Small Resource-Rich Economies and the Green Transition

Oliver Loertscher

McMaster University

September 2024

Big Picture

(1) Almost every country has signalled or is actively pursuing Net-Zero status
  - Current policy or in law: 60% of countries
  - Proposed or pledged: 37% of countries

(2) Prices of clean inputs are falling

(3) Adoption of clean energy is increasing

Big Picture

(1) Almost every country has signalled or is actively pursuing Net-Zero status

- Current policy or in law: 60% of countries
- Proposed or pledged: 37% of countries

(2) Prices of clean inputs are falling

(3) Adoption of clean energy is increasing

If these trends hold and the world reaches Net-Zero, what are the welfare implications in fossil-fuel producing economies?

Motivation

- Net-Zero Targets:
  - Large Economies: China (2060), Germany (2045), India (2070), Japan (2050), USA (2050)
  - Small Resource-Rich Economies: Australia (2050), Canada (2050), Nigeria (2070), Norway (2030)

Motivation

- Net-Zero Targets:
  - Large Economies: China (2060), Germany (2045), India (2070), Japan (2050), USA (2050)
  - Small Resource-Rich Economies: Australia (2050), Canada (2050), Nigeria (2070), Norway (2030)
- Fossil fuel extraction (coal, oil, gas) accounts for:
  - Australia: 7.4% of GDP, 35% of value of goods exported
  - Canada: 3%, 26%
  - Nigeria: 6%, 90%
  - Norway: 26%, 67%

Motivation

- Net-Zero Targets:
  - Large Economies: China (2060), Germany (2045), India (2070), Japan (2050), USA (2050)
  - Small Resource-Rich Economies: Australia (2050), Canada (2050), Nigeria (2070), Norway (2030)
- Fossil fuel extraction (coal, oil, gas) accounts for:
  - Australia: 7.4% of GDP, 35% of value of goods exported
  - Canada: 3%, 26%
  - Nigeria: 6%, 90%
  - Norway: 26%, 67%
- Little understanding of the welfare impacts of such a transition across households
  - Age cohorts vs wealth vs region

This Paper

- I develop a SOE model to study welfare impact of green transition in resource-rich economies

This Paper

- I develop a SOE model to study welfare impact of green transition in resource-rich economies
  - Two domestic regions: Fossil producing and Clean producing
  - Demand side: Heterogeneous households
  - Supply side: 5 sectors (Final good, Non-Energy, Energy, Fossil, Clean)

This Paper

- I develop a SOE model to study welfare impact of green transition in resource-rich economies
  - Two domestic regions: Fossil producing and Clean producing
  - Demand side: Heterogeneous households
  - Supply side: 5 sectors (Final good, Non-Energy, Energy, Fossil, Clean)
- Model calibrated to Canadian data.
  - Given this context, "fossil" maps to "oil and gas"
  - "Fossil" region = Alberta, "Clean" region = BC, Ontario, Québec
  - Price of oil exogenous (hence "open" economy)

This Paper

- I develop a SOE model to study welfare impact of green transition in resource-rich economies
  - Two domestic regions: Fossil producing and Clean producing
  - Demand side: Heterogeneous households
  - Supply side: 5 sectors (Final good, Non-Energy, Energy, Fossil, Clean)
- Model calibrated to Canadian data.
  - Given this context, "fossil" maps to "oil and gas"
  - "Fossil" region = Alberta, "Clean" region = BC, Ontario, Québec
  - Price of oil exogenous (hence "open" economy)
- Two quantitative exercises:
  1. How ***did*** the rise of oil prices from 1997-2020 affect welfare across households?
  2. How ***will*** a global green transition affect welfare across households?

