Small Resource-Rich Economies and the Green Transition*

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Abstract

The global transition to clean energy carries significant implications for countries with large resource extraction sectors. I evaluate the welfare impact of falling global demand for fossil fuels and an expanding clean energy sector in small, resource-rich economies. I develop a quantitative model of a two-region, multisector, small open economy with heterogeneous households featuring both fossil and clean production. Calibrating the model to Canadian data, I find that the transition to a Net Zero world by 2050 reduces welfare by 0.73% among young, low-income households living in the fossil extracting region of the economy. The magnitude of these losses decrease with age and with income. In order for the transition to be welfare enhancing for the economy, the annualized growth rate in non-energy productivity needs to increase by 1 percentage point.

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1 Introduction

There is strong evidence to suggest we are witnessing a transition towards clean energy. The cost per kilowatt-hour of clean energy sources has plummeted, while global adoption of clean and renewable energy sources is increasing. Almost every major country has introduced policies and signed international agreements to reduce dependence on fossil fuels. Concerns over carbon emissions and fossil fuel dependency have led to the implementation of carbon taxes and other efforts to curtail demand. This poses a unique set of challenges for fossil-exporters as they face diminishing demand, both internationally and domestically, in a key industry. A boom in commodity prices at the turn of the 2000s spurred massive investment in the resource extraction sectors of several economies. Nations such as Australia, Canada, Nigeria, and Norway (among others) derive a large fraction of their economic production and export revenues from fossil fuel extraction. The expansion of this industry has produced spillover effects throughout the broader economy.

This paper asks how changes in the global demand for fossil fuels affect welfare across the age and income distributions in small, open, resource-rich economies. While the rise in oil prices between 1997 and 2020 particularly benefited young households at the bottom of the income distribution, a global fall in demand for fossil fuels produces a symmetric effect. Using the International Energy Agency's recommendations for attaining a Net Zero world by 2050, I find that this "Green Transition" decreases welfare across the age, income and regional distributions. The largest losses are experienced by young households at the bottom of the income distribution in fossil extracting regions of the economy. These households suffer from a decrease in their lifetime earnings primarily due to dampened wage growth, lower returns on savings and the declining profits from the fossil sector. However, faster growth in either the clean or non-energy sectors can potentially be welfare enhancing, particularly for young households.

I develop an overlapping generations model featuring two domestic regions with multiple production sectors to quantitatively assess the welfare effects of the global transition to clean energy. The model features household heterogeneity through age, assets and productivity differences in the style of Bewley (1977), Imrohoroğlu (1989), Huggett (1993), and Aiyagari (1994). The production structure adapts Fried, Novan, and Peterman (2022), where the final consumption and investment good is produced using energy and non-energy inputs. Regions in the model each produce a unique energy and non-energy intermediate good. The key distinction here is that one region specializes in the production of a fossil input into energy, and the other produces a clean input. Each type of energy intermediate is highly substitutable in energy production, and non-energy intermediates are highly substitutable in non-energy production. Energy and non-energy inputs are modelled as perfect complements to capture the difficulties in substituting between the two over short time horizons. International demand for the fossil good is captured purely through the price, which is exogenous.

I validate the model by calibrating the parameters to Canadian data and evaluate the welfare effects of the oil price boom between 1997 and 2020. The model can replicate several trends in aggregates, in particular the observed fact that wages, consumption, and GDP grew faster in the fossil-producing region than the clean-producing region between 1997 and 2020. Reinforcing the key mechanism of the model, I show that these trends are inverted if the price of the fossil good is held constant, highlighting the importance of the resource boom as a driving factor in this economy. I find that the boom in oil prices produced positive but heterogeneous welfare gains along the transition path. The gains specifically from the rise in the price of the fossil good are more pronounced in the fossil-producing region, particularly among young households and low-income households. These gains are monotonically decreasing with age. Households across the economy benefit from rising profits driven by the fossil sector. Younger households benefit from the positive wage growth and high profits associated with the expansion of the fossil sector along the transition path, as well as from increases in the return on savings driven by the fossil sector's demand for capital.

Next, I quantify the welfare impacts of a "Green Transition." For the purpose of this paper, I adopt the International Energy Agency's "Net Zero by 2050" recommendations (IEA, 2021). This scenario calls for (1) 90% of the domestic electricity production to be derived from clean sources and (2) for demand for coal and oil falling by 50% from 2020 levels. To mimic this scenario in my model, I recalibrate the productivity in the clean sector and the price of the fossil good so that along the transition path, clean energy grows to account for 90% of inputs into energy production, and fossil production falls to 50% of 2020 levels. I allow TFP in the non-energy sectors to continue to grow along the observed trend between 2010 and 2020. Through the lens of the model, I find that the fall in demand for fossil fuels produces heterogeneous welfare losses across households. These losses are most pronounced in the fossil-producing region and decrease with age, as young households are most impacted. Similarly, households at the bottom of the income distribution experience the largest losses due to declining demand for fossil fuel. However, in the benchmark case, welfare losses are on the order of less than 1% across all household types. The losses due to falling international demand for fossil fuels are partially offset by the gains from expansion of the clean sector. I investigate whether growth in the clean sector or non-energy sectors can make the transition welfare enhancing across the economy. Rapid, extreme growth in the clean energy sector is welfare improving in aggregate. Almost all households across both regions experience welfare gains in this scenario, save for the households at the bottom of the income distribution in the fossil producing region. I find that stronger growth in the non-energy sector over the next 30 years is also welfare enhancing, However, in both of these welfare improving experiments, the top of the income distribution experience the largest gains in both regions.

This paper contributes to and expands upon three distinct areas of the literature. First, this paper contributes to the existing literature on clean energy transitions. Many papers focus on the roles of taxes and subsidies in driving a change from a dirty to a clean technology (see Besley and Persson, 2023; Helm and Mier, 2021; Lennox and Witajewski-Baltvilks, 2017; Acemoglu et al., 2016). Recent additions to the literature, such as Arkolakis and Walsh (2023), highlight the welfare losses fossil fuel exporters face in a world moving towards clean energy due to the loss of export revenues. My paper expands on this work by modelling and analyzing the effects of both a fall in global demand for fossil fuels and a rapid increase in clean technology across the age and income distributions. Contrary to existing work, I find that the losses associated with falling international demand can be negated by strong productivity growth in other sectors, specifically in the clean and non-energy sectors. This paper also contributes to the literature arguing that the Green Transition will produce heterogeneous outcomes, such as Baldwin et al. (2020), which argues that long-run outcomes of a clean energy transition depend on how easily the dirty capital stock can be converted to clean, and Borenstein and Davis (2016), which finds that U.S. income tax credits aimed at adopting clean technology have mostly benefited high-income Americans. Consistent with this last paper, I find that the top of the income distribution benefits the most over the course of the transition.

Second, this paper contributes to the expanding literature applying quantitative macroeconomic models to environmental and resource economics. A common feature of these models, as highlighted in Hassler, Krusell, and Olovsson (2021, 2022) and Casey (2023), is the inability to substitute between natural resources (or energy inputs) with other productive resources in the short-run. Given this paper's focus on short-run dynamics, I adhere to this approach by modelling energy and non-energy inputs as perfect complements in production. The literature typically employs a representative, infinitely lived agent framework and abstracts the production technology used in the fossil sector, omitting the role of capital and labour. My paper offers a novel contribution in two ways: first, I add an overlapping generations framework with heterogeneous agents. This allows me to produce a richer understanding of how changes in global demand and production of fossil fuels are transmitted across households by age and income. Second, I calibrate the production parameters to capture the fact that fossil extraction is extremely capital intensive, as evidenced in Loertscher and Pujolas (2024), which shows the disproportionate flow of capital into the oil and gas sector in Canada in the 2000s.

Finally, this paper contributes to the large literature concerned with the economic impacts of commodity price booms. Thus far, the existing literature suggests positive income and welfare effects for regions that benefit from expanding fossil fuel extraction. This is true of all fossil production booms, be it coal (see Black et al., 2005), natural gas (see Bartik et al., 2019), and oil (see Michaels, 2011). This paper is consistent with the existing literature, emphasizing that the largest beneficiaries of the fossil price boom were younger, low income households, driven primarily by the impacts of profits from the fossil sector on per capita income. My paper highlights how these benefits are distributed across the age distribution and is able to decompose the welfare gains derived from the rise in commodity prices and the welfare gains derived from productivity gains in other sectors.

The rest of the paper is organized as follows: Section 2 summarizes the relevant evidence indicative of a transition towards growing adoption of clean energy. Section 3 presents the model, which features an overlapping generations framework with heterogeneous agents, two regions, an energy sector utilizing both clean and dirty inputs, a fossil extraction sector, a clean sector, and non-energy intermediate production. Section 4 details the estimation and calibration of the model. Section 5 presents the model performance with respect to non-targeted moments and the results of the benchmark transition exercise to quantify the welfare impact of the observed oil price trends from 1997 to 2020. Section 6 discusses the model predictions regarding the welfare effects of a clean energy transition, characterized by a drop in global demand for fossil inputs and a decrease in the relative price of clean inputs. Through the lens of the model, this occurs via a fall in the exogenous price of the fossil good, and rapid growth in the productivity of the clean sector Finally, Section 7 concludes the paper and highlights areas for future research.

2 Empirical Evidence of the Green Transition

There are currently 120 nations that have some commitment to Net Zero status in writing, whether in an official policy document or actively signed into law. An additional 70 countries have proposed or pledged (in some non-binding manner) to attain Net Zero status. While pledges and proposals are not enforceable or binding agreements, there is a consensus among almost every country that reducing or removing emissions is an urgent priority. Table 1 summarizes the state of Net Zero commitments internationally. The numbers are sourced from data taken from "The Net Zero Tracker," a collaborative project between the Energy

& Climate Intelligence Unit, the Data-Driven EnviroLab, the NewClimate Institute, and the Oxford Net Zero project, which collects data on targets and progress towards emissions reduction and net zero status among all nations, as well as cities and companies. The concept of Net Zero refers to the reduction or removal of greenhouse gas emissions from the earth's atmosphere.

