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 quantify the welfare impact of this transition for a small, resource-rich country. I develop a quantitative, overlapping generations model of a multi-region, multi-sector, small open economy with heterogeneous households featuring both fossil and clean energy production and calibrate it to the Canadian economy. In a backward-looking exercise, I find that the global rise in oil prices from 1997 to 2020 can quantitatively account for wage, consumption, and GDP growth differences across Canadian regions with and without fossil fuel extraction. In forward-looking counterfactual experiments, I quantitatively evaluate the effects of a global transition to clean energy as laid out in the International Energy Agency's path to a Net Zero world by 2050. Through the lens of the model, this scenario calls for a 50% reduction in global fossil fuel demand and an expansion of the clean energy sector to account for 90% of domestic energy production. I find that the reduction in international demand for fossil fuels decreases lifetime consumption by 0.56% overall. These losses are most pronounced among young, low-income households in the fossil extracting region, whose lifetime consumption decreases by 0.77%. The expansion of the clean energy sector dampens the aggregate losses by 15%. An immediate expansion in the clean sector reduces the losses by 54%.

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1 Introduction

There is strong evidence to suggest that 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.

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 an inverted outcome. Using the International Energy Agency's recommendations for attaining a Net Zero world by 2050, I find that the fall in demand for fossil fuels decreases welfare across the age, income, and regional distributions. Overall, lifetime consumption decreases by 0.56%. The largest losses are experienced by young households at the bottom of the income distribution in fossil extracting regions of the economy, primarily due to dampened wage growth, lower returns on savings and the declining profits from the fossil sector. The expansion of the clean energy sector dampens these losses by 15%. In a counterfactual exercise, I find that an immediate expansion of the clean sector dampens the losses due to fossil fuel demand by 54%. Among young, low income households, rapid expansion in the production of clean energy reduces losses by 20% in the fossil producing region and by 85% in the clean producing region.

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, whose lifetime consumption increased by 16%. These gains are monotonically decreasing with both age and income. This result is driven by the stronger wage growth, increased return to savings and higher profits from the fossil sector, which boost lifetime income.

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 results in an aggregate decrease of lifetime consumption by 0.56%. These losses are most pronounced in the fossil-producing region and decrease with age and income. This scenario is largely the inverse story of the backward looking exercise: falling demand for fossil fuels (which is reflected in a decrease in the price) dampens growth in wages and the interest rate, and amplifies the fall in fossil sector profits along the transition path. Households at the bottom of the age and income distribution experience the largest losses in this scenario. However, the losses due to falling international demand for fossil fuels are partially offset by the gains from expansion of the clean sector. This Green Transition dampens aggregate losses by 15%. I investigate whether faster growth in the clean sector can further mitigate these losses. I find that an immediate expansion in clean energy sector dampens the losses from declining demand for fossil fuels by 54%. This expansion dampens the losses among young, low income households in both regions, by 19% in the fossil producing region, and by 85% in the clean producing region.

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, and is the first paper to quantitatively study the macroeconomic impacts of a global transition to a Net Zero world by 2050. 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).

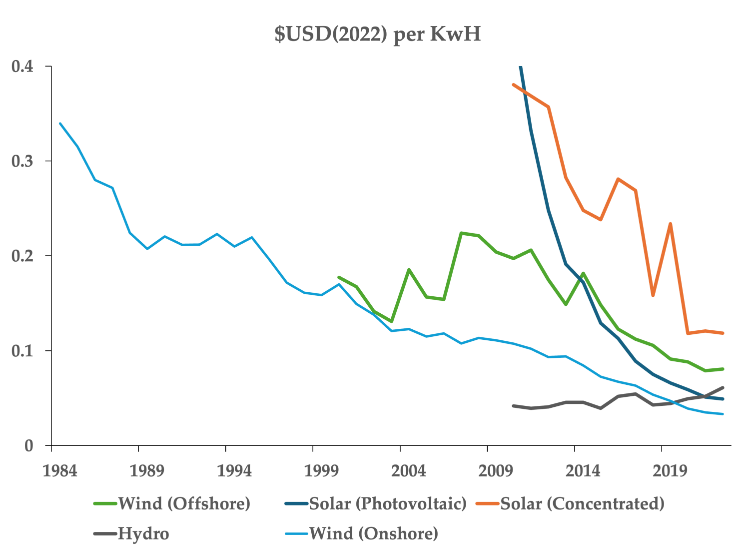


Figure 1: Levelized costs of clean energy

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 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.