Key Results: Oil price boom, 1997-2020

- Model is able to replicate several differences between regions along transition path
- 2000s oil price boom was welfare enhancing, impacts are heterogeneous:
  - Both regions benefited, but Fossil region (Alberta) welfare gains higher
  - Youngest workers at bottom of income distribution benefited the most

Key Results: Transition to Net-Zero 2050

- Modeled as a simultaneous boom in clean productivity and collapse in fossil demand
- Path to Net-Zero is welfare diminishing, but effects are heterogeneous
  - Fall in oil demand produces negative welfare effects
  - Magnitude depends on reduction targets (how much fossil demand declines by 2050)
  - Youngest workers at bottom of income distribution lose the most

Contribution

- Economics of the green transition
  - Acemoglu et al. (2016), Baldwin et al. (2020), Arkolakis and Walsh (2023), Besley and Persson (2023)
  - ***First paper to study welfare impacts of a clean energy transition across generations/regions/income***

Contribution

- Economics of the green transition
  - Acemoglu et al. (2016), Baldwin et al. (2020), Arkolakis and Walsh (2023), Besley and Persson (2023)
  - ***First paper to study welfare impacts of a clean energy transition across generations/regions/income***
- Macroeconomics and the environment/resource economics
  - Hassler et al. (2018), Fried (2022), Casey (2023), Jaimes (2023)
  - ***First paper to model regional energy production differences in small resource-rich countries***

Contribution

- Economics of the green transition
  - Acemoglu et al. (2016), Baldwin et al. (2020), Arkolakis and Walsh (2023), Besley and Persson (2023)
  - ***First paper to study welfare impacts of a clean energy transition across generations/regions/income***
- Macroeconomics and the environment/resource economics
  - Hassler et al. (2018), Fried (2022), Casey (2023), Jaimes (2023)
  - ***First paper to model regional energy production differences in small resource-rich countries***
- Extraction booms and the economy
  - Hassler and Sinn (2016), Leach (2022), Loertscher and Pujolas (2024)
  - ***First paper to measure the distributional welfare impacts of the resource boom across generations/regions/income***

Outline

Outline

Background: Most of the world signalling/pursuing Net-Zero goals

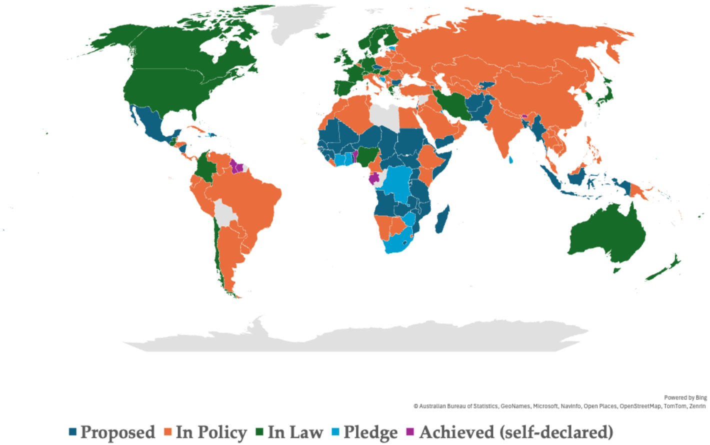


Figure 1: Source: Energy and Climate Intelligence Unit, Data-Driven EnviroLab, NewClimate Institute, Oxford Net Zero - Net Zero Tracker (2023)

Background: Price of clean inputs falling

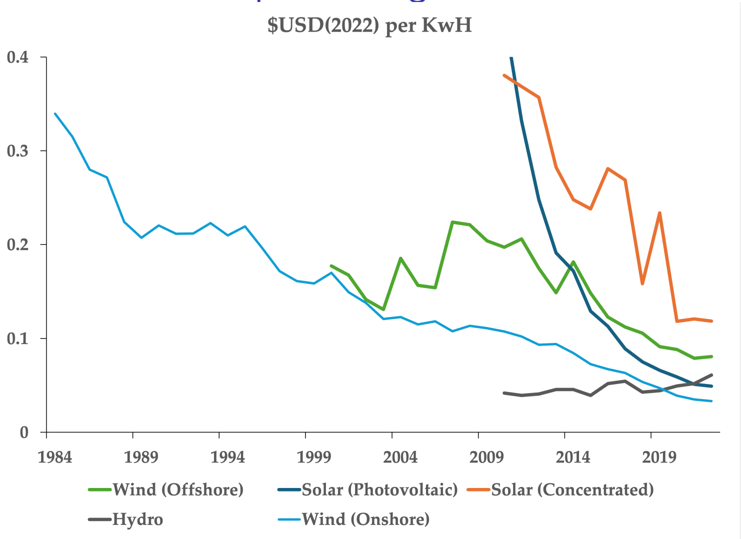


Figure 2: Source: International Renewable Energy Agency (2023)

