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## Article

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## A preliminary assessment of the economic effects of energy and climate in Chile<sup>☆</sup>

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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.

### 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 et al. \(2011\)](#) 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

<sup>☆</sup> 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, participants of the IV Central Bank Conference on Environmental Risks and the Macroeconomic Modeling team of the Central Bank of Chile for helpful comments and feedback.

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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%, and 5.2% of GDP 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.

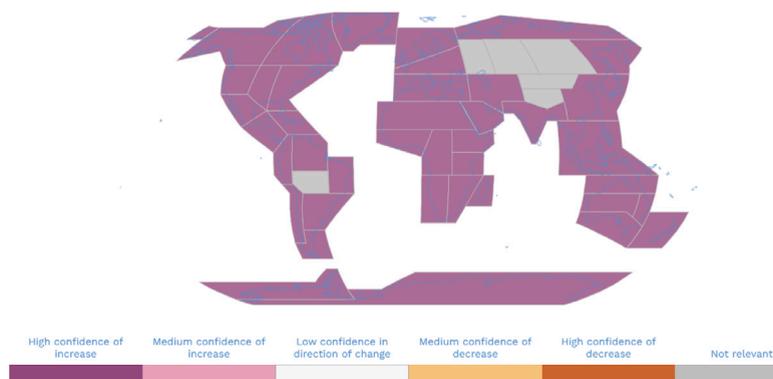
In this respect, the IPCC WGI Interactive Atlas (Gutiérrez et al., 2021) offers a complementary assessment by summarizing the predictions from a range of models presented in the IPCC reports on the impact of changes in key atmospheric and oceanic variables. As an example, the atlas shows that there is a high level of confidence across models that ocean acidity will increase (see Fig. 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.

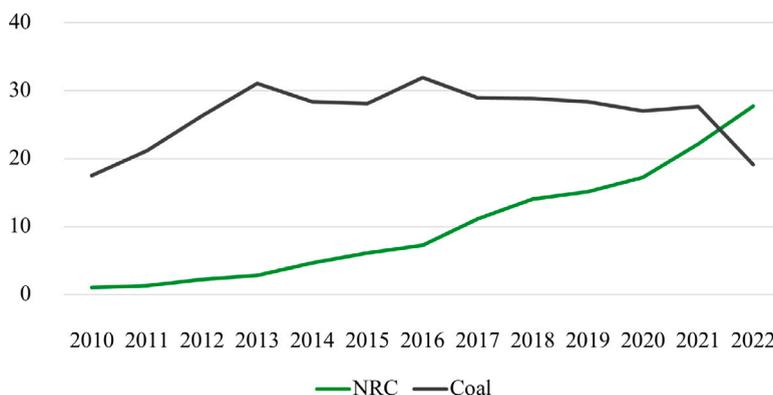
These predictions are well aligned with past and current measurements for Chile which show that the number of fires and burned areas have increased (Jolly et al., 2015; Urrutia-Jalabert et al., 2018), that there has been a significant increment in the duration and frequency of heatwaves (Piticar, 2018), 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).

Finally, Table 1 categorizes the findings from a selection of papers regarding the severity of the effects of physical risks in Chile. The table includes both economic papers focusing on the effect on GDP (first column) and also interdisciplinary papers focusing on the impact on environmental variables such as temperatures and heat (second to last column). This review highlights once more that even though there is some degree of uncertainty regarding the impacts, overall Chile is poised to experience significant effects going forward.

**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 Ministry of Energy (2020a)). This commitment is well reflected in Fig. 2, which illustrates a gradual decline in coal generation, starting around 2016, and a continuous increase in energy production



**Fig. 1.** IPCC Regional synthesis: Ocean acidity.  
 Source: IPCC WGI Interactive Atlas- Regional Synthesis.



**Fig. 2.** Electric generation (Coal and NRC) thousands of GWh. Note: The Figure presents the evolution of electric generation shares between Coal and Non Conventional Renewable Energy (NRC) in GWh. through time.  
 Source: National Electric Coordinator.

**Table 1**  
 Summary of physical risks for Chile in literature.

	GDP	Average T°	Extreme heat	Coastal floods	# Fires	Sea levels
<i>Empirical economic studies</i>						
Roson and Sartori (2016)	a					
Kalkuhl and Wenz (2020)	c					
Kahn et al. (2021)	c					
<i>Structural economic studies</i>						
OECD (2015)	a					
Cruz and Rossi-Hansberg (2021)	b					
Guo et al. (2021)	b					
<i>Interdisciplinary studies</i>						
Gutiérrez et al. (2021)		b	b	b	b	b
Jolly et al. (2015)					c	
Urrutia-Jalabert et al. (2018)					c	
Piticar (2018)			c			
Campos Caba (2016)						c

Note: The table shows the impact of climate change on the physical risks for Chile as documented by a selection of papers.

<sup>a</sup> The negative impacts on different variables of interest are classified as low.

<sup>b</sup> The negative impacts on different variables of interest are classified as medium.

<sup>c</sup> The negative impacts on different variables of interest are classified as high.

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 Energy, 2020b). 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. (2024) 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; Airaud 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 (IPCC, 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 product yield and land allocation under the assumption of higher temperatures.<sup>1</sup> 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.<sup>2</sup>

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 CO<sub>2</sub>. Furthermore, in terms of overall carbon footprint, the manufacturing and mining sectors exhibit the highest levels of CO<sub>2</sub> 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.

Drawing from the existing literature, Table 2 summarizes a list of challenges and opportunities that transitioning to a low carbon economy will bring about. The studies highlight the importance of greater public and private investment in resilience and adaptation, especially when it comes to infrastructure that allows reducing physical and transition risks; as well as the investment necessary to take advantage of the enormous potential of renewable energy (as in the case of green hydrogen).

<sup>1</sup> 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/spmssp-projections-of.html](https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/spmssp-projections-of.html).

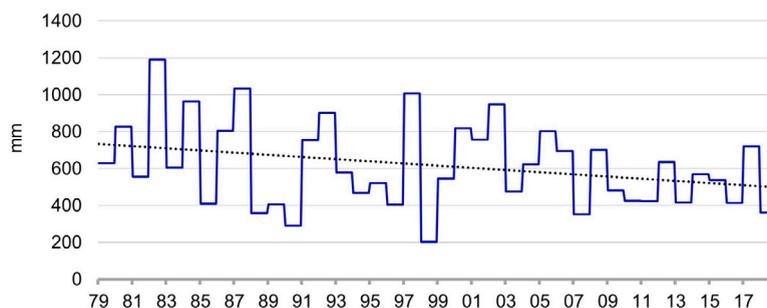
<sup>2</sup> Specifically, other agricultural studies quantified that the economic impacts of climate change, under the A2-2040 scenario, would range from 10% (Samani et al., 2009) to 5% (Melo et al., 2010) of agricultural income.