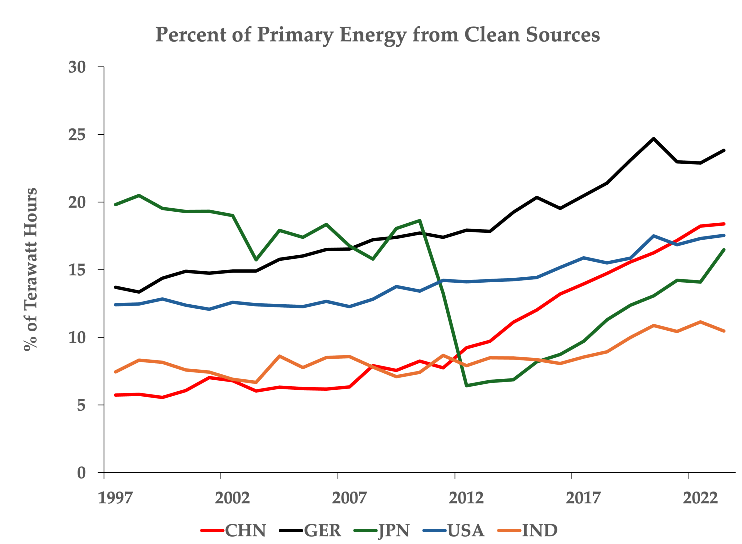


Figure 2: Adoption of clean energy

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.

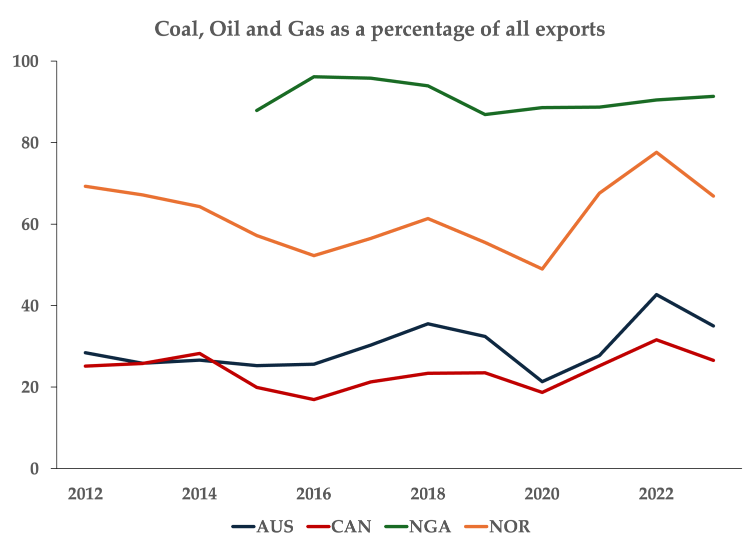


Figure 3: Coal, Oil, and Gas as a share of exports

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 towards clean energy. 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 $s \in \{F, C\}$. The regions each produce a specialized energy and non-energy intermediate good. The key distinction is region F produces the fossil energy intermediate (denoted by $\mathcal{F}$) and region C produces the clean energy intermediate (denoted by $\mathcal{C}$). 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 $s \in \{F, C\}$ correspond to the profits from the energy intermediate producers specific to each region. A household living in region F receives the profits from the fossil producers $\pi_{\mathcal{F}}$, while a household living in region C 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), 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:

$$SS + G = \tau_{c,F} C_F + \tau_{c,C} C_C + \int T(y)\ d\Omega(j, a, \epsilon, s) \tag{3.4}$$

where $\Omega(j, a, \epsilon, s)$ is the distribution across all household types in the economy, and C_F and C_C 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. Each region specializes in producing a non-energy intermediate good and an energy intermediate good. Non-energy inputs are denoted with subscripts $\{F, C\}$, while energy intermediate inputs are denoted with calligraphic subscripts $\{\mathcal{F}, \mathcal{C}\}$. Intermediates are then aggregated into the energy good and the final good. The energy good (denoted with $\mathcal{E}$) uses region specific energy intermediates $x_{j,\mathcal{E}}$ for $j \in \{\mathcal{F}, \mathcal{C}\}$. Final good production uses non-energy intermediates $x_{s,Y}$ for $s \in \{F, C\}$ and the aggregated energy good $x_{\mathcal{E},Y}$.