Background: Adoption of clean energy rising

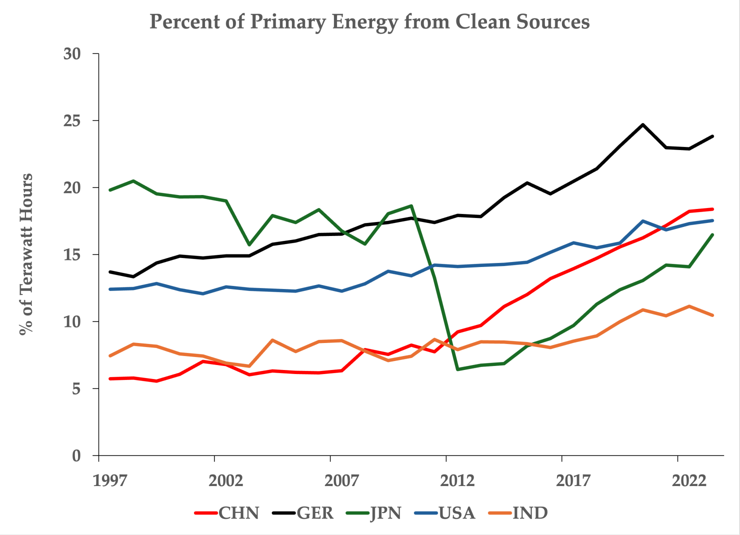


Figure 3: Source: Energy Institute - Statistical Review of World Energy (2024)

Takeaways

- (Nearly) every country is signalling Net-Zero as a target within the next 30-50 years
- Prices of clean energy sources are falling
- Adoption of clean energy is rising among main trading partners for resource-rich economies

Outline

Model

I build a Small Open Economy multi-sector model

- 2 regions: One produces fossil inputs, one produces clean inputs
- Households: OLG, Heterogeneous Agent model à la Aiyagari (1994), Bewley (1977), Huggett (1993) and Imrohoroğlu (1989)
- Production: Final good, Energy, Clean, Fossil, Non-Energy as in Fried et al. (2022)
- Price of fossil good (oil) assumed to be exogenous
    - Trade balances every period (international demand reflected in price)

Household Demographics

- Continuum of households, distributed uniformly over two regions
- Households can be of working age or retired, live for a max of J years
- Workers:
  - Idiosyncratic, stochastic ability
  - Supply labour inelastically, make savings decisions
  - Receive bequests and profits from Fossil or Clean sectors (depending on location)
- Retirees:
  - Forced retirement at age j_{ret}
  - Receive retirement benefits, bequests and profits
- All households face age specific probability of dying

Household Endowments

- Idiosyncratic productivity:
  - $\epsilon \in \{\epsilon_1, \dots, \epsilon_N\}$
  - Follows AR(1) process with

$$\log \epsilon' = \rho_\epsilon \log \epsilon + e, \quad e \sim N(0,1)$$

- Age specific productivity θ_j for $j \in \{1, \dots, j_{ret} - 1\}$
- Initial capital endowment: bequest
- Time endowments ℓ_s, depending on region $s \in \{A, B\}$

Household Problem

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

subject to

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

$$q, a' \geq 0$$

- (a, b, ϵ, j): assets, accidental bequests, idiosyncratic productivity, age
- (θ_j, ψ_j): age specific productivity and survival probability
- $\pi_s = \begin{cases} \pi_F & \text{if } s = A \\ \pi_C & \text{if } s = B \end{cases}$

