Energy Security and the Energy Transition*

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Abstract

The energy transition - reductions in the cost of solar, wind, batteries and electric vehicles - provides a pathway for fossil-fuel dependent economies to reduce their vulnerability to energy price shocks. We show that the macroeconomic cost of the transition is likely to be modest and lower vulnerability to external shocks. The energy transition is likely to both appreciate the real exchange rate and improve the current account despite elevated investment expenditures. We calibrate a quantitative macro-energy model to Japan and find that the transition to net zero has small present value consumption costs and markedly lower volatility of output and consumption due to lower dependence on fossil fuel imports.

Keywords: Net zero, energy transition, small open economy
JEL Classification: E22, E23, Q43, Q54

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1 Introduction

In recent years, the falling cost of renewable energy, batteries, and electric vehicles coupled with increased concern about climate change have spurred faster deployment of technologies that reduce fossil fuel dependence and emissions. Even in countries with modest climate policies, the energy transition has gained traction. Battery electric vehicles now constitute nearly half of motor vehicles sales in China, while solar, wind and batteries account for the vast majority of power generation capacity added in the US over the last five years. China's rapid development and deployment of renewable energy and electric vehicles reflects primarily energy security imperatives.[1]

Meanwhile, energy price shocks from the Russian invasion of Ukraine and recent hostilities with Iran in the Persian Gulf provide a vivid reminder of the vulnerability of economies to shocks to fossil fuel supplies. The cutoff in Russian natural gas supplies to Europe in 2022 led to sharp increases in global prices for liquified natural gas, raising electricity prices across Europe and Asia. Disruptions to Russian oil exports, likewise, lead to temporary sharp increases in gasoline and diesel even for major oil producers like the US.

This paper studies the macroeconomic implications of the energy transition for energy security with a focus on fossil fuel dependent small open economies. Most countries are heavily dependent on fossil fuel imports, and sharp increases in fossil energy prices can have sizable effects on domestic consumption, production and external balance. The clean energy transition potentially lessens their reliance on fossil fuels and lowers their exposure to macroeconomic fluctuations driven by volatility in oil or natural gas prices. However, the energy transition may still, on net, raise energy prices and replace fossil fuel dependence with dependence on clean energy supply chains.

We start by summarizing the dependence of small open economies on fossil fuel imports, the magnitude of energy prices and their contribution of fossil fuel importers to global emissions. On average, domestic production of coal, natural gas and crude oil are a small fraction of domestic consumption. Several large economies like Japan and South Korea have fossil fuel import ratios of essentially one. As small economies, the energy transition has the benefit of lowering these countries' dependence on fossil fuels but at the cost of increasing dependence on the imports of clean energy capital goods.[2] Collectively the largest fossil fuel importers account for approximately 20% of global emissions in 2023. That makes these countries the third largest emitter behind the US and China. They also account for 16% of global GDP and 19% of global manufacturing value added at

[1] The primacy of energy security is reflected in continued expansion of coal power in China, large increases in crude oil strategic reserves, and self-sufficiency in refining capacity.

[2] China is also a large importer of fossil fuels and subject to energy price shocks. Including China among these countries would raise their collective emissions share to nearly 50%, and these countries would account for 1/3 of global GDP and half of global manufacturing value added.

current exchange rates.

We build a real small open economy model with an energy sector that captures the salient features of a fossil-fuel dependent open economy. A representative household in the small open economy maximizes the discounted present value of utility from consumption, with the consumption aggregate consisting of a non-tradable and tradable good. The tradable good is a CES composite of a home and foreign good that are imperfectly substitutable. The representative household supplies labor inelastically to both the tradable and non-tradable sectors and can invest in both domestic capital and foreign real bonds.

Energy is produced using either clean energy capital or fossil capital and supplied as an input to both tradable and non-tradable production. The representative household invests in each type of capital, which differ in their capital price and productivity (capacity factor). To generate power, fossil capital requires fuel that must be imported, energy generated from clean capital is perfectly substitutable with energy generated from fossil capital, and investment is irreversible. The assumptions of perfect substitutability and capital irreversibility are essential to energy systems approaches to modeling the energy transition. The country borrowing rate rises inversely with the net foreign asset position.