Table 1: Net Zero Progress among all nations

	Proposed	In policy document	Pledged	In law
Number of countries	53	87	17	33

Most of these countries have also highlighted 2050 as an important benchmark year. 50% of countries that have an official policy document or enacted a law and 84% of those who have pledged or proposed a Net Zero goal have signalled 2050 as the target date. Meeting this deadline requires rapid improvements in the costs and efficiency of non-fossil fuel energy sources, and for these emerging technologies to be adopted.

Figure 1 tracks the fall in the levelized cost of energy (LCOE) measured in 2022 US dollars per kilowatt-hour from a number of renewable energy sources. LCOE is a measure used to assess the minimum price at which the energy generated can be sold to offset the production costs. The data presented here is taken from the International Renewable Energy Agency (IRENA).

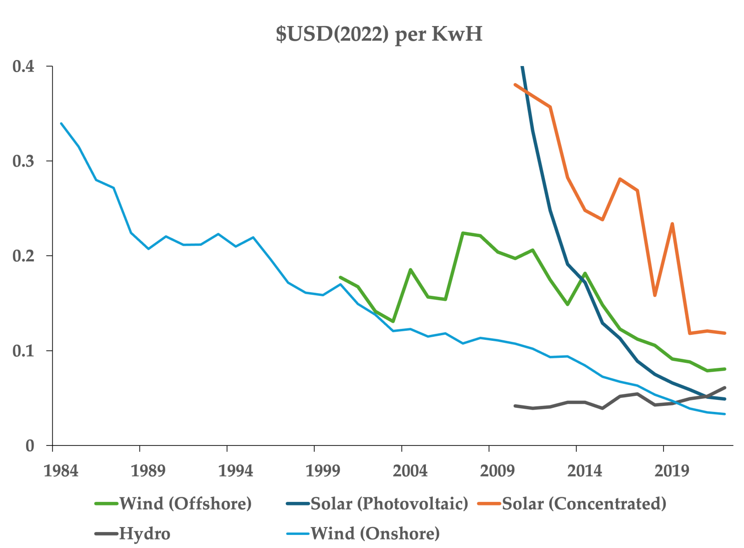


Figure 1: Levelized costs of clean energy

Other than hydroelectricity, which is low cost but fairly constant, the costs of using renewables have been declining steadily. The cost of onshore wind power has been trending downwards for the last 40 years. In the last decade, the LCOE of offshore wind has become comparable to hydro. The most dramatic improvements are in solar power. Photovoltaic solar power, which absorbs sunlight and converts it directly into electricity, has seen a particularly stark improvement in recent years. The price per kilowatt-hour has fallen from 0.44$ to 0.05$. This also coincides with a dramatic fall in the price of a single solar PV panel. This is indicative of a trend in which clean energy is becoming increasingly cost-effective and cheaper to adopt as well.

Concurrent with this fall in costs, many large countries have been increasing their use of clean energy in primary energy consumption. Figure 2 tracks the growth in clean sources as a percentage of all terawatt-hours of primary energy consumed. For the purpose of this paper, any reference to clean energy implies renewables (solar, wind, hydro) and nuclear energy. Any reference to fossil fuels or oil implies oil, gas, and coal. The data comes is taken from Our World in Data, who processed the data from the Energy Institute's Statistical Review of World Energy (2024). The period from 2012 to 2022 shows an upward trend (to varying degrees) among a number of major countries. Japan had a sharp decline at the time of the 2011 Fukushima nuclear accident but has since steadily increased the share of energy derived from clean sources. China has accelerated clean adoption over this period, nearly doubling from 9% to 18%. India and the United States have also increased their shares, albeit at a slower pace. In 2012, clean sources accounted for 8% of India's primary energy consumption and 14% in the United States. In 2023, those numbers had grown to 10% and 17%, respectively. Germany shows the most consistent growth in clean energy adoption since 1997, growing from 14% to 18% by 2012, and to 24% by 2023.

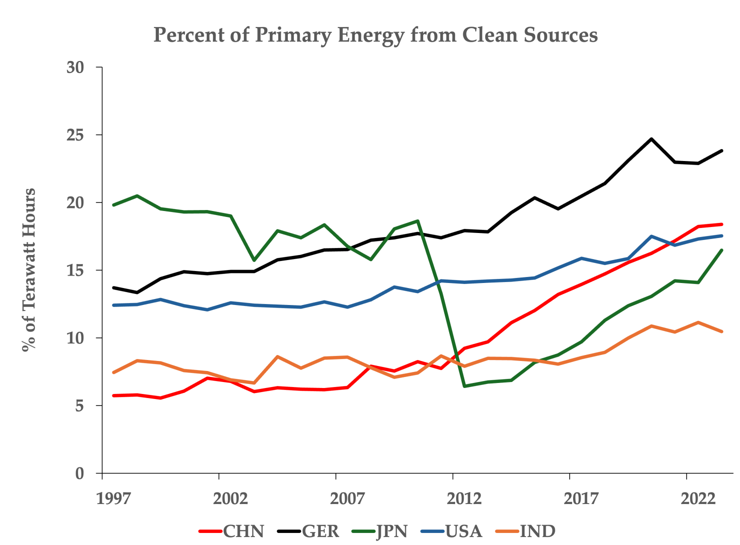


Figure 2: Adoption of clean energy

These countries account for a significant fraction of global emissions (in particular the United States, China and India), and have the largest ability to affect global demand for fossil fuels if they maintain or accelerate these trends. They are also responsible for the lion's share of the international demand among small resource-rich countries. "Small" in this context refers to the country's ability to influence the world price of an export good. Australia, Canada, Nigeria, and Norway (among others) are significant exporters of fossil fuels. Figure 3 plots fossil fuel exports as a percentage of the value of all exports for each country. Among this set of nations, fossil fuels account for at least 20% of all export revenue. If global demand for fossil fuels falls, these countries and other small fossil exporters are significantly exposed to potential losses.

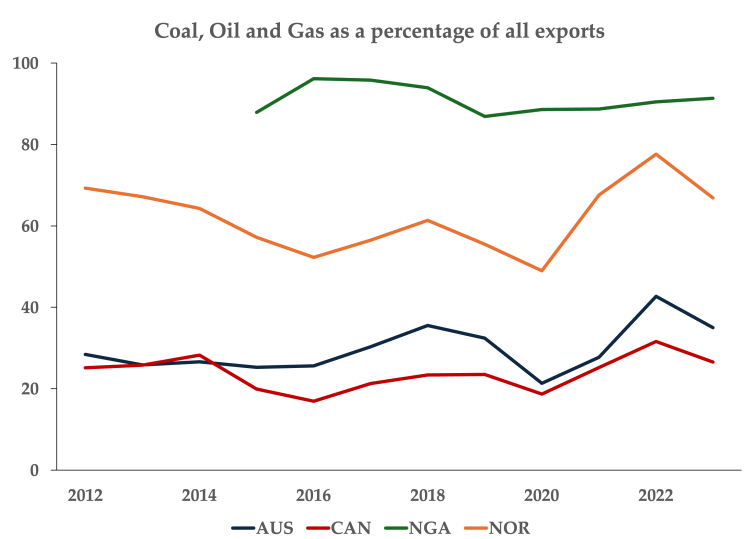


Figure 3: Coal, Oil, and Gas as a share of exports

The primary motivation of this paper is outlined in the facts presented here. Nearly every nation is signalling an intent to dramatically reduce their emissions by 2050. The price of the technology to substitute away from fossil fuels has plummeted in the last decade, and there are signs that key players in this transition are beginning this substitution in earnest. For small, resource-rich economies, this foreshadows a significant contraction in a key sector.

3 Model

In this section, I build a Small Open Economy model with two regions and multiple sectors. Households follow an overlapping generations structure with heterogeneity due to both age-specific productivity and survival probability differences, as well as idiosyncratic productivity differences. On the production side, the economy is organized into a final good producer, which uses non-energy and energy intermediate inputs, an energy sector which uses clean and fossil intermediate inputs, a clean sector which produces the clean energy input using a capital-labour composite, a fossil sector which produces the fossil intermediate using a capital-labour composite and a fossil intermediate, and region-specific non-energy intermediate producers who use capital and labour. The price of the fossil good is assumed to be exogenous. Both the fossil good and the final consumption good can be bought and sold on the international market, and trade is balanced every period. The structure of the model adds to the use of overlapping generations models in the climate literature, as in Laurent-Lucchetti and Leach (2011) and Jaimes (2023), both of which study climate policy in an OLG setting. On the production side, this paper builds on the structures of Fried et al. (2022) and Casey (2023), by explicitly modelling the clean and fossil sectors, and assuming the extreme case that final good production employs a Leontief structure where energy and non-energy inputs are complements.

3.1 Regions

There are two regions in the model denoted by $s \in \{A, B\}$. The regions each produce a specialized energy and non-energy intermediate good. The key distinction is region A produces the fossil energy intermediate and region B produces the clean energy intermediate. The fossil good, whose price $p_{\mathcal{F}}$ is determined exogenously, is sold both domestically and internationally. The clean good and the two non-energy goods are both produced and sold domestically.

3.2 Households

Households in each region supply labour inelastically and maximize expected lifetime utility given their age j, current level of assets a, and idiosyncratic productivity ϵ by choosing consumption c and next period assets a'. I assume that there is no labour mobility between regions, but capital is perfectly mobile. Hence, wages are region specific but the interest rate is common across regions. The problem of the household is given by:

$$V(j, a, \epsilon, s) = \max_{a', c} \frac{c^{1-\sigma}}{1-\sigma} + \psi_j \beta \mathbb{E}_{\epsilon'|\epsilon} V(j+1, a', \epsilon', s) \tag{3.1}$$

subject to:

$$(1+\tau_{c,s})c + a' = \begin{cases} w_s \epsilon \theta_j + (1+r)(a+b) + \pi_s - T(y) & if \ j < j_{ret} \\ ss + (1+r)(a+b) + \pi_s - T(y) & if \ j \geq j_{ret} \end{cases}$$

$$c, a' \geq 0$$

where time subscripts t are suppressed for ease of notation.