**Table 2**  
Summary of transition and sectoral effects for Chile in the literature.

	Challenges	Opportunities
<i>Policy papers</i>		
Gobierno de Chile (2017) Ernst & Young (2023) Ministry of Energy (2020a) Ministry of Energy (2020b)	Higher investment in adaptation  Change in energy matrix	Renewable energy potential  Green hydrogen
<i>Academic papers</i>		
Givovich et al. (2022) Moreno et al. (2024) Airaudo et al. (2022) Cortina and Madeira (2023) Ponce et al. (2014) Avilés-Lucero et al. (2017)	Higher investment in public infrastructure Exposure of real estate to climate risks Investment in adaptation (reallocation of the land) Use of fossil fuels in the productive matrix	Green hydrogen Renewable energy potential and green hydrogen R&D in green technologies  Welfare effects on agricultural sector

**Table 3**  
Percentage decrease in accumulated precipitation between 1979 and 2018.  
Source: Ministry of the Environment, Proyect ARCLIM. <https://arclim.mma.gob.cl/>.

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%



**Fig. 3.** Rainfall evolution - Navidad.  
Source: ARCLIM.

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:

- 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 3 summarizes the percentage decrease in cumulative precipitation, measured annually between 1979 and 2018 across different geographic areas.
- 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 Fig. 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.
- 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, Fig. 4 illustrates the number of days per year with temperatures exceeding 30 °C 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.

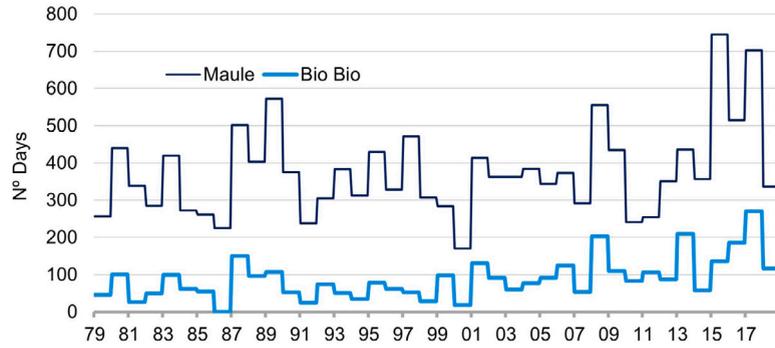


Fig. 4. Days per year with  $T^{\circ} > 30^{\circ} \text{C}$ .  
Source: ARCLIM.

### 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 Division of the Central Bank of Chile is developing a research agenda, with the objective of incorporating environmental and energy aspects into standard macroeconomic models.<sup>3</sup> 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 within the context of net-zero objectives.

#### 3.1. Presentation of the framework

In this section we describe the building blocks of the framework developed by Durand et al. (2024), which extends the Neo-Keynesian Small Open Economy model of Gali and Monacelli (2005) by allowing for a detailed energy input matrix.<sup>4</sup> In the following we will only detail the extensions associated with adding an energy bloc and refer the reader to Appendix for a description of the non-energy related parts of the model, together with the full set of equilibrium conditions.

##### 3.1.1. Intermediate goods producers

As in standard textbook models, the final goods producer demands  $X_t^Z(i)$  from intermediate goods producer  $i$ . However, while in standard models the intermediate good is produced only with capital ( $k$ ) and labor ( $h$ ) using a Cobb–Douglas production function,

$$Y_t^Z(i) = z_t^Z (k_{t-1}(i))^{\alpha} (h_t(i))^{1-\alpha} \tag{1}$$

(where  $z_t^Z$  denotes an exogenous productivity term), our extension assumes that the intermediate goods also require an energy input, which is made by combining oil and electricity.<sup>5</sup>

In particular, we model the intermediate goods produced by firm  $i$  using a Constant Elasticity of Substitution (CES) technology that combines a “value-added” non-energy productive input (utilizing physical capital and labor, as above) with an energy input:

$$y_t^H(i) = z_t \left[ e^{\frac{1}{\eta_H}} \left( X_t^Z(i) \right)^{\frac{\eta_H-1}{\eta_H}} + (1 - e^{\frac{1}{\eta_H}}) \left( X_t^{EB}(i) \right)^{\frac{\eta_H-1}{\eta_H}} \right]^{\frac{\eta_H}{\eta_H-1}} \tag{2}$$

where the parameters  $e_{\bar{H}} \in (0, 1), \eta_{\bar{H}} > 0$  are the inputs shares and elasticity of intra-temporal substitution, respectively.<sup>6</sup> The variable  $X_t^{EB}$  is the energy input, and the non-energy productive input is produced following the specification in Eq. (1). Now the intermediate goods producer not only chooses how much capital to rent and labor to hire, but also how much energy,  $X_t^{EB}(i)$ , to use in production. Since, once accounting for the energy bundle component, the maximization problem of these firms is standard we refer the reader to Appendix for further details.

<sup>3</sup> Other divisions of the Central Bank of Chile are also involved in other projects associated with climate change; 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.

<sup>4</sup> In order to streamline the presentation of the model we organized the equilibrium conditions associated with each maximization program in Appendix.

<sup>5</sup> Note that in this document we will use  $X_t^i$  to denote the demand for a specific type of good and  $Y_t^i$  to denote the supply of the same good.

<sup>6</sup> A similar nomenclature is used throughout the text for the other firms.

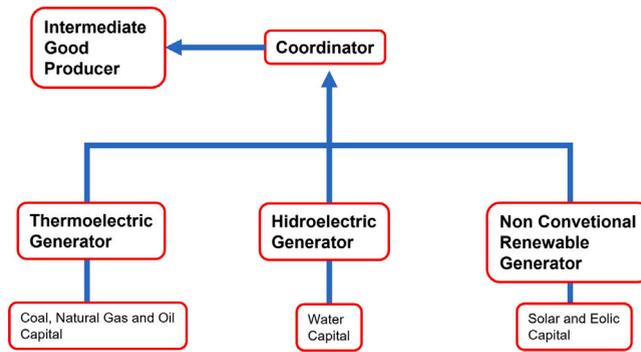


Fig. 5. Electric block components. Note: The Figure presents a stylized representation of the nested electricity production structure included in the model.