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 $\nu_{\mathcal{F}} \in (0,1)$. 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:

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

subject to:

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

Profits $\pi_{\mathcal{F}} = p_{\mathcal{F}}Y_{\mathcal{F}} - (r+\delta)K_{\mathcal{F}} - w_F L_{\mathcal{F}} - p_{\mathcal{F}}x_{\mathcal{F},\mathcal{F}}$ are distributed back to the households in region F 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 C using capital $K_{\mathcal{C}}$ and labour $L_{\mathcal{C}}$. Clean producers make production choices to maximize profits according to:

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

subject to:

$$\begin{aligned} &Y_{\mathcal{C}} = Z_{\mathcal{C}}(K_{\mathcal{C}}^{\eta}L_{\mathcal{C}}^{1-\eta})^{\nu_{\mathcal{C}}} \\ &\nu_{\mathcal{C}} \in (0,1) \end{aligned}$$

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

3.4.3 Non-Energy Producers

The non-energy good Y_s produced in each region $s \in \{F, C\}$ 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 $Y_{\mathcal{E}}$ is produced by combining the Clean energy intermediate $x_{\mathcal{C},\mathcal{E}}$ and the Fossil energy intermediate $x_{\mathcal{F},\mathcal{E}}$, both of which are region-specific. The problem of the energy producer is:

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

subject to:

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

3.4.5 Final Good Producer

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

$$\max_{x_{F,Y}, x_{C,Y}, x_{\mathcal{E},Y}} p_Y Y - p_F x_{F,Y} - p_C x_{C,Y} - p_{\mathcal{E}} x_{\mathcal{E},Y} \tag{3.9}$$

subject to:

$$Y = \min \left\{ x_{N,Y}, \mu_{\mathcal{E}} x_{\mathcal{E},Y} \right\}$$
$$x_{N,Y} = \left(x_{F,Y}^{\rho_Y} + x_{C,Y}^{\rho_Y} \right)^{1/\rho_Y}$$

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 $\{w_s, r, p_F, p_C, p_{\mathcal{C}}, p_{\mathcal{E}}, p_{\mathcal{F}}\}$, a stationary distribution $\Omega(j,a,\epsilon,s)$, factor demands K_F, K_C, $K_{\mathcal{F}}$, $K_{\mathcal{C}}$, L_F, L_C, $L_{\mathcal{F}}$, $L_{\mathcal{C}}$, $x_{F,Y}$, $x_{C,Y}$, $x_{\mathcal{E},Y}$, $x_{\mathcal{C},\mathcal{E}}$, $x_{\mathcal{F},\mathcal{E}}$, $x_{\mathcal{F},\mathcal{F}}$ and aggregate quantities $Y, Y_{\mathcal{E}}, Y_F, Y_C, Y_{\mathcal{C}}, Y_{\mathcal{F}}$ 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 $\{w_s, r, p_F, p_C, p_{\mathcal{C}}, p_{\mathcal{E}}, p_{\mathcal{F}}\}$.

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.

$$\int_1^{j_{ret}} \quad d\Omega(j,a,\epsilon,F) = L_F + L_{\mathcal{F}}$$
$$\int_1^{j_{ret}} \quad d\Omega(j,a,\epsilon,C) = L_C + L_{\mathcal{C}}$$

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

$$\int a'(j,a,\epsilon,s) \;\; d\Omega(j,a,\epsilon,s) = K'_F + K'_C + K'_{\mathcal{F}} + K'_{\mathcal{C}}$$

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

clears, ie.

$$
\begin{aligned}
Y_{\mathcal{C}} &= x_{\mathcal{C},\mathcal{E}} \\
Y_{F} &= x_{F,Y} \\
Y_{C} &= x_{C,Y} \\
Y_{\mathcal{E}} &= x_{\mathcal{E},Y}
\end{aligned}
$$

7. Trade is balanced in each period, ie.

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

where

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

for $i \in \{F, C\}$

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 $\rho_{\mathcal{E}} = 0.66$. 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
$\rho_{\mathcal{E}}$	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 $\nu_{\mathcal{F}}$ and $\nu_{\mathcal{C}}$ are set 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

$$\nu_j = 1 - \frac{\pi_j}{Y_j}$$

where π_j is profits and Y_j is revenues. 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

$$\kappa = \frac{1}{9} \sum_{t=1997}^{2006} \frac{Y^S_{\mathcal{F},t}}{Y^S_{\mathcal{M},t}}$$

where $Y^S_{\mathcal{F}}$ corresponds to value added in "Support activities for oil and gas extraction", and $Y^S_{\mathcal{M}}$ corresponds to "Support activities for mining, and oil and gas extraction". 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 as a fraction of all support activities in mining is fairly constant, accounting for approximately 96% value added between 2007 and 2020. I then construct a series for value added in the fossil sector as

$$\hat{Y}_{\mathcal{F},t} = \begin{cases} \kappa Y^S_{\mathcal{M},t} + Y_{\mathcal{F},t} & if \quad t \in \{1997, \ldots, 2006\} \\ Y^S_{\mathcal{F},t} + Y_{\mathcal{F},t} & if \quad t \in \{2007, \ldots, 2020\} \end{cases}$$