Profits π_s for $s \in \{A, B\}$ correspond to the profits from the energy intermediate producers specific to each region. A household living in region A receives the profits from the fossil producers $\pi_{\mathcal{F}}$, while a household living in region B receives the profits from the clean producers $\pi_{\mathcal{C}}$.

Agents enter at $j = 1$ and live until a maximum age of J years. Agents all retire exogenously at age j_{ret}. From ages $j = 1$ to $j_{ret} - 1$, agents supply one unit of labour inelastically at the market wage rate for their region w_s. Retired households receive no labour income and collect social security benefits ss. At the beginning of each period, agents are transferred accidental bequests b, which consist of the assets of agents who did not survive from period $t-1$ to t. These bequests are uniformly distributed among the remaining agents and added to their existing asset holdings a. Agents aged $j = 1$ enter with the bequest transfers as their initial endowment of assets.

Household idiosyncratic productivity ϵ is assumed to follow an AR(1) process so that $\log \epsilon' = \rho_\epsilon \log \epsilon + e$ where $e \sim N(0, 1)$. There is also an age-specific productivity component θ_j common to all agents with age j. An individual aged j survives to $j + 1$ with probability ψ_j. Agents who do not survive to the next period have their assets uniformly redistributed in the form of accidental bequests b.

Consumption choices c are taxed at a rate $\tau_{c,s}$ depending on the region. Following Heathcote et al. (2017) and Moschini et al. (2024), market income is taxed progressively according to the tax function:

$$T(y) = y - \lambda y^{1-\tau_p} \tag{3.2}$$

where:

$$y = \begin{cases} w_s \epsilon \theta_j + (1+r)(a+b) + \pi_s & if\ j < j_{ret} \\ (1+r)(a+b) + \pi_s & if\ j \geq j_{ret} \end{cases} \tag{3.3}$$

The parameter τ_p governs the tax progressivity, and λ is determined in equilibrium to balance the government's budget each period. The income tax function is assumed to be the same across each region.

3.3 Government

The government consumes the final good and pays social security transfers. These expenditures are financed via consumption taxes and income taxes. The government budget is balanced each period so that:

$$SS + G = \tau_{c,A} C_A + \tau_{c,B} C_B + \int T(y)\ d\Omega(j, a, \epsilon, s) \tag{3.4}$$

where $\Omega(j, a, \epsilon, s)$ is the distribution across all household types in the economy, and C_A and C_B are the aggregated consumption decisions in each region.

Government consumption G is assumed to be a fraction of the total output of the final consumption good, so that $G = gY$, $g \in (0, 1)$. The government issues no bonds and incurs no debts.

3.4 Production

Intermediate production in this economy is region-specific. Intermediates are then aggregated into the energy good and the final good. Final good production uses non-energy intermediates and the aggregated energy good.

3.4.1 Fossil Producers

The fossil energy good $Y_{\mathcal{F}}$ is produced in region A using capital $K_{\mathcal{F}}$, labour $L_{\mathcal{F}}$, and fossil intermediate $x_{\mathcal{F},\mathcal{F}}$ with a decreasing returns to scale technology governed by $\nu \in (0, 1)$. Fossil producers take the world price $p_{\mathcal{F}}$ as given each period and make their production decisions accordingly. The problem of a fossil producer is given by:

$$\max_{K_{\mathcal{F}},L_{\mathcal{F}},x_{\mathcal{F},\mathcal{F}}} p_{\mathcal{F}}Y_{\mathcal{F}} - (r+\delta)K_{\mathcal{F}} - w_A L_{\mathcal{F}} - p_{\mathcal{F}}x_{\mathcal{F},\mathcal{F}} \tag{3.5}$$

subject to:

$$Y_{\mathcal{F}} = \min\{Z_{\mathcal{F}}(K_{\mathcal{F}}^{\gamma}L_{\mathcal{F}}^{1-\gamma})^{\nu_{\mathcal{F}}}, \mu_{\mathcal{F}}x_{\mathcal{F},\mathcal{F}}\}$$
$$\nu \in (0,1)$$

Profits $\pi_{\mathcal{F}} = p_{\mathcal{F}}Y_{\mathcal{F}} - (r+\delta)K_{\mathcal{F}} - w_A L_{\mathcal{F}} - p_{\mathcal{F}}x_{\mathcal{F},\mathcal{F}}$ are distributed back to the households in region A uniformly. Here the Leontief production structure captures the idea that scaling production up is costly. As the world price $p_{\mathcal{F}}$ rises, fossil producers will want to increase production to take advantage. However, they are constrained in that they need to use some fraction of their own output, $x_{\mathcal{F},\mathcal{F}}$ to produce the desired output. The decreasing returns to scale parameter $\nu_{\mathcal{F}}$ captures the notion that each marginal unit of fossil production requires more inputs to produce.

3.4.2 Clean Energy Producers

The clean energy good $Y_{\mathcal{C}}$ is produced in region B using capital $K_{\mathcal{C}}$ and labour $L_{\mathcal{C}}$. Clean producers make production choices to maximize profits according to:

$$\max_{K_{\mathcal{C}},L_{\mathcal{C}}} p_{\mathcal{C}}Y_{\mathcal{C}} - (r+\delta)K_{\mathcal{C}} - w_B L_{\mathcal{C}} \tag{3.6}$$

subject to:

$$Y_{\mathcal{C}} = Z_{\mathcal{C}}(K_{\mathcal{C}}^{\eta}L_{\mathcal{C}}^{1-\eta})^{\nu_{\mathcal{C}}}$$

Clean profits $\pi_{\mathcal{C}} = p_{\mathcal{C}}Y_{\mathcal{C}} - (r+\delta)K_{\mathcal{C}} - w_B L_{\mathcal{C}}$ are redistributed uniformly to households in region B.

3.4.3 Non-Energy Producers

The non-energy good Y_s produced in each region $s \in \{A, B\}$ uses capital K_s and labour L_s. The problem of a non-energy producer is given by:

$$\max_{K_s,L_s} p_s Y_s - (r+\delta)K_s - w_s L_s \tag{3.7}$$

subject to:

$$Y_s = Z_s K_s^{\alpha} L_s^{1-\alpha}$$

3.4.4 Energy Producers

The final energy good Y_E is produced by combining the Clean energy intermediate x_C and the Fossil energy intermediate x_F, both of which are region-specific. The problem of the energy producer is:

$$\max_{x_{\mathcal{C},E} x_{\mathcal{F},E}} p_E Y_E - p_{\mathcal{C}} x_{\mathcal{C},E} - p_{\mathcal{F}} x_{\mathcal{F},E} \tag{3.8}$$

subject to:

$$Y_E = \left(x_{\mathcal{C},E}^{\rho_E} + x_{\mathcal{F},E}^{\rho_E} \right)^{1/\rho_E}$$

3.4.5 Final Good Producer

The final good Y is produced using region-specific non-energy intermediates $x_{A,Y}$, $x_{B,Y}$, and the energy good $x_{E,Y}$. The final good producer takes prices for each intermediate as given and makes input decisions according to:

$$\max_{x_{A,Y}, x_{B,Y}, x_{E,Y}} p_Y Y - p_A x_{A,Y} - p_B x_{B,Y} - p_E x_{E,Y} \tag{3.9}$$

subject to:

$$Y = \min \left\{ x_{N,Y}, \mu_E x_{E,Y} \right\}$$

$$x_{N,Y} = \left(x_{A,Y}^{\rho_y} + x_{B,Y}^{\rho_Y} \right)^{1/\rho_Y}$$

3.5 Equilibrium

The equilibrium of the model is defined as follows. A stationary, recursive equilibrium consists of a value function $V(j,a,\epsilon,s)$, decision rules $c(j,a,\epsilon,s)$ and $a'(j,a,\epsilon,s)$ for all j,a,ϵ,s, prices $\{w_s,r,p_A,p_B,p_{\mathcal{C}},p_E,p_{\mathcal{F}}\}$, a stationary distribution $\Omega(j,a,\epsilon,s)$, factor demands K_A, K_B, $K_{\mathcal{F}}$, $K_{\mathcal{C}}$, L_A, L_B, $L_{\mathcal{F}}$, $L_{\mathcal{C}}$, $x_{A,Y}$, $x_{B,Y}$, $x_{E,Y}$, $x_{\mathcal{C},E}$, $x_{\mathcal{F},E}$, $x_{\mathcal{F},\mathcal{F}}$ and aggregate quantities $Y,Y_E,Y_A,Y_B,Y_{\mathcal{C}},Y_{\mathcal{F}}$ such that:

1. Household decision rules $c(j,a,\epsilon,s)$ and $a'(j,a,\epsilon,s)$ solve the household problem (3.1) given prices $\{w_s,r,p_A,p_B,p_{\mathcal{C}},p_E,p_{\mathcal{F}}\}$.