3.1.2. Energy bundle producers

The energy bundle input is in turn produced by a representative wholesale firm who chooses a combination of oil and electricity, with the oil input accounting for usage in transportation and heavy industry. We assume the following CES technology:

$$Y_t^{EB} = \left[ e_{EC}^{\frac{1}{\eta_{EB}}} (X_t^{EC})^{\frac{\eta_{EB}-1}{\eta_{EB}}} + e_{EO} (X_t^O)^{\frac{\eta_{EB}-1}{\eta_{EB}}} \right]^{\frac{\eta_{EB}}{\eta_{EB}-1}} \tag{3}$$

where  $e_{EC}$ ,  $X_t^{EC}$  are the share of electricity used in the production of the energy bundle and the demand of electricity, respectively, and  $e_O$ ,  $X_t^O$  are the share of oil used in the production of the energy bundle and the demand of oil, respectively. Finally,  $\eta_{EB}$  is the elasticity of substitution between electricity and oil in the energy bundle. We assume that this input is produced by a representative energy bundle firm, who maximizes profits as follows:

$$\max_{Y_t^{EB}, X_t^{EC}, X_t^O} P_t^{EB} Y_t^{EB} - P_t^{EC} X_t^{EC} - P_t^O X_t^O \tag{4}$$

Allowing for oil as a separate input in the energy bundle follows the recent literature (Coenen et al., 2023; Argentiero et al., 2017) and reflects that oil is not only used as an input for electric generation but also for other activities within the production chain, such as transportation and manufacturing. Introducing the energy bundle has non-trivial effects on the economy. For instance, changes in its costs affect output and inflation, also depending on the degree of substitution and its share in the overall production costs. In addition, changes in the amount and the cost of electricity can also affect total output and inflation.

3.1.3. Electricity generation

Electricity is produced using various technologies, including thermo-electricity, hydro-electricity, and other non-conventional renewable electricity (NCR). We assume that a representative 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 Fig. 5.

The coordinator sells the energy bundle to the wholesale firm, choosing the combination of different electricity inputs so as to maximize profits:

$$\max_{Y_t^{EC}, X_t^{ET}, X_t^{EHy}, X_t^{ER}} P_t^{EC} Y_t^{EC} - P_t^{ET} X_t^{ET} - P_t^{EHy} X_t^{EHy} - P_t^{ER} X_t^{ER} \tag{5}$$

s.t.

$$Y_t^{EC} = z_t^{EC} \left( e_{ET}^{\frac{1}{\eta_{EC}}} (X_t^{ET})^{\frac{\eta_{EC}-1}{\eta_{EC}}} + e_{EHy}^{\frac{1}{\eta_{EC}}} (X_t^{EHy})^{\frac{\eta_{EC}-1}{\eta_{EC}}} + e_{ER}^{\frac{1}{\eta_{EC}}} (X_t^{ER})^{\frac{\eta_{EC}-1}{\eta_{EC}}} \right)^{\frac{\eta_{EC}}{\eta_{EC}-1}} \tag{6}$$

where  $X_t^{ET}$ ,  $X_t^{EHy}$ ,  $X_t^{ER}$  denote the amount of electricity demanded from thermo-power (ET), hydro-power (EHy), and other renewable sources, (ER), and  $e_{ET}$ ,  $e_{EHy}$ ,  $e_{ER}$  denote their respective shares. Finally, the variable  $z_t^{EC}$  allows to capture exogenous efficiency gains in production of electricity (see Schreiner and Madlener (2022)). With the assumption of a CES technology 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.<sup>7</sup> Each electricity input is in turn assumed to be produced using a Cobb–Douglas technology, as further described below.

The thermo-electric generator representative firm imports oil,  $X_t^{TO}$ , natural gas,  $X_t^{TG}$  and coal,  $X_t^{TCO}$  at international prices in dollars  $P_t^{O*}$  for oil,  $P_t^{TG*}$  for natural gas and  $P_t^{TCO*}$  for coal. In local currency these prices are given by  $P_t^O = e_t P_t^{O*}$  for oil,

<sup>7</sup> Like generation ramps, technical minimums or scheduled maintenance, among others.

$P_t^{TG} = e_t P_t^{TG*}$  for natural gas and  $P_t^{TCO} = e_t P_t^{TCO*}$ , where  $e_t$  denotes the nominal exchange rate. The firm optimize the combination of inputs to produce electricity. We assume that the fuel bundle is combined using a CES technology, allowing for imperfect substitutability among the fuel sources. After choosing the optimal fuel bundle,  $FB_t$ , the representative firm combines this bundle with capital to generate electricity. To simplify the algebra we separate the problem in two stages. In the first stage of the problem the minimization of costs (in local currency) is given as follows:

$$\min_{X_t^{TO}, X_t^{TG}, X_t^{TCO}} P_t^O X_t^{TO} + P_t^{TG} X_t^{TG} + P_t^{TCO} X_t^{TCO} \tag{7}$$

s.t.

$$FB_t = \left[ e_{TO}^{\frac{1}{\eta_T}} (X_t^{TO})^{\frac{\eta_T-1}{\eta_T}} + e_{TG}^{\frac{1}{\eta_T}} (X_t^{TG})^{\frac{\eta_T-1}{\eta_T}} + e_{TC}^{\frac{1}{\eta_T}} (X_t^{TCO})^{\frac{\eta_T-1}{\eta_T}} \right]^{\frac{\eta_T}{\eta_T-1}} \tag{8}$$

In the second stage, the firm decides how much to sell to the electric coordinator and how much capital to invest for future production. Therefore, the problem can be summarized as:

$$\max_{Y_t^{ET}, I_t^T, K_t^T, FB_t} \mathbb{E}_0 \sum_{t=0}^{\infty} \Xi_{0,t}^R [p_t^{ET} Y_t^{ET} - p_t^{FB} FB_t - I_t^T] \tag{9}$$

s.t.

$$Y_t^{ET} = z_t^T (K_{t-1}^T)^{\alpha^T} FB_{t,t}^{1-\alpha^T} \tag{10}$$

$$K_t^T = (1 - \delta)K_{t-1}^T + \left( 1 - \frac{\kappa^T}{2} \left( \frac{I_t^T}{I_{t-1}^T} - a \right)^2 \right) I_t^T \tag{11}$$

where  $I_t^T$  denotes investment in physical capital,  $z_t^T$  is a sector-specific exogenous productivity process, and  $\delta, \alpha^T, \kappa^T$  are the depreciation rate, the output elasticity to capital and an adjustment cost parameter, respectively.  $p^{ET}, p^{FB}$  are the relative prices (in terms of consumption goods) of the thermo-electric output and fuel bundle, respectively.<sup>8</sup> Finally  $\Xi^R$ , denotes the stochastic discount factor of the households (owners of the firms).