Taxation

- Households pay region specific consumption taxes $\tau_{q,s}$ and progressive income taxes
- Income tax function
$$T(y) = y - \lambda y^{1-\tau_y}$$

where

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

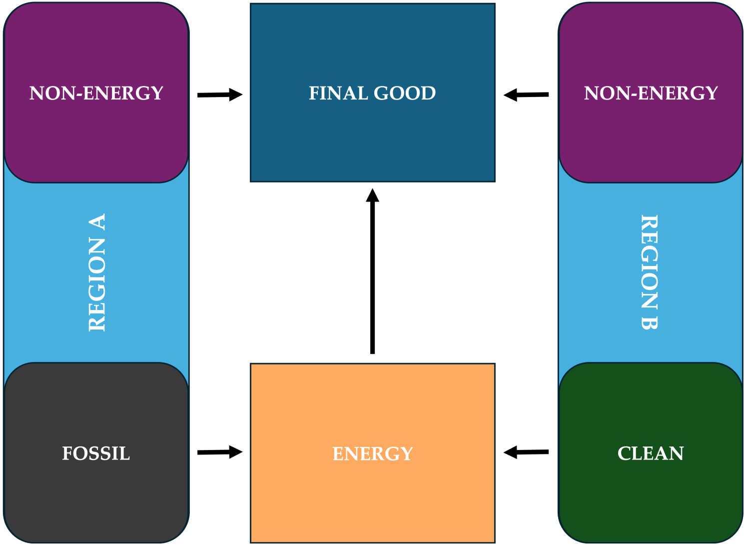
Production Geography

- Each region produces a specific non-energy intermediate and energy intermediate
- Energy Intermediates:
  - Region A: produces fossil input
  - Region B: produces clean input

Production Structure

- Final Good is produced from ***Energy*** and ***Non-Energy*** inputs
  - ***Energy*** input is produced using ***Fossil*** inputs from Region A and ***Clean*** inputs from Region B
  - ***Non-Energy*** input is produced using differentiated, region specific inputs from each region

Production Overview



Fossil Producers in Region A

- Fossil energy good Y_F produced using capital K_F, labour L_F, and fossil intermediate $x_{F,F}$ in Region A

$$\max_{K_F, L_F, x_{F,F}} p_F Y_F - (r+\delta)K_F - w_A L_F - p_F x_{F,F}$$

subject to

$$Y_F = \min\{Z_F (K_F^{\gamma} L_F^{1-\gamma})^{\nu_F}, \mu_F x_{F,F}\}$$
$$\nu_F \in (0,1)$$

Clean Producers in Region B

- The clean energy good Y_C is produced using capital K_C and labour L_C in Region B

$$\max_{K_C, L_C} p_C Y_C - (r + \delta)K_C - w_B L_C$$

subject to

$$Y_C = Z_C (K_C^{\eta} L_C^{1-\eta})^{\nu_C}$$
$$\nu_C \in (0, 1)$$

Energy Producers

- The final energy good Y_E is produced using clean and fossil intermediates $x_{C,E}$, $x_{F,E}$

$$\max_{x_{C,E}, x_{F,E}} p_E Y_E - p_C x_{C,E} - p_F x_{F,E}$$

subject to

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

Non-Energy Producers

- Non-Energy intermediates Y_s (for $s \in \{A, B\}$) is produced using capital K_s and labour L_s

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

subject to

$$Y_s = Z(K_s^{\alpha} L_s^{1-\alpha})$$

Final Good Producers

- Final good is produced using non-energy intermediates $x_{A,Y}$, $x_{B,Y}$ and an energy intermediate $x_{E,Y}$

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

subject to

$$Y = \min\left\{\left(x_{A,Y}^{\rho_y} + x_{B,Y}^{\rho_y}\right)^{1/\rho_y}, \mu_Y x_{E,Y}\right\}$$

Government

- The government consumes the final good, and pays social security transfers.
- Government budget balances each period so that

$$SS + G = \tau_{q,A} Q_A + \tau_{q,B} Q_B + \int T(y)\ d\Omega$$

- $G = gY$, $g \in (0,1)$
- Ω: distribution across types (j, a, ϵ, s)

Closing the model

- An equilibrium follows the usual definition of a stationary, recursive equilibrium
- Key equation: ***Trade balances every period so that***

$$(Y - Q_A - Q_B - I - G) + p_F(Y_F - x_{F,F} - x_{F,E}) = 0$$

Outline

Calibration: Parametrization

A period corresponds to 4 years in the data

Parameter		Description	Value
σ	Risk Aversion	Standard	2
β	Discount factor	Annualized discount factor of 0.96	0.85
δ	Capital depreciation	Annualized depreciation of 0.05	0.19
ρ_E	Elasticity of sub. in Energy prod.	Papageorgiou et al. (2017)	0.66
ρ_Y	Elasticity of sub. in Non-Energy prod.	Albrecht and Tombe (2016)	0.80

