a threat to the fishing industry due to its impact on the health of the marine ecosystem, including mollusks and other shellfish, which, in turn, are key components of the marine food web of fishes. This is particularly important for Chile as its fishing industry is at direct risk of suffering from these developments, especially in certain regions such as the Aysén region, where fishing accounts for as much as 22% of the regional GDP (Valencia Cabrera (2018)).

Other dimensions in which the IPCC predicts an increase in natural adverse events with medium to high confidence in Chile include high average surface temperatures, extreme heat, coastal floods and erosion, relative sea level rise, marine heatwaves, agricultural and ecological droughts, aridity, and fire weather. All these variables and their associated economic impacts are not explicitly accounted for in the majority of current studies on aggregate

GDP damages. Therefore, these studies are likely to downplay the full extent of adverse effects arising from climate change.

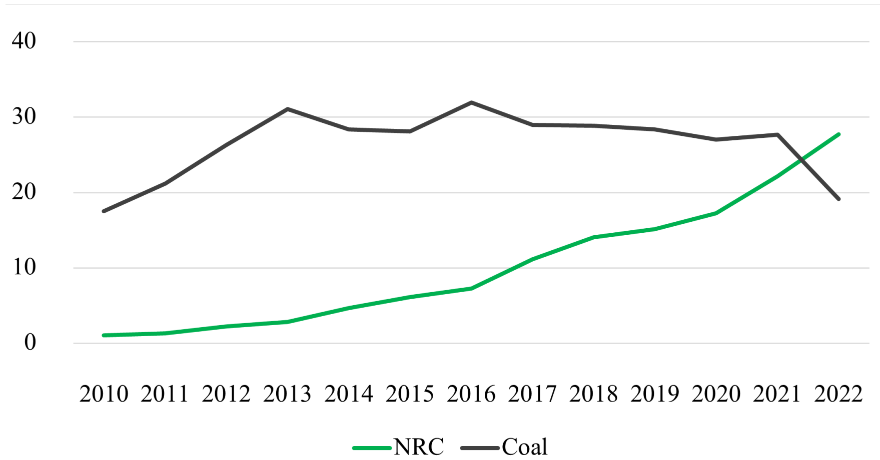
These predictions are well aligned with past and current measurements for Chile which show that the number of fires and areas burned have increased (Jolly et al. (2015), Urrutia-Jalabert et al. (2018)), that there has been a significant increment in the duration and frequency of heatwaves (Piticar (2018)), that sea levels in central Chile have risen (Campos Caba (2016)) and that there has been an expansion (5% to 20% in the last 60 years) in wave heights in the sea (Campos Caba (2016)).

Figure 1: IPCC Regional Synthesis: Ocean Acidity

Source: IPCC WGI Interactive Atlas- Regional Synthesis.

Transition Risks: Turning to transition risks, Chile is likely to face both challenges and opportunities moving forward. Specifically, Chile will need to invest considerable resources in adaptation and mitigation policies (Gobierno de Chile (2017)). Overall, the country is well-positioned to benefit from renewable energy and green investments thanks to its abundant supply of natural resources, strong government commitment, and engagement in global partnerships (Ernst & Young (2023)). In terms of mitigation policies, the government has set forth an ambitious plan, aiming for carbon neutrality by 2030, which also includes the gradual closure or conversion of coal-generating electricity plants (see Ministerio de Energia (2020)). This commitment is well reflected in Figure 2, which illustrates a gradual decline in coal generation, starting around 2016, and a continuous increase in energy production from non-conventional sources, such as wind and solar energy. Moreover, Chile, having abundant renewable energy sources and minerals that are required in a low carbon economy (such as copper and lithium) is well positioned to gain from the large increase in green investments around the globe. In this respect, in November 2020, the Government of Chile presented a plan aimed at leveraging its abundant renewable energy capacity, with the goal of becoming the cheapest producer of green hydrogen, a key component required to attain the net zero objectives (Ministry of

Figure 2: Electric Generation (Coal and NCRE)
thousands of GWh



Note: The Figure presents the evolution of electric generation (Coal and NCRE) in GWh. through time.
Source: National Electric Coordinator.