Similarly, the hydro-electric firm maximizes profits by selling hydro-electric power, which is generated 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.<sup>9</sup> Intuitively, a given water flow generates relatively greater pressure on the electricity-generating turbines if the water stock in the reservoir is relatively higher.<sup>10</sup> An interesting aspect of hydro-power generation is that the stock of available water for “production” gives rise to an intertemporal optimization problem that takes into account expected future “water” shocks (such as rain) and consumption of the stock of water that is already in the reservoir. Formally, the hydro-electric firm solves the following program:

$$\max_{Y_t^{EHy}, I_t^{Hy}, K_t^{Hy}, W_t^F, W_t^{ST}} \mathbb{E}_0 \sum_{t=0}^{\infty} \Xi_{0,t}^R (p_t^{EHy} Y_t^{EHy} - I_t^{Hy}) \tag{12}$$

s.t.

$$W_t^{ST} = W_{t-1}^{ST} - W_t^F + \zeta_t \tag{13}$$

$$K_t^{Hy} = (1 - \delta_H)K_{t-1}^{Hy} + \left( 1 - \frac{\kappa^{Hy}}{2} \left( \frac{I_t^{Hy}}{I_{t-1}^{Hy}} - a \right)^2 \right) I_t^{Hy} \tag{14}$$

$$Y_t^{EHy} = z_t^{Hy} (K_{t-1}^{Hy})^{\alpha^{Hy}} \left( (W_{t-1}^{ST})^{\varphi_{Hy}} W_t^F \right)^{1-\alpha^{Hy}} \tag{15}$$

where Eq. (13) describes how the water stock ( $W^{ST}$ ) evolves over time depending on the amount of water that is depleted ( $W^F$ ), Eq. (14) is a standard investment ( $I_t^{Hy}$ ) equation and Eq. (15) is the definition of hydroelectric output ( $Y_t^{Hy}$ ). In the latter, the second term reflects the interplay between water stock and water flow discussed above. The parameter  $\delta_{Hy}$  denotes the depreciation rate of the hydro-electric capital  $\kappa^{Hy}$  denotes the level of the investment adjustment cost and  $\varphi_{Hy}$  is a parameter that measures the sensibility of the electricity production to the level of the water and  $z_t^{Hy}$  is an exogenous productivity process. Because of the novelty of introducing the management of the resources stock, it is useful to briefly summarize the FOCs associated with this program with respect to the choice of  $W_t^F$  and  $W_t^{ST}$ :

$$[W_t^F] : \quad \lambda_t^{Hy} = (1 - \alpha^{Hy}) p_t^{Hy} \frac{Y_t^{EHy}}{W_t^F} \tag{16}$$

<sup>8</sup> In the rest of the text we will maintain this convention and describe relative prices of firms output with respect to the consumption good using small letters.

<sup>9</sup> This specification aligns with the literature on hydroelectric energy production (see Diniz and Maceira (2008), Hirsch et al. (2014) and Diniz et al. (2016)), where electricity generation is a nonlinear function of the outflow, the amount of stored water, and individual turbine efficiency curves.

<sup>10</sup> The modeling of hydro-electricity generation is limited to hydro-power generated through reservoirs and excludes run-of-river systems.

$$[W_t^{ST}] : \quad \lambda_t^{Hy} = \mathbb{E}_t \Xi_{t,t+1}^R \left[ (1 - \alpha^{Hy}) \varphi_{Hy} \rho_{t+1}^{Hy} \frac{Y_{t+1}^{EHy}}{W_t^{ST}} + \lambda_{t+1}^{Hy} \right] \quad (17)$$

where  $\lambda_t^{Hy}$  is the shadow price of water. Eq. (16) sets the latter equal to the marginal contribution that one additional unit of water passed through the turbine has in generating hydro electricity. Eq. (17) is an Hotelling Condition (Hotelling, 1931) that equates the marginal cost of conserving one additional unit of water today in terms of lost electricity production against the expected marginal benefit that originates from having a larger stock of available water to use in the next period.

In the case of hydroelectric generation, investment adjustment costs play a major role due to the complexity and scale of the construction process. According to a 2023 National Energy Commission Report, [Comisión Nacional de Energía \(2023\)](#), the cost of each Mega Watt (MW) of power in a hydroelectric plant is more expensive than the cost of thermo-electric generating plants (5205 thousands USD and 791 thousands USD, respectively). In addition, in its 2019 document, [Comisión Nacional de Energía \(2019\)](#), reports that a hydroelectric plant construction requires between 87 and 205 months to complete, compared to as little as 24 months for the case of a thermo-electric plant.

Finally, the model also includes a production function for the generation of other renewable sources of energy (such as wind, solar, and run-of-river hydro). In this case, firms combine sector specific capital and a renewable energy source. The latter is modeled as a random variable to reflect the fact that the amount of primary energy (solar, wind, hydro) received is exogenous to the firm. Therefore, the choice of the electric firm consists in only deciding how much capital to invest. The maximization of the problem is given by

$$\max_{Y_t^{ER}, I_t^R, K_t^R} \mathbb{E}_0 \sum_{t=0}^{\infty} \Xi_{0,t}^R (p_t^{ER} Y_t^{ER} - I_t^R) \quad (18)$$

*s.t*

$$K_t^R = (1 - \delta^R) K_{t-1}^R + \left( 1 - \frac{\kappa^R}{2} \left( \frac{I_t^R}{I_{t-1}^R} - a \right)^2 \right) I_t^R \quad (19)$$

$$Y_t^{ER} = z_t^R (K_{t-1}^R)^{\alpha^R} (RS_t)^{1-\alpha^R} \quad (20)$$

$$RS_t = \rho_R RS_{t-1} + \epsilon_t^{RS} \quad (21)$$

where  $RS_t$  is the renewable energy source, which evolves according to an autoregressive process determined by a parameter  $\rho_R$  and a shock  $\epsilon_t^{RS}$ , as described by Eq. (21) and  $\kappa^R$  is an adjustment cost parameter. Similar to the other firms,  $I_t^R, K_t^R, Y_t^{ER}$  denote investments, capital and output, respectively.

### 3.2. Calibration & simulations

The electricity bloc of the model is calibrated using Chilean data from the “Coordinador Electrico Nacional” and also following other papers that introduce energy in DSGE models, such as [Airaudo et al. \(2022\)](#), [Coenen et al. \(2023\)](#), and [Argentiero et al. \(2017\)](#). The non-electricity bloc is instead calibrated following the XMAS model developed by [Garcia 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 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.

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 economic dynamics following exogenous energy shocks, such as a 15% shock to the international oil price.<sup>11</sup>

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 energy source in the production of goods.<sup>12</sup> As shown in [Fig. 6](#), the differences in dynamics are significant. Modeling the energy bloc allows for increased resilience of the economy following an oil price shock. Specifically, the decline in output, investment and consumption is relatively lower. In addition, inflation has a much milder reaction.

These outcomes arise from a strong substitution away from the use of the oil input, which is now replaced by a greater relative use of alternative energy sources, namely hydro-power and other renewables, as shown in [Fig. 7](#). In terms of prices, the model predicts an increase across all sources of electricity, with thermo-electricity showing the largest change.