We show that there exists a laissez faire, fossil fuel steady state in which energy production uses only fossil capital, and the country depends on imported fossil fuel for production. However, with a sufficiently high carbon tax, there exists a clean energy steady state where the country's energy production operates only using clean energy capital and fuel imports fall to zero. A zero fossil fuel target operates like a decrease in productivity, raising the cost of energy in production. The change in energy price may have asymmetric effects depending on the energy intensity of the traded and non-traded sector.

Compared to the fossil fuel steady state, the movement in the real exchange rate in the zero emissions steady state is ambiguous, but the empirically relevant cases suggest a real appreciation. A higher price of energy makes the home traded good relatively scarce on global markets strengthening the terms of trade, resulting in a real appreciation. The clean energy steady state may also have *lower* expenditures on energy, partly due to replacing more capital intensive clean energy for more fuel intensive fossil energy. This reduction in imports also tends to appreciate the real exchange rate. As a share of GDP, the net foreign asset position and current account balance are unaffected in steady state.

We also characterize the transition path from a fossil-fuel steady state to a clean energy steady state. The energy transition operates as a composite of an anticipated negative productivity shock and an anticipated negative capital shock (energy capital is irreversible). Consumption falls on impact as households anticipate lower future income. The decline in consumption raises the net foreign asset position initially along the transition path as households income is unchanged initially, increasing asset holdings to insulate the future decline in consumption.

We analyze the effects of domestic sourcing requirements for clean energy investment. In the US, the Inflation Reduction Act (IRA) placed restrictions on clean energy subsidies requiring domestic sourcing for solar panels and batteries. Moreover, several countries undertaking the energy transition have expressed concerns about China's dominance of clean energy supply chains. A domestic sourcing requirement has distinct effects on the clean energy steady state. Domestic sourcing is neutral if foreign and domestic clean energy products have the same cost, but raises the cost of zero emissions if domestically produced capital is more costly. With imperfect substitutability between home and foreign traded goods, domestic sourcing strengthens the terms of trade by further reducing the supply of the traded home good to foreign markets.

We also consider the macroeconomic effects of a carbon border adjustment (CBAM) in a zero fossil fuel steady state, akin to the policy recently enacted by the European Union (EU). Depending on the carbon intensity of the foreign traded good, a carbon border adjustment tax acts similarly to a real appreciation, raising the domestic price of the traded good. Relative to the case of no CBAM, the real exchange rate appreciates (or depreciates) by less and the terms of trade improve. In case of perfect substitutability between the home and foreign traded good, the CBAM is neutral in terms of its effect on real allocations.

For our quantitative analysis, we enrich the model outlined above with electric power generation and end-use sectors for energy consumption. As in Mehrotra (2024), electric power generation is supplied by intermittent and dispatchable sources of power generation using a variable elasticity of substitution production function. This production function has the property that intermittent sources becomes less substitutable with dispatchable sources as the share of intermittent power generation rises. Decarbonization of electric power generation, therefore, will depend on two types of clean power generation capital: intermittent sources like solar and wind and clean dispatchable sources like nuclear, natural gas or coal with carbon capture, and geothermal.

Electricity is used to both produce both the traded and non-traded consumption goods and as fuel for a durable good which itself is also an input. This durable good represents capital goods like vehicles and building heating that must be electrified in order to decarbonize the economy. As with power generation, the fossil durable good consumes fossil fuel in fixed proportions (i.e. Leontif production) and adds an inelastic source of fuel demand. In addition to capital for electricity production and durable end-use goods, we allow for non-energy capital and adjustment costs on all types of capital and durable goods.

We calibrate our model to match data from the Japanese economy to study the transition to zero emissions in Japan's power generation and transportation sectors. Initial capital stocks stocks are chosen to match the share of carbon-free and fossil fuel power generation. The initial capital prices are set to target the share of clean and fossil fuel capital stocks. We allow the price of clean and fossil technologies to change over time, capturing expected technological progress in key clean energy technologies like solar panels, batteries, nuclear and carbon capture. Thus, even

in the baseline without a decarbonization target, the clean share of power generation rises over time. Consumption elasticities and the elasticity of interest rates to the net foreign asset position are chosen to target Japan's current account balance and net foreign asset position.