2. The government budget constraint (3.4) holds each period.

3. The fossil, clean, non-energy, energy, and final good producers maximize their respective profits given prices.

4. The labour market clears in each region, so that total labour demand equals total labour supply, ie.

$$\int_1^{j_{ret}} \quad d\Omega(j,a,\epsilon,A) = L_A + L_{\mathcal{F}}$$
$$\int_1^{j_{ret}} \quad d\Omega(j,a,\epsilon,B) = L_B + L_{\mathcal{C}}$$

5. The capital market clears such that total capital demand equals total savings, ie.

$$\int a'(j,a,\epsilon,s) \quad d\Omega(j,a,\epsilon,s) = K'_A + K'_B + K'_{\mathcal{C}} + K'_{\mathcal{F}}$$

6. The markets for clean intermediates, non-energy intermediates and energy intermediates clears, ie.

$$Y_{\mathcal{C}} = x_{C,E}$$
$$Y_A = x_{A,Y}$$
$$Y_B = x_{B,Y}$$
$$Y_E = x_{E,Y}$$

7. Trade is balanced in each period, ie.

$$p_{\mathcal{F}}(Y_{\mathcal{F}} - x_{\mathcal{F},\mathcal{F}} - x_{\mathcal{F},E}) = Y - C_A - C_B - I - G \tag{3.10}$$

where

$$C_i = \int_{s=i} c(j, a, \epsilon, A) \quad d\Omega(j, a, \epsilon, i)$$

for $i \in \{A, B\}$

4 Calibration

To speed up computation, I set a period in the model to correspond to 4 years. I calibrate my model in two steps. First, I externally calibrate several parameters. I set $j = 1$ to correspond to an agent who is 20 years old. Retirement age $j_{ret} = 13$ so agents work until their age corresponds to 64 and are retired at 68. Agents do not live past 100. I fix the parameters σ, β, δ, ρ_E and ρ_Y using values from the literature. I also externally calibrate and estimate a number of production, government and household age specific parameters directly from the data. Second, I internally calibrate the idiosyncratic productivity distribution parameters ρ_ϵ and σ_ϵ and the productivity in the fossil and clean sectors $Z_{\mathcal{F}}$ and $Z_{\mathcal{C}}$. I calibrate the parameters governing the idiosyncratic productivity process directly outside of equilibrium. TFP in the fossil and clean sectors are calibrated in equilibrium.

4.1 External Calibration

In the first step of parametrizing my model, I assume values for 6 parameters, presented in Table 2. I assume that the household risk aversion coefficient σ is set to 2, a standard value in the literature. Similarly, I assume an annualized household discount factor of 0.96 so that $\beta = 0.85$ and capital depreciates at an annual rate 0.05 so that $\delta = 0.18$. Following Fried, Novan, and Peterman (2022) and Papageorgiou, Saam, and Schulte (2017), I assume that the elasticity of substitution between clean and fossil inputs in energy production is $\rho_e = 0.66$. Papageorgiou, Saam, and Schulte (2017) report empirical estimates of the elasticity of substitution between clean and dirty inputs in energy production that fall between 0.23 an 0.66. Given the similarities between my model and Fried, Novan, and Peterman (2022), I adopt the higher value. In line with Albrecht and Tombe (2016), who estimate the interprovincial trade elasticity in Canada, I set the elasticity of substitution in the non-energy composite to $\rho_y = 0.80$.

Table 2: Assumed parameters

	Parameter	Description	Value
σ	Risk Aversion	Standard	2
β	Discount factor	Annualized rate of 0.96	0.85
δ	Capital depreciation	Annualized rate of 0.05	0.18
ρ_e	Elasticity of substitution in Energy production	Papageorgiou et al. (2017)	0.66
ρ_y	Elasticity of substitution in Non-Energy composite	Albrecht and Tombe (2016)	0.80

In the next step, I estimate several parameters directly from the data. The production parameters are presented in Table 3. I treat the production technology in this sector as identical between the two regions. The capital share in non-energy production is estimated using data on labour compensation (Table 36-10-0489-01, Statistics Canada) and value added (Table 36-10-0402-01, Statistics Canada) in the Canadian provinces of Alberta, British Columbia, Ontario and Québec net of mining (NAICS code 21) and utilities (NAICS code 22). I take the average across the years 1997-2020. I get a value of $\alpha = 0.4$. To compute Non-Energy TFP Z_s I compute the capital-labour composite $K^\alpha L^{1-\alpha}$ using the calibrated value of α, data on the stock of fixed non-residential capital by industry (Table 36-10-0096-01, Statistics Canada) and hours worked by industry (Table 36-10-0489-01, Statistics Canada). I use the values for "Geometric end-year net stock" reported in current prices for the years 1996 to 2019 and deflate them by the annual GDP deflator for Canada taken from the Federal Reserve Economic Data (FRED). Both hours worked and capital stock once again correspond to the values for all industries net of mining and utilities, in the provinces of Alberta, British Columbia, Ontario and Québec.

The decreasing returns to scale parameters ν_F and ν_C are set to using data on profits and revenues (Table 33-10-0500-01, Statistics Canada) for "Oil and gas extraction and support services" and "Utilities" respectively. I impute profits in each industry by taking the difference between "Sales of goods and services" and "Cost of goods sold." I then compute the profit-to-revenue ratio where profit corresponds to the imputed profits and revenue corresponds to "Sales of goods and services." The parameter ν_j for $j \in \{\mathcal{F}, \mathcal{C}\}$ is then given by

$$\nu_j = 1 - \frac{profits_j}{revenue_j}$$

This returns a value of $\nu_{\mathcal{F}} = 0.73$ and $\nu_{\mathcal{C}} = 0.72$. The capital share in Fossil sector γ is computed using data on labour compensation (Table 36-10-0489-01, Statistics Canada) and value added (Table 36-10-0402-01, Statistics Canada) in Oil and Gas extraction (NAICS 211) and Support activities for oil and gas extraction (NAICS 21311A) in the province of Alberta in the years 1997 to 2020. Data for value added in Support activities in oil and gas is missing between 1997-2006. I impute the value of these years by computing the average of

$$\frac{\text{Support activities for oil and gas extraction}}{\text{Support activities for mining, and oil and gas extraction}}$$

over this period. I then multiply this fraction by the value added in Support activities for mining, and oil and gas extraction between 1997 and 2006. For Alberta this is a good approximation, as Support activities in oil and gas specifically account for 96% of all support activities in the mining sector between 2007 and 2020. Using the value $\nu_{\mathcal{F}}$, I use data on compensation ($Comp$) and value added (VA) compute

$$\gamma = 1 - \frac{1}{23} \frac{\sum_{t=1997}^{2020} Comp_t}{\nu_{\mathcal{F}} \Big(\sum_{t=1997}^{2020} VA_t \Big)}$$

to arrive at $\gamma = 0.66$. Similarly, the capital share in the clean sector is estimated using data on labour compensation and value added in Electric power generation, transmission and distribution (NAICS code 2211) in British Columbia, Ontario and Québec, taking the average across 1997-2020. This is a good approximation for clean energy production in Canada. Electricity production from hydro, nuclear, solar and wind account for 94% of total terawatt hours produced in these provinces, and 81% of total clean production across all of Canada. Using the same process as computing γ, I compute

$$\eta = 1 - \frac{1}{(2020 - 1997)} \frac{\sum_{t=1997}^{2020} Comp_t}{\nu_{\mathcal{C}} \Big(\sum_{t=1997}^{2020} VA_t \Big)}$$

to arrive at $\eta = 0.60$

Table 3: Estimated Production Parameters

Parameter		**Source**	**Value**
α	Capital share, non-energy	StatsCan Tables	0.4
$Z_{A,1997}, Z_{B,1997}$	TFP in non-energy	StatsCan Tables	0.11
$Z_{A,2020}, Z_{B,2020}$	TFP in non-energy	StatsCan Tables	0.22
$\nu_{\mathcal{F}}$	DRS parameter	StatsCan Tables	0.73
$\nu_{\mathcal{C}}$	DRS parameter	StatsCan Tables	0.72
γ	Capital share, Fossil	StatsCan Tables	0.66
η	Capital share, Clean	StatsCan Tables	0.60
μ_E	Intermediate use of energy	I/O Table	38.43
$\mu_{\mathcal{F}}$	Intermediate use of Fossil	I/O Table	18.19
$p_{\mathcal{F},1997}$	Price of fossil good, 1997	WTI average	0.19
$p_{\mathcal{F},2020}$	Price of fossil good, 2020	WTI average	0.53

The Leontief intermediate parameters μ_E and $\mu_{\mathcal{F}}$ are computed from the Canadian Input-Output tables by taking the ratio of value added over intermediate used. Given the Leontief structure of production, we can compute the the parameter governing energy used in final good production, $\mu_E = Y/x_{E,Y}$ where Y maps to total value-added net of mining and utilities and $x_{E,Y}$ is energy intermediates used in this sector. "Energy" intermediates map to the sum of "Electric power generation, transmission and distribution" and "Natural gas distribution." I compute these ratios using the Input-Output tables for the years 2013-2020 and then take the average across all years to arrive at $\mu_E = 38.43$. In the Fossil sector production function, $\mu_{\mathcal{F}} = Y_{\mathcal{F}}/x_{\mathcal{F},\mathcal{F}}$ where $Y_{\mathcal{F}}$ maps to the value added in the fossil sector and $x_{\mathcal{F},\mathcal{F}}$ is fossil intermediates used in this sector. The "fossil sector" corresponds to the sum of "Conventional oil and gas extraction", "Non-conventional oil extraction" and "Support activities for oil and gas extraction" in 2013, and "Oil and gas extraction (except oil sands)", "Oil sands extraction" and "Support activities for oil and gas extraction" for the years 2014-2020. I take the average across 2013-2020 and arrive at $\mu_{\mathcal{F},\mathcal{F}} = 18.19$.

The price of the fossil good $p_{\mathcal{F}}$ in the initial and final steady states corresponds to the annualized average of the West Texas Intermediate price. I convert the values to Canadian dollars using the FRED exchange rate and deflate them with the Canadian GDP deflator. They are then re-scaled to ensure the model produces an internal solution.

Next, I estimated the consumption tax rates $\tau_{c,s}$, the income tax progressivity parameter τ_p and the government share of final good consumption g. These values are reported in Table 4. The consumption tax rates in each region $\tau_{c,s}$ is computed using the method employed in Mendoza et al. (1994), Krueger and Ludwig (2016), and Moschini et al. (2023). I sum Taxes on products with Taxes on production/(Household final consumption expenditure + Non-profit institutions serving households' final consumption expenditure + General governments final consumption expenditure - Numerator) for Alberta to correspond to region $s = A$ and for the composite Canada that consists of British Columbia, Ontario and Québec to map into region $s = B$. Values are annualized by summing the quarterly values. I then take the average for the series. Data on taxes is taken from Statistics Canada Table 36-10-0221-01 while data on consumption is taken from Statistics Canada Table 36-10-0222-01.