where $Y_{\mathcal{F},t}$ corresponds to the value added in Oil and Gas extraction (excluding support activities). Using the value $\nu_{\mathcal{F}}$, I use data on compensation (denoted $w_t L_{\mathcal{F},t}$) and value added (denoted $\hat{Y}_{\mathcal{F},t}$) compute

$$\gamma = 1 - \frac{1}{23} \sum_{t=1997}^{2020} \frac{w_t L_{\mathcal{F},t}}{\nu_{\mathcal{F}} \hat{Y}_{\mathcal{F},t}}$$

to arrive at $\gamma = 0.66$. Here, $w_t L_{\mathcal{F},t}$ corresponds to the sum of employee compensation in NAICS 211 and NAICS21311A. 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

$$\eta = 1 - \frac{1}{23}\sum_{t=1997}^{2020} \frac{w_t L_t}{\nu_{\mathcal{C}}(p_t Y_t)}$$

to arrive at $\eta = 0.60$

Table 3: Estimated Production Parameters

Parameter		Source	Value
α	Capital share, non-energy	StatsCan Tables	0.4
$Z_{F,1997}, Z_{C,1997}$	TFP in non-energy	StatsCan Tables	0.11
$Z_{F,2020}, Z_{C,2020}$	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
$\mu_{\mathcal{E}}$	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 $\mu_{\mathcal{E}}$ 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 parameter governing energy used in final good production, $\mu_E = Y/x_{\mathcal{E},Y}$ where Y maps to total value-added net of mining and utilities and $x_{\mathcal{E},Y}$ 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 $\mu_{\mathcal{E}} = 38.43$. 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. (2024). 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 $s = F$ and for the composite Canada that consists of British Columbia, Ontario and Québec to map into region $s = C$. 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
$\tau_{c,F}$	Consumption tax rate, region A	StatsCan tables	0.12
$\tau_{c,C}$	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 $\tau_p = 1 - \beta_1$ 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.

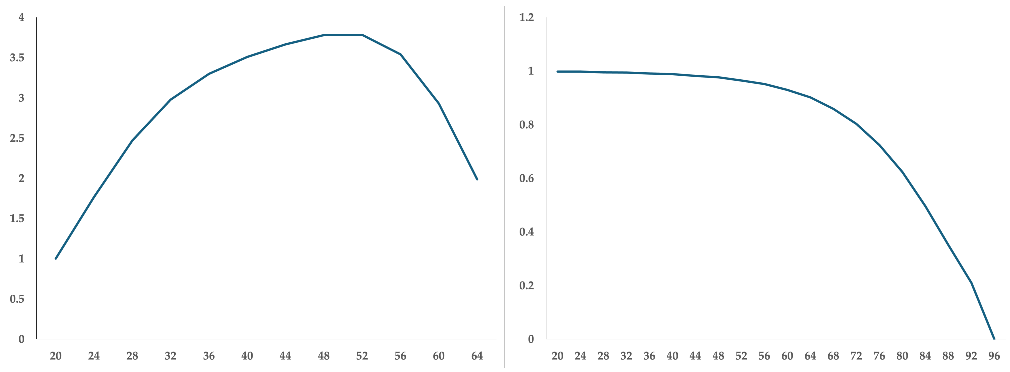
Table 5: Estimated Age specific Parameters

	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^2_ϵ	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^2_ϵ 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

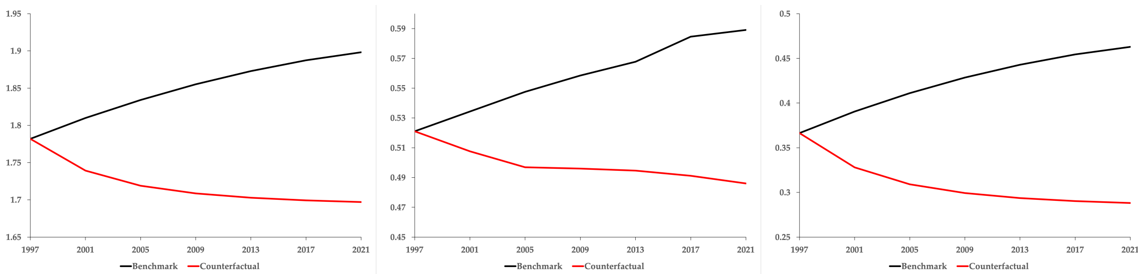
In this section I present the model performance relative to what is observed in the data. A key feature of the data is that growth in wages, consumption and GDP in the fossil producing region (Region F), corresponding to the province of Alberta, outperformed the clean producing region (Region C), corresponding 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.