Energy, Government of Chile (2020)). This plan will also boost the exports of green ammonia and clean synthetic fuels, other key energy components.

These assessments find support in current academic studies: Givovich et al. (2022) develop projections scenarios for Chile and argue that the Magallanes region, where new green hydrogen plants are being developed, could double its regional GDP due to the inflows of new green investments; Moreno et al. (2021) develop a two-blocks model and show that exporting renewable energy from Latin America to the rest of the world is welfare improving when policies discouraging the use of fossil fuels are implemented in parallel; Airaudo et al. (2022) calibrate a two sector model for Chile and show that a green transition can have positive welfare effects when coupled with public infrastructure investments.

It is important to emphasize that all the results presented so far should be considered in light of the latest IPCC Assessment Report (IPPC (2023)). This report highlights the divergence between the emissions path consistent with the Paris Agreement – limiting warming to 1.5°C or, at most, 2°C by 2100 – and the emissions trajectories pledged by countries' Nationally Defined Contributions. In particular, the report underscores that the current climate pledges until 2030 would make it "impossible" to limit warming to 1.5°C with "no or limited overshoot" and would "strongly increase the challenge" for staying within the 2°C limit. This resulting overshooting will further aggravate the risks for Chile, potentially leading to larger output losses. It exposes the world to crossing nature's multiple tipping points and increases the probability of very unfavorable scenarios with severe damage to infrastructure, low-lying coastal settlements, and natural environments with low resilience, such as mountain and coastal ecosystems on which Chile significantly relies for its prosperity.

2.2 Sectoral Analyses of Climate Change

In parallel to studies quantifying the direct, aggregate, impacts on economic activity, a growing body of literature seeks to investigate climate risks at a more granular level, for example by comparing the impacts across economic sectors or geographic areas.

An example in this direction is Cortina and Madeira (2023), who associate climate risk indicators with entries in an administrative register of real estate properties, documenting the economic exposure of real estate to climate risks in Chile. The authors quantify the exposure of different geographical areas to five distinct climate risks: loss of labor productivity in heatwaves, fires, floods, droughts, and coastal deterioration. Depending on the indicators employed, the authors find that between 16% and 39% of the total appraisal value of real estate properties in Chile is at risk, with variations in exposure depending on geographic areas. Generally, the study identifies a higher degree of risk in central and northern regions and lower exposure in the southern parts of the country. Similarly, in line with this research, Madeira (2022) estimates that over 30 percent of property valuation is vulnerable to climate risks up to 2050.

Ponce et al. (2014) highlights the importance of supplementing aggregate analyses with sectoral ones by underscoring the role that modeling assumptions can play in driving aggregate results. The authors study the agricultural industry across geographical areas and products, evaluating the impact on yield and land allocation under the assumption of higher temperatures.[1] Overall, the impacts on the Chilean agricultural sector are widespread, with considerable distributional consequences across regions and products (for instance, in the northern zone, agricultural production is predicted to decline by 48%) and regional income (net income falls by 50% and 17% in the northern and southern regions, respectively, and increases by 17% in the southern region). The authors find that country-level income effects are relatively contained, resulting in a loss of 3% of agricultural net income. The difference between changes in regional income and production, and country-level income, follows from the assumption that farmers can reallocate land to maximize profits under different yield conditions. This latter assumption strongly hinges on the ability of the country to successfully adapt to climate change, especially in terms of irrigation and efficient use of water resources. Without adaptation, other studies find significantly larger losses.[2]

With the goal of shading light on carbon emissions across industries, Avilés-Lucero et al. (2017) use an input-output approach in order to highlight that coal-based electricity generation and the manufacturing industry are the primary direct emitters of CO2. Furthermore, in terms of overall carbon footprint, the manufacturing and

[1] The author assumes an increase in temperatures consistent with the IPCC A2-2040 scenario of Working Group 1, which provided a "best estimate" increase in global temperatures equal to 3.4°C by the end of the 21st century. See: https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-projections-of.html

[2] Specifically, other agricultural studies quantified that the economic impacts of climate change, under the A2-2040 scenario, would range from 10% (Samaniego et al. (2009)) to 5% (Melo et al. (2010)) of agricultural income.

mining sectors exhibit the highest levels of CO_2 emissions incorporated. These findings are particularly relevant to evaluate the impact of the green transition, as they facilitate the precise characterization of firms and sectors that are relatively more exposed to transition costs, and in so doing also help identify those financial institutions with greatest financial stability risk.