Calibration: Externally Calibrated Parameters

Parameter		Description	Value
α	Capital share Non-Energy	Labour share	0.4
ν_C	DRS parameter	profit-to-revenue ratio in Clean	0.72
η	Capital share Clean	Labour share in Clean	0.6
ν_F	DRS parameter	profit-to-revenue ratio in Oil	0.73
γ	Capital share Oil	Labour share in Oil & Gas	0.66
$\mu_{E,Y}$	Intermediate use of energy	I/O Table	38.26
$\mu_{F,F}$	Intermediate use of oil	I/O Table	6
$\tau_{q,A}$	Consumption tax rate in AB	StatsCan tables	0.12
$\tau_{q,B}$	Consumption tax rate in ROC	StatsCan tables	0.18
τ_y	Income Tax progressivity	StatsCan tables	0.1232
g	Government consumption	I/O Table	0.2
ℓ_A	Hours worked per capita, AB	StatsCan tables	0.1673
$Z_{A,1997}, Z_{B,1997}$	TFP in non-energy	StatsCan tables	0.11
$Z_{A,2020}, Z_{B,2020}$	TFP in non-energy	StatsCan tables	0.22
$p_{F,1997}$	Real price of oil	FRED data	0.19
$p_{F,2020}$	Real price of oil	FRED data	0.53
θ_j	Age spec. productivity	GRID	Time Series
ψ_j	Age spec. survival probabilities	StatsCan tables	Time Series

Calibration: Internally Calibrated 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 Δ log res. earnings	GRID	0.53	0.53	0.21

Determined in equilibrium

Parameter	**Target**	**Source**	**Data**	**Model**	**Value**
Z_F^{1997}	$K_F/\bar{K}$ in 1997	StatsCan	0.10	0.10	1.66
Z_F^{2020}	$K_F/\bar{K}$ in 2022	StatsCan	0.22	0.22	1.46
Z_C^{1997}	Pct. clean in 1997	OWID	0.37	0.37	0.32
Z_C^{2020}	Pct. clean in 2022	OWID	0.36	0.36	0.29