As another exercise that can be useful to understand the possible effects of a green transition, we analyze a counterfactual economy where we assume a lower use of thermo-electricity as an input in production of the electricity bundle. In this case we set the share of thermo-electric production to 0.2 and increase the shares of hydro-electric and renewable electricity to 0.4 each. As [Fig. 8](#) shows, the effects of an oil price shock on the overall economy are diminished compared to the base scenario. This is expected since the thermo-electric generation, which partially relies on oil, is now assumed to be a less relevant input in production.

<sup>11</sup> We assume that a percentage of this shock also contemporaneously affects the international prices of coal and gas.

<sup>12</sup> Note that even though both models have different steady states, these differences are only marginal as energy represents only 5% of the cost of the representative good. In addition, the exercises are presented in terms of percentage deviations from steady states, which should control for some of the effect of the differences in steady states.

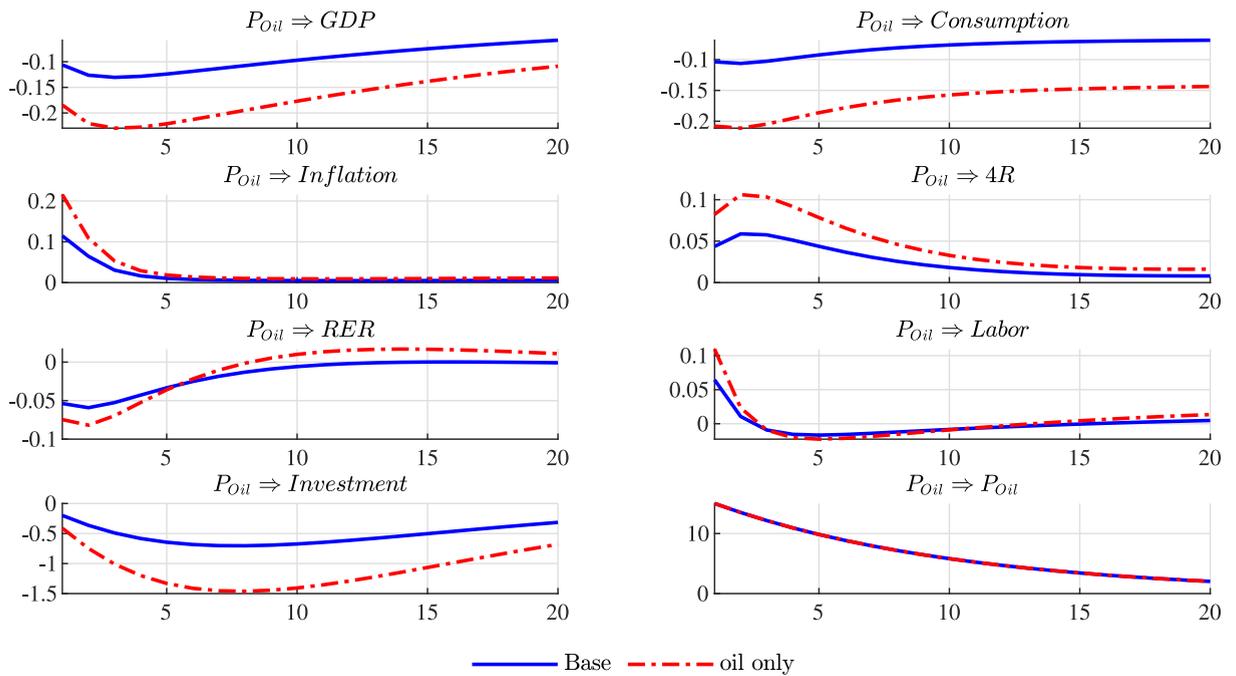


Fig. 6. Comparison of effects of oil price shocks in two economies. Note: The Figure shows the percentage deviation from steady state of a selection of variables following an international oil price transitory shock, comparing the model with electricity (Base) and the model with only oil (Oil only). RER refers to the real exchange rate and 4R to annualized the monetary policy rate. Each period corresponds to one quarter.

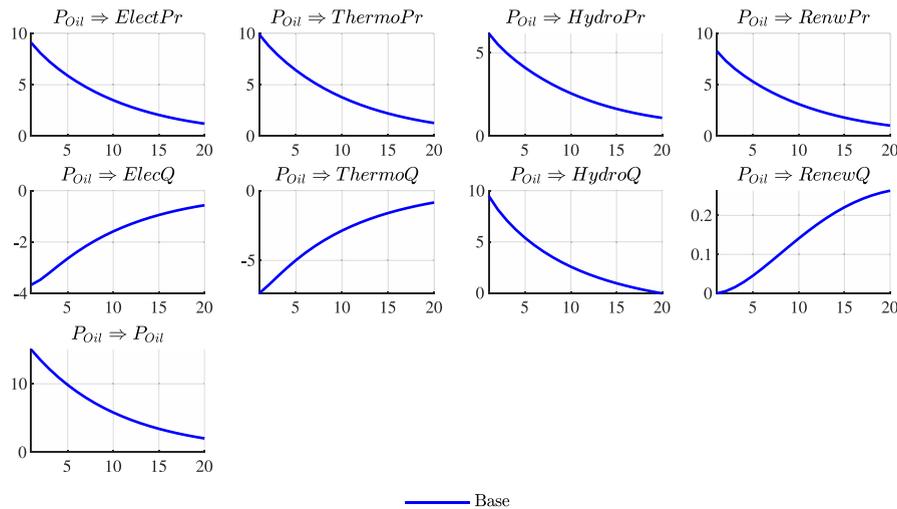
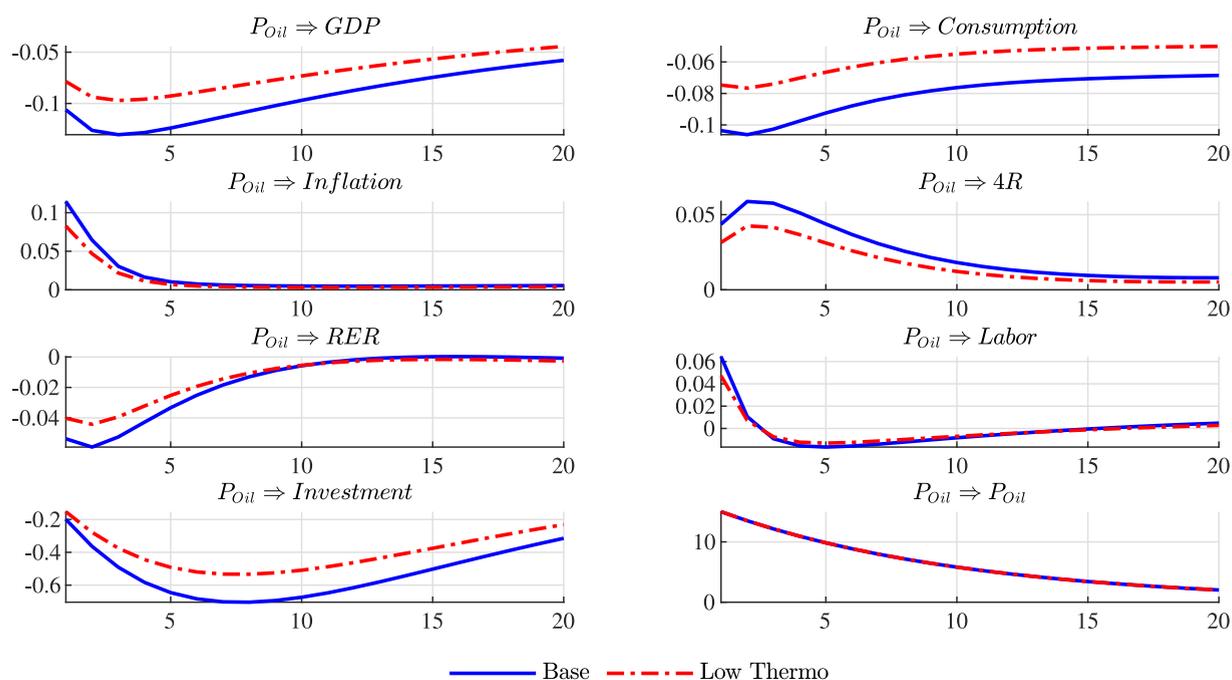