Table 8: Growth in Aggregates between Steady States

	Region F		**Region** C	
	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

The model reasonably captures the extent to which the economy of Region F benefited from the boom in fossil prices. Wages, consumption and GDP all grew by more between the two steady states in Region F than they did in Region C. To highlight the contribution specifically due to changes in $p_{\mathcal{F}}$, I evaluate the ratio of wages, consumption and GDP in Region F relative to Region C 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 C would have grown by more along the transition path than they did in Region F, decreasing the gap by about 8 percentage points.

Similarly, Figures 5b and 5c show the same inverse trend happening if the fossil boom never happens. In the benchmark transition, consumption in Region F relative to Region C



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

Figure 5

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_F and Z_C) grow, while fossil productivity ($Z_{\mathcal{F}}$) and clean productivity ($Z_{\mathcal{C}}$) 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

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

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 the benchmark transition improves welfare, and a negative value implies it reduces welfare. 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 ($p_{\mathcal{F}}$), 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. The rise in fossil prices benefits households in both regions. Lifetime consumption for households in Region F increases across all age and income groupings, with the youngest and poorest households increasing their consumption by about 16% along the transition path. The reason for this is that the wage growth over the course of their working lives in the benchmark transition is higher than in the counterfactual world, and profits from the fossil sector increase their income by more during the boom. Among these young, low income households, the gain in lifetime consumption is nearly 4 percentage points higher than the equivalent household in the clean region. For the wealthier households, the oil price boom benefitted lower income households by 0.12 percentage points more in the fossil region than in the clean region. These results are consistent with the literature on resource booms, which find that booms in resource prices benefit households at the bottom of the income distribution in the regions most exposed to the boom (for examples, see Jacobsen, 2019; Fortin and Lemieux, 2015).

These welfare outcomes are largely driven by wages, profits and the interest rate. Region F wages are higher in the benchmark world, while Region C wages are higher in the counterfactual world. This boost in Region F's wage growth is a contributing factor to the larger welfare gains that the lowest income households experience. Bequests and social security transfers are nearly identical in the two scenarios. The return on savings also grow significantly more in the benchmark transition than in the counterfactual. Similarly, profits in Region F are lower in the counterfactual world. These trends are presented in Figure 6

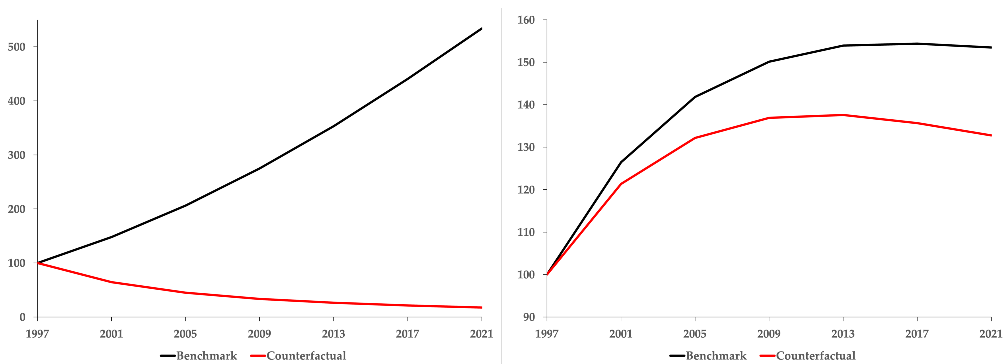
Figure 6a highlights how much households in Region F gain in the from the rise in $p_{\mathcal{F}}$. The benchmark transition results in massive growth in profits from the fossil sector, which are redistributed uniformly across households in the region, raising lifetime earnings for all

Table 9: Welfare change due to p_F increase

	Region F				
	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
20-34	15.76%	12.01%	10.74%	10.21%	9.98%
35-49	15.63%	12.14%	10.27%	9.46%	9.01%
50-64	12.73%	9.88%	8.39%	7.94%	7.87%
65-99	NA	7.75%	6.79%	6.46%	6.63%
	Region C				
20-34	11.06%	9.65%	9.39%	9.77%	9.86%
35-49	10.06%	8.80%	8.83%	8.86%	9.00%
50-64	6.73%	6.82%	7.08%	7.37%	7.77%
65-99	4.61%	5.67%	6.18%	6.55%	6.86%