Table 4: Estimated Government Parameters

	Parameter	**Source**	**Value**
$\tau_{c,A}$	Consumption tax rate, region A	StatsCan tables	0.12
$\tau_{c,B}$	Consumption tax rate, region B	StatsCan tables	0.18
τ_p	Income Tax progressivity	StatsCan tables	0.1232
g	Government consumption	I/O Table	0.2

I estimate the income tax progressivity parameter τ_p by regressing log average pre-tax income on log average post-tax by income decile for the years 1976-2021. I use share of post-tax income as regression weights. So, if Y_{AT} is after tax income, we get

$$Y_{AT} = \lambda Y^{1-\tau_y}$$

Taking logs, we get

$$\log Y_{AT} = \log \lambda + (1 - \tau_y) \log Y$$

or

$$\log Y_{AT} = \beta_0 + \beta_1 \log Y$$

I run the regression separately for each year, compute $\tau_y = 1 - \beta_1$ for each year, and then take the average across all years. All data is taken from Statistics Canada Table 11-10-0193-01.

Finally, the government consumption parameter g is taken from quarterly expenditure side national accounts (Statistics Canada Table 36-10-0104-01). Values are annualized by summing the quarterly values. Household final consumption expenditure + Non-profit institutions serving households' final consumption expenditure + General governments final consumption expenditure + Gross fixed capital formation + Investment in inventories + Exports of goods and services - Less: imports of goods and services. For each year I then compute $g = G/Y$ as General governments final consumption expenditure/Y. I then take the average.

The age specific parameters governing productivity θ_j and survival probability ψ_j are summarized in Table 5. Age specific productivity θ_j is estimated using 4th degree polynomial on age in the following way: Using data on mean log income and mean log residual income for ages 25 to 55 from the Global Repository of Income Dynamics (GRID), I construct $y_j = \log Inc_j - \log Res\ Inc_j$. I run the regression

$$y_j = \beta_0 + \beta_1 year + \mu_j \tag{4.1}$$

Here, μ_j captures $\log \theta_j$. I save the estimated $\hat{\mu}_j$ from the previous regression, and I run the regression

$$\hat{\mu}_j = \delta_0 + \delta_1 age + \delta_2 age^2 + \delta_3 age^3 + \delta_4 age^4 + \zeta \tag{4.2}$$

I save the δ_i's from this regression and interpolate

$$\hat{\theta}_j = \exp\{\hat{\delta}_0 + \hat{\delta}_1 age + \hat{\delta}_2 age^2 + \hat{\delta}_3 age_3 + \hat{\delta}_4 age_4\} \tag{4.3}$$

for $age \in \{20, \ldots, j_{ret}\}$. I then normalize the values so that $\theta_1 = 1$. The age productivity profile can be seen in Figure 4a. It follows the expected hump shape over an individuals working life: earning are lowest as an agent starts working and grow before gradually declining again in the later career years.

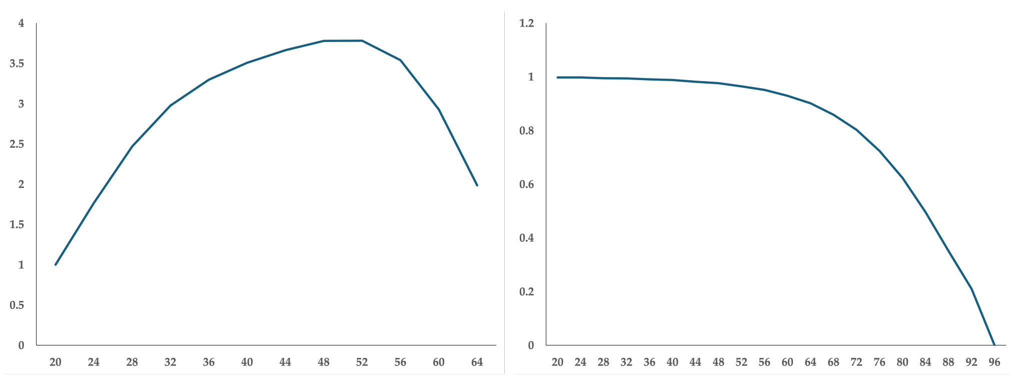
Table 5: Estimated Age specific Parameters

Parameter		Source
θ_j	Age spec. productivity	GRID
ψ_j	Age spec. survival probabilities	StatsCan tables

Age specific survival probabilities ψ_j are taken directly from Statistics Canada Table 13-10-0114-01. Given that a period in my quantitative model corresponds to four years, then the probability of survival conditional on age j, ψ_j is computed as the product of 1 year survival probabilities between years t and $t+1$. For example, to compute the probability that an individual aged 20 (corresponding to $j = 1$) survives to the next period, $\psi_j = p(21|20) \times p(22|21) \times p(23|22) \times p(24|23)$ where $p(n+1|n)$ is the probability that an individual with age n survives to age $n+1$. Statistics Canada reports these estimates annually for sample cohorts lasting two years. The first sample was measured between 1980 and 1982, and the most recent sample was measured between 2020 and 2022. I compute the probabilities for each sample period and then take the average across periods. Given that agents in my model all die at $J = 100$, I fix the probability of survival at age 96 to $\psi_{J-1} = 0$

Figure 4: Age specific parameters

(a) Age Specific Productivity (b) Survival Probabilities



4.2 Internal Calibration

Moments related to the household productivity distribution are calibrated outside of equilibrium. These parameter values are presented in Table 6.

Table 6: Parameters determined outside of equilibrium

Parameter	Target	Source	Data	Model	Value
ρ_ϵ	ACF 1 period log res. earnings	GRID	0.74	0.74	0.75
σ_ϵ^2	SD 1 period change in log res. earnings	GRID	0.53	0.53	0.21

All data is taken from the GRID for Canada. The persistence of the AR(1) process ρ_ϵ is calibrated to match the autocorrelation function of the 1 period log residual earnings, and the variance σ_ϵ^2 is calibrated to match the standard deviation of 1 period change in log residual earnings.

Table 7 presents parameter values calibrated in equilibrium. I match the productivity in the fossil sector $Z_{\mathcal{F}}$ in the initial steady state (1990) and the final steady state (2022) to match the percentage of capital used by the oil sector using data from Statistics Canada Table 36-10-0096-01. To match productivity in the clean sector $Z_{\mathcal{C}}$, I use data on primary energy consumption by source from Our World in Data (OWID). OWID sources the values from the Energy Institute's "Statistical Review of World Energy" and reports units of primary energy in terawatt hours broken down by source. To arrive at my target moments, I sum up terawatt hours of clean sources (hydro, solar, wind, other renewables and nuclear) and divide by the total number of terawatt hours across all sources.

Table 7: Parameters determined in equilibrium

Parameter	Target	Source	Data	Model	Value
$Z_{\mathcal{F}}^{1997}$	$K_{\mathcal{F}}/\bar{K}$ in 1997	StatsCan	0.10	0.10	1.66
$Z_{\mathcal{C}}^{1997}$	Share clean in 1997	OWID	0.37	0.37	0.32
$Z_{\mathcal{F}}^{2020}$	$K_{\mathcal{F}}/\bar{K}$ in 2020	StatsCan	0.22	0.22	1.46
$Z_{\mathcal{C}}^{2020}$	Share clean in 2020	OWID	0.36	0.36	0.29

5 Model Validation

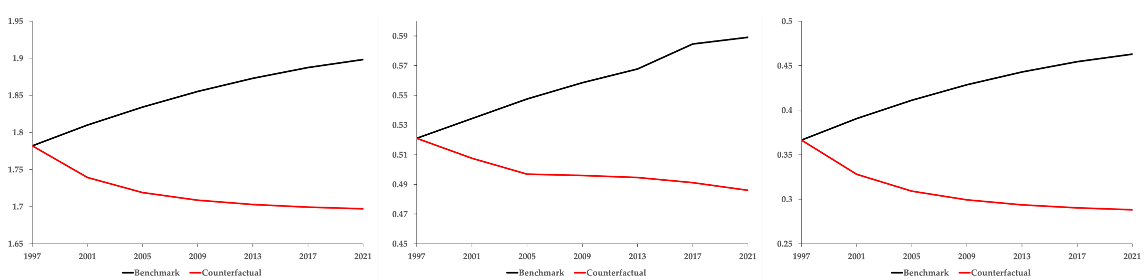
In this section I present the model performance relative to what is observed in the data. A key feature of the data is that growth in wages, consumption and GDP in the fossil producing region (Region A), corresponding to the province of Alberta, outperformed the clean producing region (Region B), corresponding to a composite of B.C., Ontario, and Québec. Table 8 presents the results. The model is able to qualitatively replicate all three of these patterns that were not explicitly targeted in the calibration.

The model reasonably captures the extent to which the economy of Region A benefited from the boom in fossil prices. Wages, consumption and GDP all grew by more between the

Table 8: Growth in Aggregates between Steady States

	Region A		**Region B**	
	Data	Model	Data	Model
Wage Growth	370.11	313.60	320.66	290.15
Consumption Growth	447.29	358.61	368.28	312.64
GDP Growth	431.81	384.16	371.53	290.63

two steady states in Region A than they did in Region B. To highlight the contribution specifically due to changes in $p_{\mathcal{F}}$, I evaluate the ratio of wages, consumption and GDP in Region A relative to Region B along the transition path in the benchmark transition and in a counterfactual world where $p_{\mathcal{F}}$ stays at the 1997 level. In Figure 5a, we can see that in the benchmark transition, the rise in $p_{\mathcal{F}}$ increases the relative wage between Regions A and B by approximately 12 percentage points. If the rise in $p_{\mathcal{F}}$ never happened, wages in Region B would have grown by more along the transition path than they did in Region A, decreasing the gap by about 8 percentage points.