Fig. 7. Effects on electric generation of an oil price shock. Note: The Figure shows the percentage deviation from steady state of a selection of variables following an oil price shock in the model with electricity (Base). Each period corresponds to one quarter.

#### 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 \(2020b,a\)](#).

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



**Fig. 8.** Effects of an oil price shock in an economy with low thermo-electricity. 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, by distinguishing between the baseline scenario (Base) and a scenario where thermo-electric production accounts for a relatively lower share of electricity production (Low Thermo). RER refers to the real exchange rate and 4R to the annualized monetary policy rate. Each period corresponds to one quarter.

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.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Disclaimer

During the preparation of this work the author(s) used ChatGPT in order to improve the style and grammar of the document. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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#### Appendix. Mathematical appendix

A.1. Neo-Keynesian model: Households and goods producing firms

As already mentioned in the main text, we follow the structure of a textbook Neo-Keynesian model (Galí, 2015) with capital and investment adjustment costs as in Nispi Landi (2021) and Wickens (2011), and extended with energy provision.

In this section we discuss the blocs of the model that were not presented in the main text. Specifically, we review in turn the maximization problem of the representative household, the representative final home good firm and the differentiated intermediate goods firms.

A.1.1. Representative household

A representative household consumes a bundle of two final goods, one produced by domestic final firms ( $c_H$ ) and the other produced by foreign final firms ( $c_F$ ) as follows:

$$c_t = \left[ (1 - \gamma)^{\frac{1}{\eta}} c_{Ht}^{\frac{\eta-1}{\eta}} + \gamma^{\frac{1}{\eta}} c_{Ft}^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} \tag{22}$$

The representative household solves a two step problem. First, she maximizes her utility function by deciding how much to save and work; second she chose how to allocate her expenditure between purchases of home and foreign goods. The first problem can be summarized as follows:

$$\max_{c_t, i_t, h_t, k_t, B_t, B_t^F} \mathbb{E}_0 \sum_{s=0}^{\infty} \beta^s \left( \frac{c_{t+s}^{1-\sigma}}{1-\sigma} - \kappa_L \frac{h_{t+s}^{1+\varphi}}{1+\varphi} \right) \tag{23}$$

s.t.

$$P_t c_t + P_t i_t + B_t + e_t B_t^F = W_t h_t + R_t^K k_{t-1} + (1 + r_{t-1}) B_{t-1} + e_t (1 + r_{t-1}^*) B_{t-1}^F \tag{24}$$

$$+ T_t + \Gamma_t - \frac{\kappa_D}{2} e_t P_t^* \left( \frac{B_t^F}{P_t^*} - \frac{B^F}{P^*} \right) \tag{25}$$

$$k_t = (1 - \delta)k_{t-1} + \left[ 1 - \frac{\kappa_I}{2} \left( \frac{i_t}{i_{t-1}} - 1 \right)^2 \right] i_t \tag{26}$$

where  $P_t, P_t^*$  are the prices of the Home and Foreign final consumption goods, respectively;  $W_t$  denotes the nominal wage rate,  $h_t$  refers to the number of hours worked,  $B_t, B_t^F$  are the holdings of one period domestic and foreign bonds, respectively;  $e_t$  is the nominal exchange rate,  $r_t, r_t^*, R_t^K$  are the nominal domestic and foreign interest rates and the (net) return on capital, respectively;  $k_{t-1}$  is the stock of capital at time  $t$  and  $i_t$  denotes investments.  $T_t, \Gamma_t$  denote nominal fiscal transfers and profits from ownership of the domestic firms. We assume that domestic households pay a quadratic adjustment cost when they change their financial position with the rest of the world and when they change their investments. The term  $B^F/P^*$  refers to a long-term average.

The second program can be described as follows:

$$\min_{c_{H,t}, c_{F,t}} \frac{1}{P_t} [P_t^H c_{H,t} + P_t^F c_{F,t}] \tag{27}$$

s.t. (22)

where  $P_t^H, P_t^F$  are the prices of the home and foreign goods, respectively.

A.1.2. The final home good firm

The final Home good firm uses a CES aggregator to produce the final good

$$Y_t^H = \left[ \int_0^1 y_t^H(i)^{\frac{\varepsilon-1}{\varepsilon}} di \right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{28}$$

and maximizes the following program:

$$\max_{y_t^H, y_t^H(i)} P_t^H Y_t^H - \int_0^1 P_t^H(i) y_t^H(i) di \tag{29}$$

s.t. (28)

A.1.3. The intermediate goods firms

The intermediate goods firms indexed by  $i$  solve two maximization problems: first they chose an optimal amount of labor and rented Home capital; second they maximize profits subject to a downward sloping demand for variety  $i$  and quadratic adjustment costs as in Rotemberg (1982), whenever they adjust prices. Step one can be summarized as:

$$\min_{h_t(i), k_{t-1}(i)} \mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \frac{\lambda_{t+s}}{\lambda_t} \frac{1}{P_{t+s}} (W_{t+s} h_{t+s}(i) + R_{t+s}^K k_{t+s-1}(i)) \tag{30}$$

s.t.