Figure 6

(a) Fossil Profits (b) Interest Rate



households. These transfers are particularly beneficial to the lower income households as they act as an additional supplement on top of the higher lifetime labour earnings. In the counterfactual experiment, profits in the fossil sector are actually decreasing. Since $p_{\mathcal{F}}$ is constant while both w_F and r are still increasing over time, the sectors costs relative to 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 in Region C across the transition. The interest rate (Figure 6b) grows 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 at the start of the transition, 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 decreasing but important share of their total income. During 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, $x_{\mathcal{C},\mathcal{E}}$ account for 90% of the intermediates used (that is $x_{\mathcal{C},\mathcal{E}}/(x_{\mathcal{C},\mathcal{E}} + x_{\mathcal{F},\mathcal{E}}) = 0.9$). 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_F, Z_C 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

Using these calibrated values, I establish my benchmark "Green Transition" (GT) scenario. Fossil demand $p_{\mathcal{F}}$ decreases from 2020 to 2050, and then remains constant, while productivity in the clean sector ($Z_{\mathcal{C}}$) grows over the same period and then remains constant. Non-energy productivity (Z_F, Z_C) grow over the same period, but by less than $Z_{\mathcal{C}}$.

6.1 Decrease in demand for fossil fuels

I begin by evaluating the welfare impacts strictly from a decrease in fossil fuel demand relative to a "No Green Transition" (NGT) scenario. The NGT transition is a world where (a) fossil demand remains at the 2020 levels (so $p_{\mathcal{F}}$ is constant) and (b) $Z_{\mathcal{C}}$, Z_F and Z_C all grow at the same rate, meaning $Z_{\mathcal{C}}$ grows slower than it does in the GT benchmark. To isolate the costs from a fall in fossil demand, I compare the NGT scenario to an identical world, except that $p_{\mathcal{F}}$ declines until 2050 along the GT path.

The decline in demand for fossil fuels produces aggregate welfare losses of 0.55% across the entire economy. The detailed breakdown is presented in Table 11. The distribution of losses is largely the mirror image of the outcomes from the backward-looking exercise in Section 5. The largest decreases in lifetime consumption are felt by households in Region F, who are the most exposed to the contraction of the fossil industry. Young, low-income households' consumption decreases by 0.77% along the transition.

The decrease in $p_{\mathcal{F}}$ implies a fall in overall fossil production $Y_{\mathcal{F}}$. Fossil production in the NGT scenario contracts as well due to movement in other aggregates. The growth in both the clean and non-energy sectors leads to rising wages and interest rate, raising production costs across the economy. As both productivity $Z_{\mathcal{F}}$ and the price $p_{\mathcal{F}}$ stay constant, this results in lower demand for both labour and capital in the sector, and lower output overall. However, the contraction of the fossil sector is more pronounced with a fall in $p_{\mathcal{F}}$.

While productivity growth in clean energy $Z_{\mathcal{C}}$ lowers the relative price between the fossil good and the clean good in both scenarios, the price does not fall enough to match the decline in $p_{\mathcal{F}}$, so fossil fuels account for an increasing share of energy inputs in this scenario. However, the combination of falling $p_{\mathcal{F}}$ alongside increasing wages w_F and interest rate r also mean profits fall. Relative to the NGT scenario, fossil profits fall by an average of 17% more over the lifetime of an individual aged 20 at the beginning of the transition, significantly reducing lifetime income. The difference in wage growth in Region F is negligible between the two scenarios, only about 0.05% which does not serve to offset the fall in profits. The interest rate is also on average 1.19% lower than it would have been if $p_{\mathcal{F}}$ stayed constant, so the return to lifetime savings is dampened as well.

Wages in Region C are about 0.6% higher on average during the working life of a 20-year-old, while profits from the clean sector are lower by about 7%. This is due to the combination of increased production costs but also due to the substitution towards using more fossil fuels in domestic energy production. In both regions, profits are lower than in the NGT scenario. However, this fall in profits is 10 percentage points more pronounced in Region F. The contraction in fossil production and increase in domestic fossil use also implies a decline in exports. Due to trade being balanced in this economy, this also implies a reduction in imports. For an initial 20-year-old, imports are on average 20% lower, while aggregate production of the final good only increases by about 1%. As a result, there is less of the consumption good available overall.