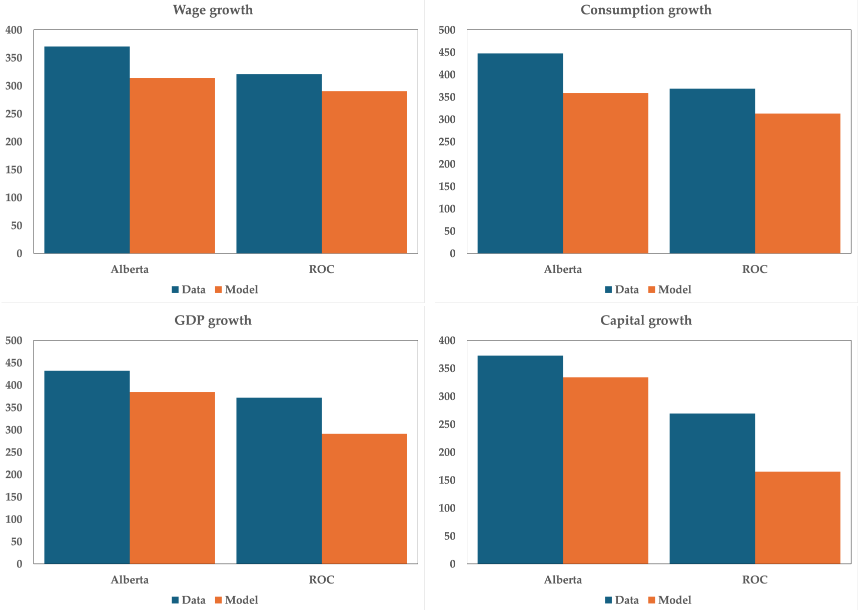
Outline

1. Background
2. Model
3. Calibration
4. Validation
5. Oil Boom Transition
6. Net-Zero Transition
7. Conclusion

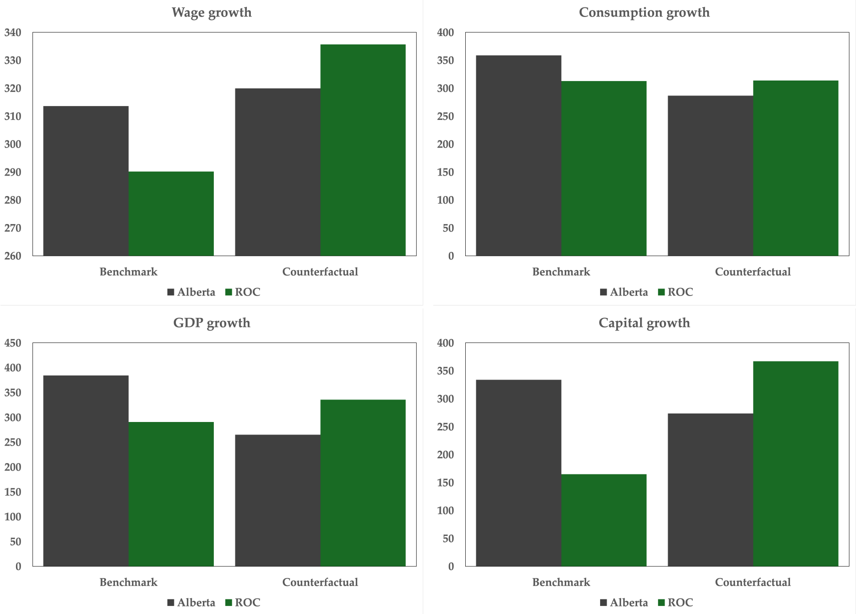
Model Validation

- I compare model to data on a number of untargeted moments across the two regions:
  - Wage growth
  - Consumption growth
  - GDP growth
  - Capital growth
- To validate the main mechanism, I compare these moments in the benchmark calibration against a counterfactual world where p_F stays at the 1997 level

Model Validation: Untargeted moments



Mechanism Validation



Outline

Oil boom transition

- I evaluate the welfare impact of the rise in oil prices between 1997 and 2020 along the transition path
- I compare the benchmark transition to a counterfactual transition where p_F stayed at 1997 level

Welfare results

	p_F const
CEV, Aggregate	-10.41%
CEV, Region A	-11.65%
CEV, Region B	-8.60%

- Absence of oil price boom leads to average CEV that is 10% lower
- Loss of welfare in counterfactual world strongest in Fossil producing region

Welfare results: Age groups and Region

	p_F const	
Age	Region A	Region B
20-35	-13.18 %	-9.74 %
36-51	-11.53 %	-8.37 %
52-67	-9.12 %	-6.50 %
68-83	-7.08 %	-5.09 %
84-99	-7.44 %	-2.88 %

- Youngest cohort experience highest welfare losses from absence of boom
- Lowest losses experienced by retirees
- Region A households lose the most across all age groups

Welfare results: Age, Income, Region

Region A

	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
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%

Region B

	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
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%

- Absence of boom produced highest welfare losses for youngest, lowest income groups

Outline

Net-Zero transition

- I evaluate welfare impact of a transtion to Net-Zero following International Energy Agency's roadmap:
  - Clean inputs account for 90% of domestic energy production by 2050
  - Fossil demand falls by 50%

Net-Zero transition

- I evaluate welfare impact of a transtion to Net-Zero following International Energy Agency's roadmap:
  - Clean inputs account for 90% of domestic energy production by 2050
  - Fossil demand falls by 50%
- I evaluate the welfare impact this benchmark and compare it to:
  (1) A counterfactual world where fossil prices remain at 2020 level
  (2) A counterfactual world where fossil demand falls by 90%