2.3 Current Advances in Measuring the Economic Impact of Climate Change

Despite the expanding aggregate and sectoral literature, there are several aspects that remain only partially addressed. Specifically, current studies generally do not fully account for the complete spectrum of feedback effects among sectors and the endogenous dynamics of climate-economy interactions. The Central Bank of Chile is currently working to address these gaps, focusing on three main dimensions, which are briefly summarized below:

1. **Geo-referencing of assets and the primary physical risks they face.** This ongoing analysis recognizes that the nature and intensity of climate risks vary by region, making a country-level analysis insufficient for quantifying the implications of climate change on economic activity. This is especially relevant for Chile, which is characterized by a high degree of spatial heterogeneity in the locations of capital assets and climatic shocks. As an illustration of the spatial heterogeneity of climate shocks, Table 1 summarizes the percentage decrease in cumulative precipitation, measured annually between 1979 and 2018 across different geographic areas.

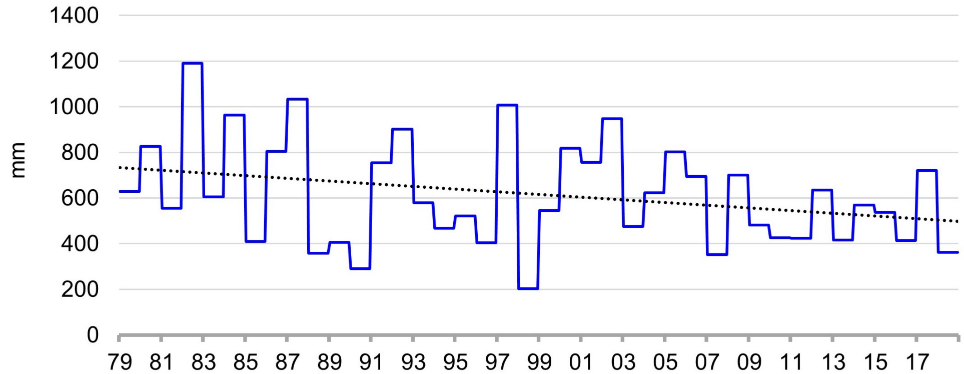
Table 1: Percentage decrease in accumulated precipitation.

Country	Great North Zone	Small North Zone	Central Zone	Central-South Zone	South Zone
11,71%	-53,95%	5,38%	29,33%	7,55%	7,08%

Source: Ministry of the Environment, Proyect ARCLIM. https://arclim.mma.gob.cl/

2. **Characterization of the transmission channels through which climate risks can propagate.** This dimension involves the analysis of spillover effects across firms, industries, and households, such as those originating from prolonged periods of drought, which can affect the available water stock for hydroelectric power generation. As shown in Figure 3, annual rainfall has decreased by 42.43% between 1979 and 2019 in the commune of Navidad, where the Rapel hydroelectric dam power plant is located. This decline can certainly impact the cost of electricity generation and percolate across the entire economy, requiring analytical frameworks capable of identifying and quantifying the shock along its transmission path.