(a) Relative Wages (b) Relative Consumption (c) Relative GDP

Figure 5

Similarly, Figures 5b and 5c show the same inverse trend happening if the fossil boom never happens. In the benchmark transition, consumption in Region A relative to Region B grows by approximately 7 percentage points, while in the counterfactual transition relative consumption falls by about 4 percentage points. Relative GDP between the two regions grows by nearly 10 percentage points in the benchmark example, and in the absence of growth in $p_{\mathcal{F}}$, falls by 7 percentage points. Note that the fossil price is not the sole driver of growth in the two regions. The continued TFP growth in the non-energy sector produces wage growth in either scenario. However, the growth in $p_{\mathcal{F}}$ is the mechanism that drives the differences between the two regions. This result is consistent with the literature on resource booms in other countries. For instance, Allcott and Keniston (2018) finds that US counties with oil and gas endowments experienced modestly higher real wages between 1969 and 2014.

5.1 Oil boom and welfare

This section evaluates the welfare impact of the rise in oil prices between 1997 and 2020 along the transition path. There are five objects in the model that change between 1997 and 2020 and then remain at a constant level until the economy reaches the new steady state: the fossil price ($p_{\mathcal{F}}$), and non-energy productivity (Z_A and Z_B) grow, while fossil productivity ($Z_{\mathcal{F}}$) and clean productivity (Z_C) contract. All objects grow (or contract) linearly between the initial and final values over 24 years before remaining constant for another 400 years. The economy reaches the final steady state well before the final period, after approximately 60 years.

Welfare is reported as a weighted average of consumption equivalent variation (CEV). CEV is a measure of the constant percentage change in consumption where an individual is indifferent between two states of the world. That is, the consumption equivalent variation for an agent with a period t state vector (j, a, ϵ, s) would be

$$g = [\mathbb{E}_0 V_{counter}(t, j, a, \epsilon, s)/\mathbb{E}_0 V_{bench}(t, j, a, \epsilon, s)]^{1/(1-\sigma)} - 1$$

where V_{bench} corresponds to the value function of the benchmark transition and $V_{counter}$ is the value function from the counterfactual transition. A positive value for g implies welfare is higher in the benchmark transition, and a negative value implies welfare is higher in the counterfactual transition. I compute the expected value function for agents prior to the start of the transition in period $t = 2$. Conceptually, consider a household with current state vector (j, a, ϵ, s) that observes the paths of all key aggregates, but has not resolved the uncertainty about their idiosyncratic productivity ϵ. I then compare this agent's expected value function with the equivalent agent in a counterfactual world where the path of those aggregates is the same except for the price of the fossil good, which is held constant. Since the two worlds are starting from the same initial steady state, the initial distribution over household types is the same, and the initial income distribution is the same.

Table 9 reports the weighted average CEV for households in specific age and income groupings between the two regions for this scenario. Households in both regions are worse off if the boom in fossil prices never occurs. Households in Region A are worse off across all age and income groupings, with the youngest and poorest households losing the most. The reason for this is that the wage growth over the course of their working lives in the benchmark transition is significantly higher than in the counterfactual world. Note that households at the bottom of the income distribution benefit the most from the rise in fossil prices. In a counterfactual world where the rise in the fossil price never happens, the welfare losses of a household that is beginning its working life (aged 20-34) in the lowest quintile is nearly 4 percentage points higher than the equivalent household in the clean region. The same household experiences losses 4.5 percentage points higher than a household of the same age in the highest quintile in the fossil region. These results are consistent with the literature on resource booms in resource producing regions which find that booms in resource prices benefit households at the bottom of the income distribution (for examples, see Jacobsen, 2019; Fortin and Lemieux, 2015).

Table 9: Welfare change if p_F were constant

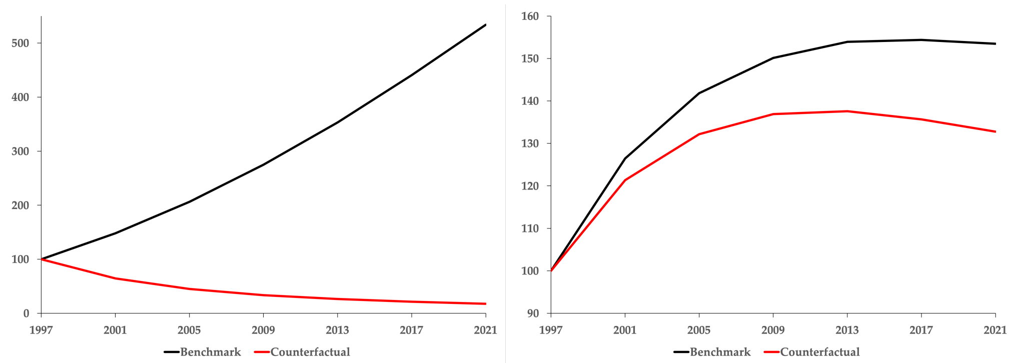
	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
Region A					
20-34	-13.61%	-10.72%	-9.70%	-9.27%	-9.07%
35-49	-13.51%	-10.82%	-9.31%	-8.64%	-8.27%
50-64	-11.29%	-8.99%	-7.74%	-7.36%	-7.29%
65-99	NA	-7.19%	-6.36%	-6.07%	-6.21%
Region B					
20-34	-9.96%	-8.80%	-8.59%	-8.90%	-8.97%
35-49	-9.14%	-8.09%	-8.11%	-8.14%	-8.25%
50-64	-6.30%	-6.38%	-6.61%	-6.87%	-7.29%
65-99	-4.41%	-5.36%	-5.82%	-6.15%	-6.42%

These welfare outcomes are largely driven by wages, profits and the interest rate. Region A wages are higher in the benchmark world, while Region B wages are higher in the counterfactual world. The dampened wage growth in Region A is a contributing factor to the larger welfare losses that the lowest income households experience. Bequests and social security transfers are nearly identical in the two scenarios. The main changes in income are derived from the return on savings, which grow significantly more in the benchmark transition than in the counterfactual. Similarly, profits in Region A are lower in the counterfactual world. These trends are presented in Figure 6

The biggest factor for households at the lower end of the income distribution is the difference in profits. Figure 6a highlights how much households in Region A lose in the counterfactual world. The benchmark transition results in massive growth in profits from the fossil sector, which are redistributed uniformly across households in the region, raising lifetime earnings for all households. These transfers are particularly beneficial to the lower income households as they act as an additional supplement to the slightly higher lifetime labour income. In the counterfactual experiment, profits in the fossil sector are actually decreasing. Since $p_{\mathcal{F}}$ is constant while both w_A and r are still increasing over time, the sectors costs relative to

Figure 6

(a) Fossil Profits (b) Interest Rate



revenue increase, even as they demand less capital and labour. Profits from the clean sector actually grow in both the benchmark and the counterfactual exercises. However, in either scenario these profits account for less than 1% of a households income across the transition. The interest rate (Figure 6b) also drives theses results. Between 1997 and 2020, r grow at a faster rate in the benchmark than it does in the counterfactual. Along the remainder of the transition path, as the economy converges to the new steady state, the interest rate is roughly 9 percentage points higher than it would have been if $p_{\mathcal{F}}$ had remained at the 1997 level. This is particularly beneficial to the youngest households in the economy as they earn significantly higher returns on their savings over their lifetime. These households labour earnings are at their lowest, given the path of the age productivity profile: at age 20, their age specific component of labour earnings is at the lowest level. During these early years, their incomes are largely supplemented by the profits. As their labour earnings grow with their age, the profit transfers from the fossil sector account for a smaller share of their total income. As they enter their retirement years, the percentage of household income derived from profits increases once social security replaces labour income.

6 Green Transition

This section evaluates the welfare impact of the Green Transition. For the purpose of this paper, I refer to the "Green Transition" as the transition path to a Net Zero world. This is difficult to define precisely, as there is no universal agreement on what the path to Net Zero looks like or how it ought to be achieved. For this reason, I adopt a simplified version of the International Energy Agency's recommendations in their "Net Zero by 2050" document (IEA, 2021). To reach Net Zero by 2050, this path calls for fossil fuel demand to fall by half, and an increase in clean sources to account for 90% of electricity production. Through the lens of the model, this occurs via two mechanisms: a fall in $p_{\mathcal{F}}$ and an increase in $Z_{\mathcal{C}}$. This path serves as a useful, though conservative, benchmark. Larger reduction targets for fossil demand serve to quantitatively amplify the welfare changes presented here, but do not qualitatively change the results.

In the benchmark experiment, I start from 2020 as an initial steady state. I recalibrate the model so that in the final steady state, fossil production $Y_{\mathcal{F}}$ falls to 50% of the initial level, and clean intermediates used in domestic energy production, $x_{\mathcal{C},E}$ account for 90% of the intermediates used (that is $x_{\mathcal{C},E}/(x_{\mathcal{C},E} + x_{\mathcal{F},E}) = 0.9$). I assume that $Z_{\mathcal{F}}$ remains constant at the 2020 level throughout the transition. I also assume that TFP in the non-energy sectors continues to grow along the same trend line as what is observed in the data from 2010 to 2020. In the transition exercise, I construct a linear path for $p_{\mathcal{F}}$, $Z_{\mathcal{C}}$ and Z_A, Z_B and solve the model along these trends. Table 10 presents the calibration results.

Table 10: Benchmark Green Transition calibration

Parameter	Target	Data	Model	Value
$p_{\mathcal{F}}^{2050}$	$0.5 \times Y_{\mathcal{F}}^{2020}$	0.61	0.61	0.49
$Z_{\mathcal{C}}^{2050}$	90% of energy intermediates are clean	0.9	0.9	1.29

6.1 Benchmark Results

I evaluate the welfare impacts of the benchmark exercise against a "No Green Transition" counterfactual. In this counterfactual world, fossil demand remains constant (ie. $p_{\mathcal{F}}$ is constant), and clean technology grows at the same pace as non-energy technology (ie. $Z_{\mathcal{C}}$ grows at the same rate as Z_A and Z_B). I then decompose the welfare effects by comparing the benchmark experiment against a world where:

(1) Fossil demand is unchanged, but $Z_{\mathcal{C}}$ grows at the same rate as it does in the benchmark scenario (ie. $p_{\mathcal{F}}$ is constant, and $Z_{\mathcal{C}}$ growth is faster than in the non-energy sector),

(2) Fossil demand falls by half but the growth of $Z_{\mathcal{C}}$ occurs at the same rate as non-energy productivity (ie. $p_{\mathcal{F}}$ falls, and $Z_{\mathcal{C}}$ grows less than in the benchmark case).