Net-Zero transition

- I evaluate welfare impact of a transtion to Net-Zero following International Energy Agency's roadmap:
  - Clean inputs account for 90% of domestic energy production by 2050
  - Fossil demand falls by 50%
- I evaluate the welfare impact this benchmark and compare it to:
  (1) A counterfactual world where fossil prices remain at 2020 level
  (2) A counterfactual world where fossil demand falls by 90%
- Main take away: transition to Net-Zero produces welfare losses, but scale of decline matters
  - IEA roadmap (50% decline in fossil production) carries welfare losses of $<1\%$ across all types
  - Across all scenarios, youngest and poorest households experience greatest losses

Benchmark: Fossil production falls by 50%

Region A					
	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
20-34	0.81%	0.65%	0.58%	0.55%	0.54%
35-49	0.77%	0.63%	0.55%	0.52%	0.50%
50-64	0.63%	0.53%	0.47%	0.45%	0.44%

Region B					
20-34	0.57%	0.49%	0.49%	0.49%	0.50%
35-49	0.52%	0.47%	0.46%	0.46%	0.47%
50-64	0.38%	0.37%	0.38%	0.39%	0.41%

- Absence of falling Fossil demand produces small welfare gains, $<1\%$ across all groups
- Largest gains are poorest, youngest in Region A

Counterfactual: Fossil demand falls by 90%

Region A

	First Quintile	Second Quintile	Third Quintile	Fourth Quintile	Fifth Quintile
20-34	5.81%	4.56%	4.11%	3.90%	3.80%
35-49	5.52%	4.44%	3.88%	3.63%	3.51%
50-64	4.46%	3.74%	3.30%	3.13%	3.09%

Region B

20-34	4.01%	3.50%	3.48%	3.49%	3.55%
35-49	3.68%	3.30%	3.23%	3.25%	3.31%
50-64	2.68%	2.63%	2.68%	2.77%	2.88%

Outline

Conclusion

- I develop a comprehensive model to analyze the welfare impacts of changes in global demand for fossil fuels in a resource-rich economy
- Oil price boom period was most beneficial for young, lowest income households in fossil region
- Transition to Net-Zero produces heterogeneous welfare losses
  - Youngest cohorts, lowest income groups experience largest losses
  - Magnitude of losses depend strongly on size of decline in fossil production
  - Losses smaller than gains from boom period
- Areas for future research: role of policy to compensate losers, local labour market responses, effects on trade in other industries

Thank you

References

Daron Acemoglu, Ufuk Akcigit, Douglas Hanley, and William Kerr. Transition to Clean Technology. *Journal of Political Economy*, 124(1):52–104, February 2016. ISSN 0022-3808. doi: 10.1086/684511. URL https://www.journals.uchicago.edu/doi/10.1086/684511. Publisher: The University of Chicago Press.

S. Rao Aiyagari. Uninsured Idiosyncratic Risk and Aggregate Saving. *The Quarterly Journal of Economics*, 109(3):659–684, 1994. ISSN 0033-5533. doi: 10.2307/2118417. URL https://www.jstor.org/stable/2118417. Publisher: Oxford University Press.

Lukas Albrecht and Trevor Tombe. Internal trade, productivity and interconnected industries: A quantitative analysis. *Canadian Journal of Economics/Revue canadienne d'économique*, 49(1):237–263, 2016. ISSN 1540-5982. doi: 10.1111/caje.12196. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/caje.12196. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/caje.12196.

Costas Arkolakis and Conor Walsh. Clean Growth, August 2023. URL https://www.nber.org/papers/w31615.

Elizabeth Baldwin, Yongyang Cai, and Karlygash Kuralbayeva. To build or not to build? Capital stocks and climate policy. *Journal of Environmental Economics and Management*, 100:102235, March 2020. ISSN 00950696. doi: 10.1016/j.jeem.2019.05.001. URL https://linkinghub.elsevier.com/retrieve/pii/S0095069617308173.

Timothy Besley and Torsten Persson. The Political Economics of Green Transitions*. *The Quarterly Journal of Economics*, 138(3):1863–1906, August 2023. ISSN 0033-5533. doi: 10.1093/qje/qjad006. URL https://doi.org/10.1093/qje/qjad006.

Truman Bewley. The permanent income hypothesis: A theoretical formulation. *Journal of Economic Theory*, 16(2):252–292, December 1977. ISSN 0022-0531. doi: 10.1016/0022-0531(77)90009-6. URL https://www.sciencedirect.com/science/article/pii/0022053177900096.