$$X_t^Z(i) = z_t^Z (k_{t-1}(i))^\alpha (h_t(i))^{1-\alpha} \tag{31}$$

while step two is given by:

$$\max_{P_t^H(i), Y_t^H(i), X_t^Z(i), X_t^{EB}(i)} \mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \frac{\lambda_{t+s}}{\lambda_t} \frac{1}{P_{t+s}} \left( P_{t+s}^H(i) Y_{t+s}^H(i) - MC_{t+s}(i) X_{t+s}^Z(i) - P_{t+s}^{EB} X_{t+s}^{EB}(i) - \frac{\kappa_p}{2} \left( \frac{P_{t+s}^H(i)}{P_{t+s-1}^H(i)} - 1 \right)^2 P_{t+s}^H Y_{t+s}^H \right) \tag{32}$$

s.t.

$$y_t^H(i) = z_t^H \left[ e^{\frac{1}{\eta_H}} \left( X_t^Z(i) \right)^{\frac{\eta_H-1}{\eta_H}} + (1 - e^{\frac{1}{\eta_H}}) \left( X_t^{EB}(i) \right)^{\frac{\eta_H-1}{\eta_H}} \right]^{\frac{\eta_H}{\eta_H-1}} \tag{33}$$

$$y_t^H(i) = \left( \frac{P_t^H(i)}{P_t^H} \right)^{-\epsilon} Y_t^H \tag{34}$$

where  $\lambda_t$  is the marginal utility of consumption of the households (who are the owners of the firms) and  $MC_t$  denotes marginal costs.

### A.2. List of equilibrium conditions

In this section we summarize all the equilibrium conditions of the Neo-Keynsian model with electricity, as presented in this paper.

#### A.2.1. Households

These equilibrium conditions directly follow from the households maximization problem described in Eqs. (23) and (27).

$$[c_t] : \quad c_t^{-\sigma} = \lambda_t \tag{35}$$

$$[h_t] : \quad w_t = \kappa_L \frac{h_t^\varphi}{\lambda_t} \tag{36}$$

$$[B_t] : \quad \lambda_t = \beta \mathbb{E}_t \left[ \lambda_{t+1} \frac{1 + r_t}{1 + \pi_{t+1}} \right] \tag{37}$$

$$[B_t^F] : \quad (1 + \kappa_D (b_t^F - b^F)) = \beta \mathbb{E}_t \left[ \frac{\lambda_{t+1}}{\lambda_t} \frac{s_{t+1}}{s_t} \frac{1 + r_t^*}{1 + \pi_{t+1}^*} \right] \tag{38}$$

$$[k_t] : \quad 1 = \beta \mathbb{E}_t \left[ \frac{\lambda_{t+1}}{\lambda_t} \frac{r_{t+1}^k + q_{t+1} (1 - \delta)}{q_t} \right] \tag{39}$$

$$[i_t] : \quad 1 = q_t \left( 1 - \frac{\kappa_I}{2} \left( \frac{i_t}{i_{t-1}} - 1 \right)^2 - \kappa_I \left( \frac{i_t}{i_{t-1}} - 1 \right) \frac{i_t}{i_{t-1}} \right) + \beta \kappa_I \mathbb{E}_t \left[ q_{t+1} \frac{\lambda_{t+1}}{\lambda_t} \left( \frac{i_{t+1}}{i_t} - 1 \right) \left( \frac{i_{t+1}}{i_t} \right)^2 \right] \tag{40}$$

$$[c_{H,t}] : \quad c_{H,t} = (1 - \gamma) \left( \frac{p_t^H}{\lambda_t^C} \right)^{-\eta} c_t \tag{41}$$

$$[c_{F,t}] : \quad c_{F,t} = \gamma \left( \frac{p_t^F}{\lambda_t^C} \right)^{-\eta} c_t \tag{42}$$

In the equations above,  $c_{H,t}, c_{F,t}$  refer to the consumption of the  $H, F$  produced goods, respectively and  $c_t$  is the final consumption good.  $\lambda_t, \lambda_t^C$  are the shadow values associated with the households and consumption programs. The variable  $w_t$  refers to the wage rate and  $h_t$  denotes the number of hours worked;  $b_t^F$  is the (real) holdings of one period foreign bonds;  $r_t, r_t^*, r_t^K$  are the nominal domestic and foreign interest rates and the (net) real return on capital, respectively;  $s_t$  is the real exchange rate;  $k_{t-1}$  is the stock of capital at time  $t$  and  $i_t$  denotes investments;  $q_t$  is the shadow price of investments.  $p_t^H, p_t^F$  are the (real) prices of the  $H, F$  goods.  $\kappa_D, \kappa_I$  are parameters.

#### A.2.2. The final home good firm

These equilibrium conditions directly follow from the maximization problem described in Eq. (29).

$$[y_t^H(i)] : y_t^H(i) = \left( \frac{P_t^H(i)}{P_t^H} \right)^{-\epsilon} Y_t^H \tag{43}$$

A.2.3. The intermediate goods firms

These equilibrium conditions directly follow from the intermediate goods firms maximization problems described in Eqs. (30) and (32).<sup>13</sup>

$$[h_t] : (1 - \alpha) z_t^Z m_{c_t} \left( \frac{k_{t-1}}{h_t} \right)^\alpha = w_t \tag{44}$$

$$[k_{t-1}] : \alpha z_t^Z m_{c_t} \left( \frac{h_t}{k_{t-1}} \right)^{1-\alpha} = r_t^k \tag{45}$$

$$[X_t^{\tilde{Z}}] : X_t^{\tilde{Z}} = z_t^{\eta_{\tilde{H}}} e_{\tilde{H}} \left( \frac{m_{c_t}}{\mu_t^H} \right)^{-\eta_{\tilde{H}}} y_t^H(i) \tag{46}$$

$$[X_t^{EB}] : X_t^{EB} = z_t^{\eta_{\tilde{H}}} (1 - e_{\tilde{H}}) \left( \frac{p_t^{EB}}{\mu_t^H} \right)^{-\eta_{\tilde{H}}} y_t^H(i) \tag{47}$$

$$[P_t^H(i)] : \beta E_t \left[ \frac{\lambda_{t+1}}{\lambda_t} \kappa_p \frac{P_t^H}{P_{t+1}} \frac{P_{t+1}^H(i)}{(P_{t+1}^H(i))^2} \left( \frac{P_{t+1}^H(i)}{P_t^H(i)} - 1 \right) Y_{t+1}^H \right] = \frac{1}{P_t} \left[ \varepsilon \frac{P_t^H(i)}{P_t^H} \left( \frac{P_t^H(i)}{P_t^H} \right)^{-1-\varepsilon} Y_t^{H-} \right. \\ \left. \left( \frac{P_t^H(i)}{P_t^H} \right)^{-\varepsilon} Y_t^H + \kappa_p \frac{P_t^H}{P_{t-1}^H(i)} \left( \frac{P_t^H(i)}{P_{t-1}^H(i)} - 1 \right) Y_t^H - \varepsilon \left( \frac{P_t^H(i)}{P_t^H} \right)^{-1-\varepsilon} \frac{\mu_t^H}{P_t^H} Y_t^H \right] \tag{48}$$

where  $m_{c_t}$  stands for marginal costs and  $\mu_t^H$  is a shadow price.