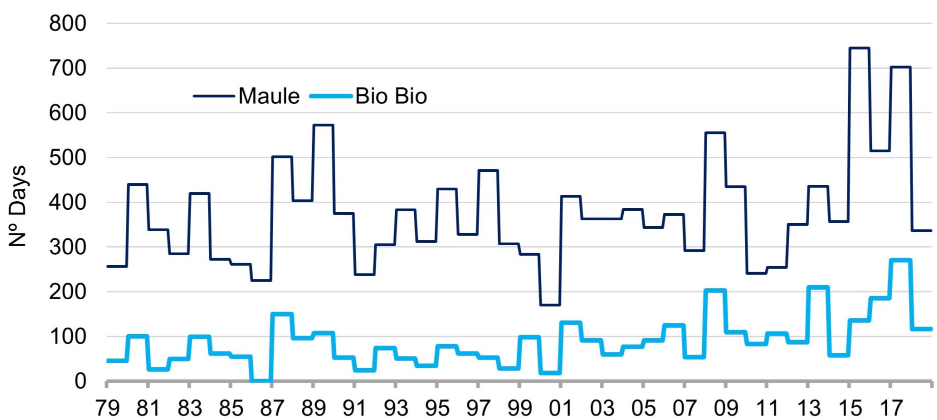
Figure 3: Rainfall Evolution - Navidad



Source: ARCLIM.

3. **Change in the uncertainty of climatic events**. Current estimations of climate shocks often assume a time-invariant stationary distribution, which is typically incorrect. For instance, Figure 4 illustrates the number of days per year with temperatures exceeding 30ºC in two primarily agricultural regions, the Maule and Bio Bio Regions. In both regions, the number of days per year characterized by extreme temperatures is increasing over the sample period, indicating a time-varying distribution of climatic events.

Figure 4: Days per year with Tº>30ºC



Source: ARCLIM.

3 An Overview of the Structural Research Agenda at the Central Bank of Chile

In order to study the role that climate and energy play in economic projections and assessments, the Macroeconomic Modeling Department of the Monetary Policy Department of the Central Bank of Chile is developing a research agenda, with the objective of incorporating environmental and energy aspects into standard macroeconomic models.[3] This type of frameworks will enable the analysis of both acute and chronic effects of climate, such as transitory energy price shocks or the consequences arising from structural changes due to higher temperatures. Additionally, it will provide a benchmark for quantifying the impact of green transition initiatives and net-zero objectives.

Presentation of the Framework: In this section we describe an extension of the textbook Neo-Keynesian Small Open Economy model (Gali and Monacelli (2005)) by allowing for a detailed energy input matrix. In addition to capital and labor, as in Landi (2021), we assume that domestic goods are produced combining oil and electricity.

We model the intermediate good i using a Constant Elasticity of Substitution (CES) technology that combines a "value-added" input (utilizing physical capital and labor) with an energy input. The latter input comprises a combination of oil and electricity, with the oil input accounting for usage in transportation and heavy industry. Electricity is produced using various technologies, including thermo-electricity, hydro-electricity, and other non-conventional renewable electricity (NCR). We assume that an agent, referred to as the Coordinator, aggregates the different types of electricity and is responsible for determining how much of each type enters the electric grid. This structure mirrors the design of the Chilean electricity markets, where a National Coordinator determines each electricity firm's production based on marginal costs. An overview of the structure of the electricity block is provided in Figure 5.

In the framework, electricity output is also assumed as a CES aggregator, as follows:

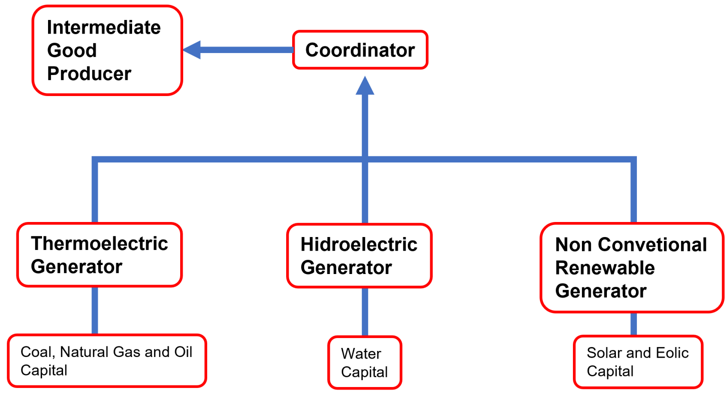
$$Y_t^E = \left[\phi_t^E \left(\gamma_T (X_t^{ET})^{\frac{\sigma_E - 1}{\sigma_E}} + \gamma_H (X_t^{EH})^{\frac{\sigma_E - 1}{\sigma_E}} + \gamma_R (X_t^{ER})^{\frac{\sigma_E - 1}{\sigma_E}}\right)\right]^{\frac{\sigma_E}{\sigma_E - 1}}$$