Scenario (1) isolates the welfare impacts directly influenced by growth in the clean sector, while Scenario (2) isolates the welfare impacts driven by falling fossil demand

6.1.1 No Green Transition

Table 11 summarizes the welfare impact of the benchmark Green Transition relative to a world where (1) $p_{\mathcal{F}}$ stays at the price in 2020 and (2) clean technology $Z_{\mathcal{C}}$ grows at the same rate as non-energy technology $\{Z_s\}_{s\in\{A,B\}}$. Looking at the breakdown by age, income and region, we see that the "No Green Transition" scenario is slightly welfare enhancing relative to the benchmark. The largest gains are among younger low-income households in the Fossil producing region. These gains decrease with age and with income in both regions with the exception of retired households in the first income quintile in Region B.

Table 11: No Green Transition

	Region A				
	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
20-34	0.73%	0.51%	0.42%	0.37%	0.34%
35-49	0.69%	0.51%	0.41%	0.35%	0.32%
50-64	0.57%	0.45%	0.37%	0.32%	0.29%
65-99	NA	0.43%	0.31%	0.27%	0.25%
	Region B				
20-34	0.38%	0.28%	0.24%	0.23%	0.23%
35-49	0.34%	0.26%	0.24%	0.22%	0.22%
50-64	0.25%	0.22%	0.21%	0.20%	0.19%
65-99	0.16%	0.21%	0.20%	0.19%	0.19%

Overall, the welfare impacts are quite low. The benefits of No Green Transition are less than 1% for all household types. Both regions benefit from sustained wage growth. The benefits are strongest in Region A largely due to the fact that profits are higher. Figure 7a plots the decline in profits from the fossil sector in the two scenarios. The reason is straightforward and mechanical. In the benchmark Green Transition case, the price $p_{\mathcal{F}}$ is falling while wages w_A and the interest rate r are increasing (driven by the non-energy sector and growth in Z_A). Since production costs are increasing while the price of output is falling, profits decline. In the "No Green Transition" world, the price $p_{\mathcal{F}}$ is constant, but production costs w_A and r are still increasing. In fact, both w_A and r grow slightly more in the counterfactual scenario than they do in the benchmark.

The case for why Region B benefits more from No Green Transition is a little more nuanced. Profits from the clean sector in the No Green Transition world are lower as the sector is slightly less productive. Wages grow slightly more in the benchmark Green Transition exercise than they do in the No Green Transition world. In fact, the difference in wage growth in between the two scenarios is negligible.

The key aggregate that is driving these differences is the one that affects both regions: the interest rate. In Figure 9, we see that in the early years of the transition, the growth in the interest rate in the two worlds is indistinguishable. However, in the No Green Transition

Figure 7: Profits

(a) Fossil Profits (b) Clean Profits

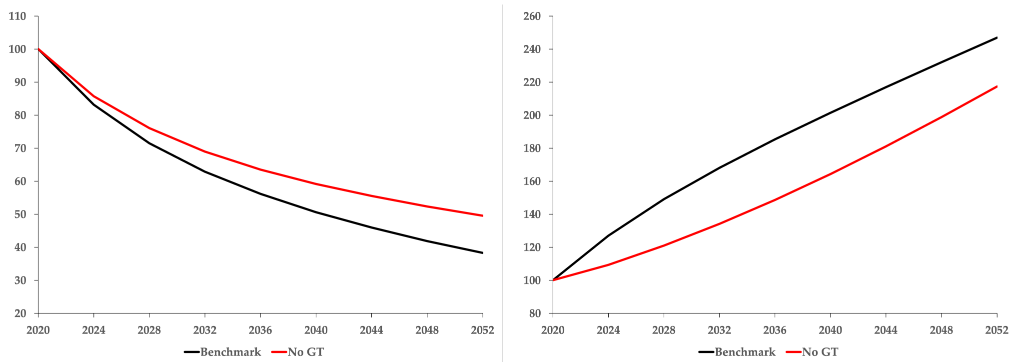
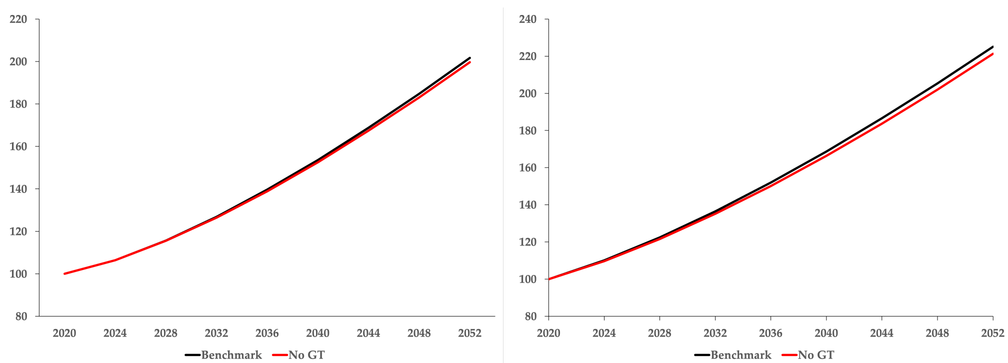


Figure 8: Wages

(a) Region A (b) Region B



world, after the initial rise, the interest rate falls, but converges to a higher level in the final steady state than in the benchmark world.

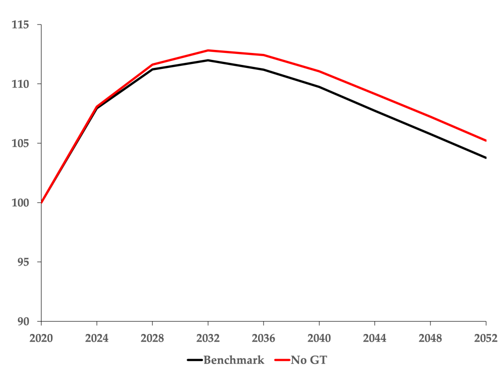


Figure 9: Interest Rate

This is driven by the fossil sector. In this economy, both the fossil sector and the clean sector are capital intensive. In both the benchmark and the counterfactual world, Z_C grows, driving up the the clean sectors demand for capital. However the capital demand in clean production is lower in the counterfactual because $Z_{\mathcal{C}}$ grows at a slower rate than it does in the benchmark scenario. In the fossil sector, capital demand falls from the initial steady state level, but is permanently higher in the counterfactual transition than it is in the benchmark. The higher value for $p_{\mathcal{F}}$ amplifies the sectors demand for capital, driving the interest rate higher.

Since the interest rate is common to both regions, this higher return on savings benefits the households in Region B as well. Younger households across the economy benefit the most due to the higher returns on lifetime savings, and workers at the lower end of the income distribution in Region A benefit from the higher transfers from profits.

6.1.2 Impact of $p_{\mathcal{F}}$

Table 12 summarizes the welfare impact of a counterfactual world where $Z_{\mathcal{C}}$ grows along the benchmark path (faster than non-energy productivity) and $p_{\mathcal{F}}$ is constant. Comparing this world to the benchmark transition highlights how much of the changes in welfare are driven by falling fossil demand. The welfare implications in this counterfactual world are qualitatively identical to the "No Green Transition" world and quantitatively slightly stronger, particularly in Region B. All households benefit from global demand for the fossil good remaining at a higher level than it is in the benchmark transition, while welfare in Region B is higher by nearly 0.1 percentage point thanks to the rapid growth in clean technology.

Table 12: Impact of $p_{\mathcal{F}}$

	Region A				
	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
20-34	0.76%	0.58%	0.51%	0.48%	0.46%
35-49	0.72%	0.57%	0.49%	0.45%	0.43%
50-64	0.60%	0.50%	0.43%	0.40%	0.39%
65-99	NA	0.46%	0.37%	0.34%	0.33%
	Region B				
20-34	0.48%	0.41%	0.40%	0.40%	0.40%
35-49	0.44%	0.39%	0.38%	0.38%	0.38%
50-64	0.34%	0.33%	0.32%	0.33%	0.33%
65-99	0.25%	0.29%	0.29%	0.30%	0.30%

The welfare gains of this counterfactual scenario are similar to the No Green Transition scenario: higher returns on savings, and profit gains in both regions. While profits fall in Region A, they are still higher overall than they are in the benchmark scenario. In Region B, the growth in profits due to the productivity boom in the clean sector is significant. In both regions, wages grow by less than they do in benchmark, though this is more pronounced in Region B. Similar to the No Green Transition scenario, the higher price for the fossil good drives demand for capital up, which results in a higher interest rate along the transition path than in the benchmark case. The higher return on savings overall makes households in both regions better off. The smaller decline in profits from the fossil sector leave households in Region A better off than they are under the benchmark scenario, particularly younger households who benefit from the higher profits over their lives, and poorer households who benefit from the higher income (despite the slightly lower wages). Households in Region B benefit in this scenario as well. The profit story is the same as in Region A: higher profits received over their lifetime benefit younger and lower income households. However the added benefit of the higher interest rates, driven by the higher international demand for the fossil good, spills over into the non-fossil producing Region as well.

6.1.3 Impact of $Z_{\mathcal{C}}$

Table 13 summarizes the welfare results of a counterfactual world where clean and non-energy technology grow at the same rate but $p_{\mathcal{F}}$ falls along the same path as the benchmark transition. This scenario isolates the welfare impact due to the expansion of the clean sector in the Green Transition. This counterfactual world is actually welfare decreasing relative to the benchmark, highlighting the extent to which technological growth in the clean sector is actually beneficial. Households in both regions are worse off in this counterfactual world. Losses are increasing with income and with age in both regions. Region B loses the most in this scenario.