A.2.4. The energy bundle firm

These equilibrium conditions directly follow from the maximization described in Eq. (4) in the main text.

$$[X_t^{EC}] : X_t^{EC} = e_{EC} \left( \frac{p_t^{EC}}{p_t^{EB}} \right)^{-\eta_{EB}} Y_t^{EB} \tag{49}$$

$$[X_t^{EO}] : X_t^{EO} = e_{EO} \left( \frac{p_t^O}{p_t^{EB}} \right)^{-\eta_{EB}} Y_t^{EB} \tag{50}$$

A.2.5. The coordinator

These equilibrium conditions directly follow from the maximization described in Eq. (5) in the main text.

$$[X_t^{ET}] : X_t^{ET} = (z_t^{EC})^{\eta_{EC}} e_{ET} \left( \frac{p_t^{ET}}{p_t^{EC}} \right)^{-\eta_{EC}} Y_t^{EC} \tag{51}$$

$$[X_t^{EHy}] : X_t^{EHy} = (z_t^{EC})^{\eta_{EC}} e_{EHy} \left( \frac{p_t^{EHy}}{p_t^{EC}} \right)^{-\eta_{EC}} Y_t^{EC} \tag{52}$$

$$[X_t^{ER}] : X_t^{ER} = (z_t^{EC})^{\eta_{EC}} e_{ER} \left( \frac{p_t^{ER}}{p_t^{EC}} \right)^{-\eta_{EC}} Y_t^{EC} \tag{53}$$

A.2.6. The thermo-electric generation firm

From the first stage maximization (Eq. (7)) problem we can derive the following equilibrium conditions which give the optimal demands for  $X_t^{TO}$ ,  $X_t^{TG}$  and  $X_t^{TCo}$ :

$$X_t^{TO} = e_{TO} \left( \frac{p_t^O}{p_t^{FB}} \right)^{-\eta_T} F B_t \tag{54}$$

$$X_t^{TG} = e_{TG} \left( \frac{p_t^{TG}}{p_t^{FB}} \right)^{-\eta_T} F B_t \tag{55}$$

$$X_t^{TCo} = e_{TCo} \left( \frac{p_t^{TCo}}{p_t^{FB}} \right)^{-\eta_T} F B_t \tag{56}$$

Solving the second stage maximization problem (Eq. (9)) in turn leads to:

$$[F B_t] : p_t^{ET} (1 - \alpha^T) \frac{Y_t^{ET}}{F B_t} = p_t^{FB} \tag{57}$$

<sup>13</sup> In order to reduce clutter we omit the indexing ( $i$ ) from some of the FOCs.

$$[K_t^{KT}] : \mathbb{E}_t \left[ \Xi_{t,t+1}^R \left( \mu_{t+1}^{KT} (1 - \delta) + p_{t+1}^{ET} \alpha^T \frac{Y_{t+1}^{ET}}{K_t^{KT}} \right) \right] = \mu_t^{KT} \tag{58}$$

$$[I_t^{KT}] : \mu_t^{Hy} \left( 1 - \frac{\kappa^T}{2} \left( \frac{I_t^T}{I_{t-1}^T} - a \right)^2 - \kappa^T \left( \frac{I_t^T}{I_{t-1}^T} - a \right) \frac{I_t^T}{I_{t-1}^T} \right) + \mathbb{E}_t \left[ \Xi_{t,t+1}^R \kappa^T \mu_{t+1}^{KT} \left( \frac{I_{t+1}^T}{I_t^T} - a \right) \left( \frac{I_{t+1}^T}{I_t^T} \right)^2 \right] = 1 \tag{59}$$

where  $\mu_t^{KT}$  stands for the lagrange multiplier associated with the maximization problem.

**A.2.7. The hydro-electric generation firm**

These equilibrium conditions directly follow from the maximization described in Eq. (12) in the main text and complement the FOCs with respect to  $W_t^S, W_t^F$ , which we have already presented in Eqs. (16) and (17).

$$[K_t^{Hy}] : \mu_t^{Hy} = \mathbb{E}_t \left[ \Xi_{t,t+1}^R \left( \alpha^{Hy} p_{t+1}^{EHy} \frac{Y_{t+1}^{EHy}}{K_t^{Hy}} + \mu_{t+1}^{Hy} (1 - \delta_H) \right) \right] \tag{60}$$

$$[I_t^{Hy}] : 1 = \mu_t^{Hy} \left( 1 - \frac{\kappa^{Hy}}{2} \left( \frac{I_t^{Hy}}{I_{t-1}^{Hy}} - a \right)^2 - \kappa^{Hy} \left( \frac{I_t^{Hy}}{I_{t-1}^{Hy}} - a \right) \frac{I_t^{Hy}}{I_{t-1}^{Hy}} \right) + \mathbb{E}_t \left[ \mu_{t+1}^{Hy} \Xi_{t,t+1}^R \kappa^{Hy} \left( \frac{I_{t+1}^{Hy}}{I_t^{Hy}} - a \right) \left( \frac{I_{t+1}^{Hy}}{I_t^{Hy}} \right)^2 \right] \tag{61}$$

where  $\mu_t^{Hy}$  stands for the lagrange multiplier associated with the maximization problem.

**A.2.8. The other-renewables energy firm**

These equilibrium conditions directly follow from the maximization described in Eq. (18) in the main text.

$$[K_t^R] : \mu_t^R = \mathbb{E}_t \left[ \Xi_{t,t+1}^R \left( \alpha^R p_{t+1}^{ER} \frac{Y_{t+1}^{ER}}{K_t^R} + \mu_{t+1}^R (1 - \delta^{ORS}) \right) \right] \tag{62}$$

$$[I_t^R] : 1 = \mu_t^R \left( 1 - \frac{\kappa^R}{2} \left( \frac{I_t^R}{I_{t-1}^R} - a \right)^2 - \kappa^R \left( \frac{I_t^R}{I_{t-1}^R} - a \right) \frac{I_t^R}{I_{t-1}^R} \right) + \mathbb{E}_t \left[ \mu_{t+1}^R \Xi_{t,t+1}^R \kappa^R \left( \frac{I_{t+1}^R}{I_t^R} - a \right) \left( \frac{I_{t+1}^R}{I_t^R} \right)^2 \right] \tag{63}$$

where  $\mu_t^R$  stands for the lagrange multiplier associated with the maximization problem.

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