where X^{ET}, X^{EH}, X^{ER} denote the electricity inputs purchased from thermo-electric generating firms, hydro-electric generating firms and NCR generating firms, $\gamma_T, \gamma_H, \gamma_R$ are the shares of each input and σ_E is the elasticity of substitution. It should be noted that by modeling energy through a CES aggregator rather than a linear production function, we account for the fact that there are characteristics that do not make the various energy inputs perfect substitutes.[4] A parameter ϕ^E allows to account for transmission productivity due, for example, to the state of the

[3]Other divisions of the Central Bank of Chile are also involved in other projects associated with climate chnage; for example, The Statistics Division of the Central Bank of Chile is working on the development of methodologies for measuring Chile's natural capital, in line with the framework derived from the United Nations' System of Economic and Environmental Accounting.

[4]Like generation ramps, technical minimums or scheduled maintenance, among others.

Figure 5: Electric Block Components



Note: The Figure presents a stylized representation of the nested electricity production structure included in the model.

electricity grid infrastructure (see Schreiner and Madlener (2022)). Each electricity input is in turn assumed to be produced using a Cobb-Douglas technology, as further described below.

The thermo-electricity firm generates electricity using capital and a combination of diesel oil, natural gas, and coal, which are imported at market prices. Similarly, the hydro-electric firm produces electricity using capital and water. A distinctive feature of this firm is that water enters the production function in two forms. First, as a flow, accounting for the water used to spin the turbine that generates electricity. Second, as a stock, representing the level of water in the reservoir, which generates downward pressure on the generator.[5] Intuitively, a given water flow might generate relatively greater pressure on the electricity-generating turbines if the water stock in the reservoir is relatively higher.[6] An interesting aspect of hydro-power generation is that the stock of available water for "production" generates an intertemporal optimization problem, subject to expected future "water" shocks (such as rain) and consumption of the stock of water that is already in the reservoir.

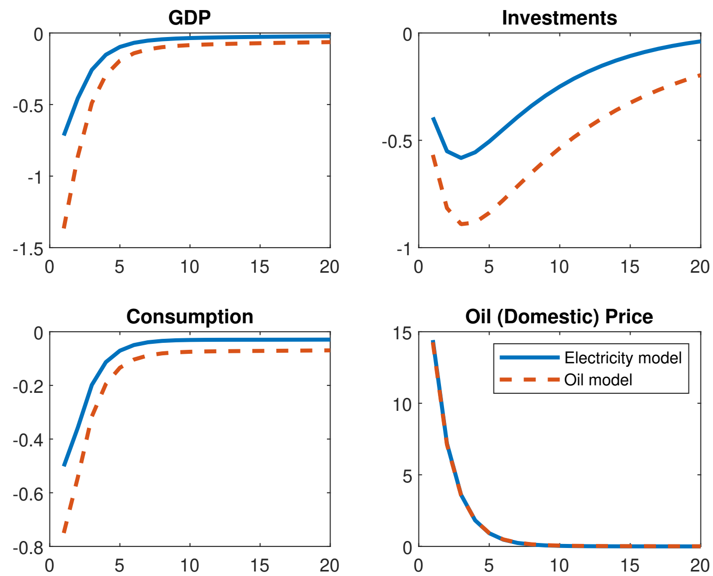
Finally, the model also includes a production function for the generation of NRC energy (such as wind, solar, and run-of-river hydro). In this case, the production function utilizes physical capital and a climate variable that follows a Markov process, reflecting that the energy input originates from natural forces (sun, wind, water).

Calibration: The model is calibrated using Chilean data sources, particularly data from the "Coordinador Electrico Nacional," and from the XMAS model developed by Garcıa et al. (2019). We set the energy share equal to 0.05, based on national accounts data, considering the average historical weight of both oil and electricity in aggregate

[5]This specification aligns with the literature on hydroelectric energy production (see Diniz and Maceira (2008), Hirsch et al. (2014), Diniz et al. (2016)), where electricity generation is a nonlinear function of the turbined outflow, the amount of stored water, and individual turbine efficiency curves.