Table 13: Impact of $Z_{\mathcal{C}}$

	Region A				
	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
20-34	-0.04%	-0.08%	-0.10%	-0.12%	-0.13%
35-49	-0.04%	-0.07%	-0.09%	-0.11%	-0.12%
50-64	-0.04%	-0.06%	-0.08%	-0.09%	-0.11%
65-99	NA	-0.04%	-0.07%	-0.08%	-0.09%
	Region B				
20-34	-0.12%	-0.14%	-0.16%	-0.17%	-0.18%
35-49	-0.12%	-0.13%	-0.15%	-0.16%	-0.17%
50-64	-0.10%	-0.11%	-0.12%	-0.13%	-0.15%
65-99	-0.10%	-0.09%	-0.10%	-0.11%	-0.12%

Lower growth in the clean sector is welfare reducing for households across the economy. Unlike the No Green Transition case, this is not driven primarily by the interest rate. Here, the path of r is nearly identical to the benchmark case. Households in Region B are most impacted. Younger households in the region receive lower wages over their working lives, and all households receive lower profits than they would in a world where $Z_{\mathcal{C}}$ grows more rapidly. In Region A, profits from the fossil sector are roughly the same, as both the interest rate and wages in the Region are approximately equal to what they are in the benchmark case. The aggregate capital stock in this world grows by less than it does in the benchmark transition. This is due to lower overall savings in Region B. The lower wages and lower profits received along the transition path reduce savings in Region B. Since capital is mobile between the two regions and since the stock of labour is fixed, this lowers how much the economy actually produces. GDP growth in the two regions is lower than in the benchmark case, but this difference is amplified in Region B. Since Region A, and in particular the fossil sector, are producing roughly the same amount, they use more of the (lower) capital stock than Region B. Hence, the difference in wage growth is less pronounced in A than B.

While overall the Green Transition produces welfare losses for households across the economy, this decomposition highlights that there is the potential for these losses to be negated. Households in both regions are better off in the Green Transition world with higher growth in the clean sector than they are in a world where the clean sector grows at a lower level. This opens the question of how rapidly the clean sector must grow in order to counteract the welfare losses from the fall in international fossil demand.

6.1.4 Alternative Scenario: Faster growth in clean productivity

In my first alternative scenario, I compare the "No Green Transition" world to a new benchmark where $Z_{\mathcal{C}}$ arrives immediately at the final steady state level in the first period of the transition. This is a world where the demand for the fossil good falls between 2020 and 2050 so that the economy produces 50% of 2020 levels, non-energy productivity grows along the 2010-2020 trend, and clean technology is instantaneously productive enough to account for 90% of energy inputs. I then treat this transition as the alternative benchmark derive the welfare results relative to the "No Green Transition" scenario from the previous section. Table 14 compares the regional welfare outcomes from the benchmark (relative to No Green Transition) and the alternative benchmark.

An instantaneous growth in $Z_{\mathcal{C}}$ reduces the welfare gains of the "No Green Transition" scenario, particularly among households in Region B. In fact, faster growth in the clean sector makes the path nearly welfare neutral among the youngest and oldest households in Region B, and welfare enhancing for middle- and late-career households. Table 15 breaks down the gains across the age and income distribution in each region. Comparing the results of this

Table 14: Impact of clean scenario

	Benchmark		Alternative Benchmark	
Age Cohort	Region A	Region B	Region A	Region B
20-34	0.70%	0.36%	0.57%	0.03%
35-49	0.57%	0.28%	0.38%	-0.10%
50-64	0.45%	0.22%	0.32%	-0.08%
65-99	0.42%	0.18%	0.34%	0.03%

exercise to Table 11, it is clear that faster growth in clean technology can potentially offset many of the welfare losses associated with the Green Transition.

Table 15: Alternative Benchmark: Instantaneous growth in $Z_{\mathcal{C}}$

	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
Region A					
20-34	0.63%	0.23%	0.06%	-0.05%	-0.10%
35-49	0.59%	0.28%	0.11%	0.00%	-0.08%
50-64	0.53%	0.32%	0.16%	0.06%	-0.02%
65-99	NA	0.36%	0.16%	0.07%	0.01%
Region B					
20-34	0.08%	-0.17%	-0.27%	-0.32%	-0.35%
35-49	0.04%	-0.13%	-0.20%	-0.26%	-0.30%
50-64	0.05%	-0.06%	-0.13%	-0.19%	-0.23%
65-99	0.04%	0.02%	-0.05%	-0.08%	-0.11%

Suppose instead that $Z_{\mathcal{C}}$ grows twice as much in the first period. In this scenario the model predicts that in aggregate, for the entire economy, the Green Transition is welfare enhancing. Table 16 summarizes the welfare results relative to the "No Green Transition" scenario

For households in Region A at the bottom of the income distribution (and retirees in the second quintile), the No Green Transition scenario is still welfare enhancing. However, the welfare gains compared to the benchmark scenario in Table 11 are significantly lower. For everyone else in this economy, a Green Transition with rapid and significant growth in the clean sector is preferable to No Green Transition. The losses of the Green Transition not happening are most pronounced among the youngest and wealthiest households. In Region B, younger households benefit the most from the boost in their lifetime incomes from the higher wage growth. Wages in both regions grow more than under the benchmark scenario, by roughly 1 percentage point on average in Region A and 0.89 of a percentage point in Region B. The interest rate is slightly higher under the alternative benchmark, producing higher returns to savings for all households across the economy. In Region A, fossil profits

Table 16: Alternative Benchmark: Faster instantaneous growth in $Z_{\mathcal{C}}$

	Region A				
	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
20-34	0.13%	-0.22%	-0.38%	-0.48%	-0.53%
35-49	0.12%	-0.14%	-0.29%	-0.39%	-0.47%
50-64	0.14%	-0.03%	-0.17%	-0.27%	-0.36%
65-99	NA	0.05%	-0.12%	-0.21%	-0.27%
	Region B				
20-34	-0.29%	-0.56%	-0.68%	-0.74%	-0.78%
35-49	-0.30%	-0.48%	-0.57%	-0.64%	-0.69%
50-64	-0.19%	-0.33%	-0.43%	-0.51%	-0.57%
65-99	-0.08%	-0.20%	-0.29%	-0.35%	-0.39%

are slightly higher under the alternative benchmark, despite the increase in factor prices.

This scenario highlights that the benefits of the Green Transition derived from an expansion of the clean sector are able to counter the negative welfare effects of the proposed path to Net Zero. However, extremely rapid (unrealistic) growth is required in order to achieve this outcome. It is also important to note that the households who stand to benefit the most from the Green Transition are the wealthiest households, who benefit the most from the higher return on savings that the model predicts.

6.1.5 Alternative Scenario: Faster growth in non-energy productivity

Suppose that instead of an immediate jump in $Z_{\mathcal{C}}$, the non-energy sector grows more rapidly. In this world, $p_{\mathcal{F}}$ decreases at the same rate as the benchmark, $Z_{\mathcal{C}}$ grows at the same rate as the benchmark, but Z_A and Z_B are 10% higher in the final steady state. This exercise highlights the extent to which expansion in the non-energy sector of the economy is able to counteract the losses in the Green Transition. Table 17 summarizes the welfare results.

This scenario, produces stronger welfare gains than the extreme and immediate expansion of the clean sector is able to produce. Households at the bottom of the income distribution in Region A are still better off in a world where the Green Transition does not occur. However, all other households in the economy are better off in a world where the Green Transition occurs (with higher growth in the non-energy sector). Wage growth in both regions is stronger than in the benchmark case, due to the fact that the non-energy sector is more labour intensive. The boom in clean productivity amplifies the upward pressure on the interest rate as well, producing an interest rate that is higher along the transition path than in either the benchmark or the No Green Transition cases.

Table 17: Alternative Benchmark: Higher growth in Non-Energy sector

	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
Region A					
20-34	0.12%	-0.52%	-0.83%	-1.02%	-1.11%
35-49	0.09%	-0.39%	-0.67%	-0.86%	-1.02%
50-64	0.08%	-0.22%	-0.48%	-0.67%	-0.82%
65-99	NA	-0.15%	-0.42%	-0.57%	-0.67%
Region B					
20-34	-0.82%	-1.24%	-1.43%	-1.54%	-1.63%
35-49	-0.83%	-1.10%	-1.25%	-1.37%	-1.46%
50-64	-0.66%	-0.85%	-1.00%	-1.12%	-1.23%
65-99	-0.64%	-0.63%	-0.75%	-0.83%	-0.89%

7 Conclusion

This paper evaluates the welfare impact of a Green Transition to a Net Zero world in small, resource-rich economies. While the fossil boom in the 2000's produced large welfare gains across the age and income distribution, the model predicts modest welfare losses of less than 1% along the transition path in a world with declining demand for fossil fuels. These losses are most pronounced among the youngest and poorest households residing in the fossil producing region of the economy. Using the IEA's recommendations for reaching a Net Zero world, the fall in fossil demand lowers welfare more than the growth of the clean sector increases it. However, growth in the clean sector has the potential to dampen, and even eliminate the welfare losses associated with the energy transition if it occurs rapidly enough. This requires extreme and immediate growth in the sector, which is likely unfeasible. Stronger, steady growth in the non-energy sector has the highest potential to mitigate the negative welfare effects of the green transition. However, in all scenarios the top of the income distribution reaps the largest benefits. This paper omits some of the finer details of how local labour markets respond to these changes. Further study of frictions in labour movements between industries and between regions would further clarify who bears the costs of the Green Transition. This paper also highlights the channels through which the costs of the Green Transition can be negated, namely via growth in other sectors of the economy. Future work focusing on policy changes that boost productivity in order to offset the costs of the transition is needed. Alternatively, further work studying redistributive policies to compensate the low income households who are adversely impacted may yield further insights.

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