Table 11: Impact of $p_{\mathcal{F}}$

	Region F				
	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
20-34	-0.77%	-0.59%	-0.52%	-0.49%	-0.47%
35-49	-0.73%	-0.58%	-0.50%	-0.46%	-0.44%
50-64	-0.61%	-0.51%	-0.44%	-0.41%	-0.39%
65-99	NA	-0.47%	-0.38%	-0.35%	-0.34%
	Region C				
20-34	-0.49%	-0.42%	-0.40%	-0.40%	-0.41%
35-49	-0.45%	-0.40%	-0.38%	-0.38%	-0.38%
50-64	-0.35%	-0.33%	-0.33%	-0.33%	-0.34%
65-99	-0.26%	-0.29%	-0.30%	-0.30%	-0.31%

6.1.1 Green Transition

To assess the overall benefits to the economy from faster growth in the clean energy sector, I compare the welfare impact of the benchmark Green Transition (GT) (relative to NGT) with the impact due solely to falling $p_{\mathcal{F}}$ from the previous section. Table 12 summarizes the welfare results by age and income groups across the two regions. To isolate the effect of expansion in clean energy production (i.e. growth in $Z_{\mathcal{C}}$), I take the ratio of the CEV's. Then the impact on overall welfare from growth in the clean sector is given by

$$1 - \frac{CEV_{GT}}{CEV_{p_{\mathcal{F}}}}$$

where the numerator is the measure of consumption equivalence from the benchmark Green Transition (relative to NGT) and the denominator is the measure of consumption equivalence from the fall in fossil demand from the previous section. The domestic growth in clean energy production produces modest welfare improvements, dampening the aggregate losses by 15% in aggregate. This expansion is not sufficient to completely negate the welfare losses from falling demand for fossil fuels, but it does produce some substantial improvement for some households. The youngest, poorest households in Region F benefit the least and only see an improvement in lifetime consumption of 5.68%. Moving up the income distribution, the wealthiest households in the region see their overall welfare improve by between 27 and 28% thanks to the expansion in the clean sector. In Region C, the bottom of the age and income distribution see their welfare improve by roughly 22%. The losses for the wealthiest households decrease between 38% and 44%.

Fossil production contracts by more in this scenario than in the previous section, due to the falling domestic demand for fossil fuels. The relative price between clean and fossil inputs falls by enough so that energy production substitutes away from fossil fuels and increases the use of clean inputs. This also means the price of the energy good is significantly lower during the Green Transition. On average, over the course of the transition the energy price in the GT scenario is 38% lower than it was in the previous exercise. This results in final good production expanding by slightly more (about 0.31% higher per year). Expanding production of the final good produces an increase in demand for non-energy inputs from both regions, which can account for the stronger wage growth that the Green Transition produces. A 20-year-old in Region F will have labour income that is on average 0.61% higher over the course of the Green Transition than they would have if there was no concurrent expansion in the clean sector. In Region C, wages are 0.66% higher over this period.

Due to the fall in domestic demand for fossil energy, exports as a fraction of output in the fossil sector increase. While the fossil sector contracts slightly more in the Green Transition than it would absent the expansion of the clean sector, and even though in both scenarios exports decline over time, the economy still sells slightly more of the fossil good to the rest of the world in the GT scenario than in the previous section. As a result, due to the balanced trade condition the economy imports slightly more of the final consumption and investment good. Since the aggregate economy can both produce more of the final consumption good and import more of it, households in both regions are able to consume and invest slightly more thanks to the expansion of the clean sector.

The interest rate is on average 0.15% lower over the lifetime of an initial 20-year-old than the interest rate in the previous section was, but aggregate savings are higher, due to the increase in the total quantity of the final good available for consumption and investment. As a result, the annual income from savings over the lifetime of an initial 20-year-old is 0.68% higher thanks to the expansion of the clean sector. This increase in savings income and labour income in both regions work to dampen the welfare losses from falling fossil demand, particularly at the top of the income distribution among young households. These households benefit from higher labour income during their working lives, and can save more, thus reaping additional gains from the higher savings.

This increase in labour income and return to savings is higher than the decrease in profits from the fossil sector. Over the lifetime of the youngest households, profits from the fossil sector are 0.32% lower than in the previous section. This decline is less than the growth in labour income and savings, which explains why households in Region F gain. In Region C, profits from the clean sector are 24% higher, which helps to explain the significant dampening of the losses from the previous section.

Table 12: Impact of the Green Transition

	Region F				
	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
20-34	-0.73%	-0.51%	-0.42%	-0.37%	-0.34%
35-49	-0.68%	-0.50%	-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 C				
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%

6.1.2 Alternative Scenario: Faster growth in clean productivity

I now explore how much welfare improves if the domestic production of clean energy happens more rapidly. 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. For the entire economy, this immediate expansion of the clean energy sector reduces the losses from falling fossil fuel demand by 54%. Table 13 summarizes the welfare outcomes from the alternative benchmark relative to the "No Green Transition" scenario. An instantaneous growth in $Z_{\mathcal{C}}$ dampens the welfare losses by significantly more than in the previous exercise, particularly among households in Region C. Faster growth in the clean sector makes the path nearly welfare neutral among the youngest and oldest households in Region C, and welfare enhancing for middle- and late-career households.