[6]The modeling of hydro-electricity generation is limited to hydro power generated through reservoirs and excludes run-of-river reservoirs.

Figure 6: Oil Price Shock



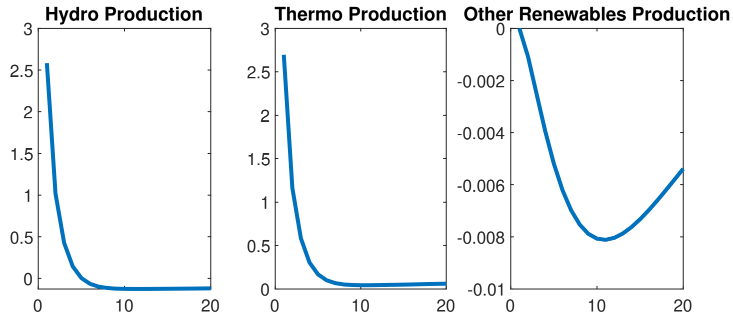
Note: The Figure shows the percentage deviation from steady state of a selection of variables following an oil price shock in the model with electricity (Electricity model) and the model with only oil (Oil model).

production. The shares of thermo-electricity, hydro-electricity, and other renewables ($\gamma_T, \gamma_H, \gamma_R$) are set equal to 0.55, 0.17, and 0.28, respectively, following the average usage in the years from 2013 to the present.

Simulations: The relevance of the proposed framework can be assessed by focusing on simple qualitative exercises that highlight the role of the electricity matrix in generating more nuanced dynamics following exogenous energy shocks, such as an exogenous shock in the international oil price. In particular, we compare the Impulse Response Functions (IRFs) of the model presented above with a counterfactual version of the model, which uses only oil as an intermediate input in the production of goods. As shown in Figure 6, the differences in dynamics are significant. Modeling the energy block allows for increased resilience of the economy following an energy shock. Specifically, the decline in output and investment is relatively lower, while the trade deficit is more contained. These outcomes arise from a strong substitution away from the use of oil input, which is now replaced by a greater use of alternative energy sources, namely hydro-power and thermo-power, as shown in Figure 7.[7] Importantly, these dynamics result from both an increase in the use of electricity as an intermediate input in the production of differentiated goods and a substitution away from oil as an input used in thermo-electricity generation.

[7]Notice that, differently from the cases of hydro and thermo-electric production, electricity generated from other renewable resources falls relative to the steady state. This result follows from the decline in investments (which arises across all economic sectors) together with the assumption of no changes in the "climate" input required for NRC production.

Figure 7: Oil Price Shock



Note: The Figure shows the percentage deviation from steady state of a selection of variables following an oil price shock in the model with electricity.

4 Conclusion

Understanding the impact of physical and transition risks of climate change has become a priority for policymakers around the world. In the case of Chile, direct impact of higher temperatures are overall predicted to be medium to strong, and the economy is already facing new challenges and opportunities, as the world embarks on ambitious net-zero goals, which will propel new investments and a reshaping of the economy. In this respect, the country has already accelerated its energy transition through private-public partnerships and innovative green technologies as seen, for example, in Ministry of Energy, Government of Chile (2020) and Ministerio de Energia (2020).

This policy note summarized the results from several studies that quantify the impacts of climate in Chile, with an emphasis on both the macroeconomic and sectoral effects of higher temperatures and other climate events. The review highlighted the need to expand the analytical efforts to quantify the impacts of climate in Chile along three main dimensions, namely geo-referencing of physical and financial assets, characterization of the transmission channels through which climate shocks can spread throughout the economy and accounting for the fact that climate events are not stationary. Finally, the note presented the results from a first modeling effort aimed at integrating climate aspects within a standard general equilibrium model. This structural modeling step will help address some of the dimensions discussed above, by mapping the transmission mechanisms of climate shocks on energy productions, prices and eventually consumption and investments.

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