Gregory Casey. Energy Efficiency and Directed Technical Change: Implications for Climate Change Mitigation. *The Review of Economic Studies*, page rdad001, March 2023. ISSN 0034-6527. doi: 10.1093/restud/rdad001. URL https://doi.org/10.1093/restud/rdad001.

Stephie Fried. Seawalls and Stilts: A Quantitative Macro Study of Climate Adaptation. *The Review of Economic Studies*, 89(6):3303–3344, November 2022. ISSN 0034-6527, 1467-937X. doi: 10.1093/restud/rdab099. URL https://academic.oup.com/restud/article/89/6/3303/6484653.

Stephie Fried, Kevin Novan, and William B. Peterman. Climate policy transition risk and the macroeconomy. *European Economic Review*, 147:104174, August 2022. ISSN 00142921. doi: 10.1016/j.euroecorev.2022.104174. URL https://linkinghub.elsevier.com/retrieve/pii/S0014292122000988.

John Hassler and Hans-Werner Sinn. The fossil episode. *Journal of Monetary Economics*, 83:14–26, October 2016. ISSN 0304-3932. doi: 10.1016/j.jmoneco.2016.08.001. URL https://www.sciencedirect.com/science/article/pii/S0304393216300733.

John Hassler, Per Krusell, and Conny Olovsson. The Consequences of Uncertainty: Climate Sensitivity and Economic Sensitivity to the Climate. *Annual Review of Economics*, 10(1):189–205, 2018. doi: 10.1146/annurev-economics-080217-053229. URL https://doi.org/10.1146/annurev-economics-080217-053229. _eprint: https://doi.org/10.1146/annurev-economics-080217-053229.

Mark Huggett. The risk-free rate in heterogeneous-agent incomplete-insurance economies. *Journal of Economic Dynamics and Control*, 17(5):953–969, September 1993. ISSN 0165-1889. doi: 10.1016/0165-1889(93)90024-M. URL https://www.sciencedirect.com/science/article/pii/016518899390024M.

Ayșe Imrohoroğlu. Cost of Business Cycles with Indivisibilities and Liquidity Constraints. *Journal of Political Economy*, 97(6):1364–1383, 1989. ISSN 0022-3808. URL https://www.jstor.org/stable/1833243. Publisher: University of Chicago Press.

Richard Jaimes. Optimal climate and fiscal policy in an OLG economy. *Journal of Public Economic Theory*, 25(4):727–752, 2023. ISSN 1467-9779. doi: 10.1111/jpet.12637. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/jpet.12637. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/jpet.12637.

Andrew Leach. Canada's oil sands in a carbon-constrained world. *Canadian Foreign Policy Journal*, 28(3):285–304, September 2022. ISSN 1192-6422. doi: 10.1080/11926422.2022.2120508. URL https://doi.org/10.1080/11926422.2022.2120508. Publisher: Routledge _eprint: https://doi.org/10.1080/11926422.2022.2120508.

Oliver Loertscher and Pau S. Pujolas. Canadian productivity growth: Stuck in the oil sands. *Canadian Journal of Economics/Revue canadienne d'économique*, 57(2): 478–501, 2024. ISSN 1540-5982. doi: 10.1111/caje.12707. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/caje.12707. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/caje.12707.

Chris Papageorgiou, Marianne Saam, and Patrick Schulte. Substitution between Clean and Dirty Energy Inputs: A Macroeconomic Perspective. *The Review of Economics and Statistics*, 99(2):281–290, May 2017. ISSN 0034-6535. doi: 10.1162/REST_a_00592. URL https://doi.org/10.1162/REST_a_00592.

Appendix

Equilibrium

(1) Given prices, bequests, profits, tax policies and transfers, households maximize lifetime expected utility

(2) Given prices and factor allocations, firms in each sector maximize profits

(3) Markets clear (for Y_E, Y_C, capital and labour in each region)

(4) Given tax rates and transfer policies, the government budget is balanced

(5) Trade is balanced

$$(Y - Q_A - Q_B - I - G) + p_F(Y_F - x_{F,F} - x_{F,E}) = 0$$