For households in Region F, the dampening in the costs of the fall in oil demand is largely driven by the expansion of both final good production and imports and the growth in wages. Production of the fossil good is on average 0.22% lower than it was in the benchmark Green Transition. Due to the accelerated substitution towards clean energy inputs, from 2020 to 2052 fossil exports account for a slightly higher share of total fossil production (between 1 and 3 percentage points) before converging to approximately the same levels. As a result, imports are slightly higher than in the benchmark GT. Final good production is also on average 0.13 percentage points higher than in the benchmark transition, for the same reasons as discussed in the previous section: lower energy costs due to the extreme growth in $Z_{\mathcal{C}}$ allows for an expansion in final good production. This generates an increase in the demand for non-energy inputs in both regions; demand for Region F's non-energy intermediate is 0.18% higher, and 0.13% higher for Region C's non-energy intermediate. For the working life of the 20-year-olds at the start of the transition, wages in Region F are 0.27% higher than they are in in the benchmark, and 0.30% higher than the benchmark in Region C. The profits from the fossil sector are 0.22% lower than they are in the benchmark case, and the interest rate is 0.06% lower.

In Region C, profits from the clean sector increase during the transition but are about 7% lower on average than they are in the GT benchmark. This is because the price $p_{\mathcal{C}}$ falls much more rapidly and labour costs increase by more. Across the economy, the return on savings is slightly lower than the benchmark but the actual capital stock is about 0.20% higher. Between 2020 and 2028 the total return on savings in the economy is slightly higher in the alternative benchmark (with faster growth in $Z_{\mathcal{C}}$), which largely benefits the households at the upper end of the income distribution. In Region F, we can see this in the last column Table 13 where the younger, wealthier households gain from the Green Transition. The youngest households in Region F benefit from the higher lifetime labour earnings, and the slightly higher return on savings early in the transition. Similarly in Region C, the gains from the transition are most pronounced among the youngest and wealthiest households for the same reasons. Their total savings are higher at the start of the transition, and they benefit from the combination of those initial higher returns to savings, growing profits and higher wages during their working years.

Table 13: Alternative Benchmark: Instantaneous growth in $Z_{\mathcal{C}}$

	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
Region F					
20-34	-0.62%	-0.23%	-0.06%	0.05%	0.10%
35-49	-0.59%	-0.28%	-0.11%	0.00%	0.08%
50-64	-0.52%	-0.32%	-0.16%	-0.06%	0.02%
65-99	NA	-0.35%	-0.16%	-0.07%	-0.01%
Region C					
20-34	-0.08%	0.17%	0.27%	0.32%	0.35%
35-49	-0.04%	0.13%	0.21%	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%

7 Concluding Remarks

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 decreases in lifetime consumption of 0.56% along the transition path in a world with declining demand for fossil fuels. Using the IEA's recommendations for reaching a Net Zero world, I find that these losses are most pronounced among the youngest and poorest households residing in the fossil producing region of the economy, for whom lifetime consumption decreases by 0.77%. This is largely driven by falling profits from the fossil sector, slower wage growth and lower returns to savings.

These losses are dampened by the expansion of the clean energy sector. In the benchmark Green Transition scenario, the expansion of clean energy to account for 90% of domestic energy inputs by 2050 reduces the aggregate welfare losses from falling demand for fossil fuels by 15%. Accelerating this expansion of the clean energy sector to has an even stronger impact, reducing the losses by 54%. While the decrease in consumption due to a fall in fossil fuel demand are largest among young, low-income households, the expansion of the clean sector dampens their losses 19% and 85% in the fossil producing and clean producing regions respectively. The largest beneficiaries of an accelerated expansion of the clean energy sector are the wealthiest young households.

This paper leaves some of the finer details of how local labour markets respond to these changes to future work. The model abstracts from potential challenges in switching jobs that workers in the fossil producing region experience, or for possible changes to interregional migration patterns that may arise. Using microdata on employment dynamics within the fossil fuel industry to inform a similar model that includes job search would be particularly insightful.

Extensions of this paper may also shed light on the potential costs stemming from capital adjustment costs and stranded assets. This paper assumes capital is perfectly mobile across regions and between industries. There is a rich literature on the economics of climate change and the potential for capital investments to become stranded and worthless. For a summary of the relevant literature, see von Dulong et al. (2023). The results in this model are partially driven by changes in the interest rate and profits. However, this occurs within a static production structure. Adjusting the model to incorporate dynamic, industry specific investment decisions will be beneficial.

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. Extending the model to allow for the emergence of a clean energy sector in the fossil producing region would likely dampen some of the negative impacts in the fossil region. Future work focusing on policy changes that boost productivity 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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