We compute both the steady state cost of achieving zero emissions in Japan and the cost over the transition. Steady state costs are modest (less than 2% of consumption in the highest cost scenario) because of expected price declines in key decarbonization technologies: solar, wind, nuclear and carbon capture. Unilateral decarbonization is projected to result in a real appreciation in steady state of 4% as the import bill from fossil fuels falls or is eliminated. The cost of power sector decarbonization is higher in Japan than in the US because the underlying renewable resource potential is poorer. The costs and import savings also hinge crucially on whether Japan reopens and further expands its nuclear power fleet.[3]

Given estimated adjustment costs, the response of consumption, output, and electricity prices overshoot their long-run level. The implicit carbon tax must overshoot to hit the 2050 target, implying additional transition costs above and beyond the steady state cost of achieving net zero. Nevertheless, these transition costs are modest; in consumption equivalent terms, the transition cost is lower than the long-run steady state cost due to discounting and consumption gaps to the business-as-usual case are relatively larger in the future.

The energy transition reduces exposure to terms of trade shocks from fossil fuel prices. Using a second-order approximation of the model, we measure the welfare costs of fossil fuel price shocks around both the business-as-usual steady state. We show that zero emissions results in significant declines in consumption volatility, with consumption and output volatility falling by 60 to 90%. Even in the business as usual case with no carbon tax, reductions in the cost of solar and wind energy reduce output and consumption volatility from fossil energy shocks as an increasing share of power is provided by those resources. The welfare impacts of this decline in volatility is small but may be understated given the assumed utility function.

The rest of the paper is organized as follows. Section 1.1 summarizes the related literature and outlines our contribution. Section 2 briefly provides stylized facts on energy trade, fossil energy price shocks and emissions that motivate our modeling choices. Section 3 presents the small open economy model of the energy transition and provides analytical results. Section 4 presents the richer quantitative model and describes the calibration strategy for the Japanese economy and energy system. Section 5 provides results on the long-run and transition costs of decarbonization of power and transportation sectors in Japan. Section 6 concludes.

[3]Japan's new prime minister supports increase power generation from nuclear power but public resistance remains high in the wake of the Fukashima nuclear accident.

1.1 Related Literature

This paper builds on a literature modeling energy use in the macroeconomy, and, in particular, using energy systems modeling which brings a more detailed and realistic representation of economy-wide energy use than in typical macroeconomic models. Energy systems models describe detailed pathways through which changes in technology costs and policy make the energy mix more or less fossil intensive. For instance, Bistline, Mehrotra and Wolfram (2023) use the EPRI-REGEN model to analyze the impact of the Inflation Reduction Act on US electric power generation, electric vehicle adoption adoption, carbon dioxide emissions, and electricity prices. Bistline et al. (2023) offers a comparison across nine energy systems models to quantify the likely energy market impacts of IRA.[4] While these models have detailed structural representations of fuel use, electricity production, and the end use of energy, they are typically partial equilibrium (taking commodity prices and interest rates as given). This paper takes an approach in between reduced form integrated assessment models and detailed energy systems models - maintaining the analytical tractability of simple IAMs while incorporating structural features of energy production.

Our analysis is closer to macroeconomic models with a structural representation of energy production. Fried (2018) quantitatively examines how a carbon tax induces innovation in clean energy in a model with clean, fossil and non-energy capital. Casey, Jeon and Traeger (2023) study the implications of subsidies to clean energy relative to a carbon tax in a dynamic macroeconomic model where clean and fossil energy are complements. Our approach is closer to Arkolakis and Walsh (2023) who write a spatial model that features perfect substitutability between clean and fossil electricity production in a given location, emphasizing the growth impacts of falling solar and battery prices. Carton et al. (2023) propose a large-scale open economy macro model with energy production and trade that also features non-constant elasticities of substitution but does not incorporate technological progress.

This paper relates to an emerging literature studying the macroeconomic implications of the energy transition. Mehrotra (2024) characterizes the energy transition for closed economies and derives a bound on the macroeconomic cost of the transition for the US. Airaudo, Pappa and Seoane (2024) is closest to this paper, examining the monetary policy and inflation implications of the energy transition in Chile. Their paper focuses on the inflationary effects of carbon taxes and subsidies in a SOE model calibrated to Chilean data. Our paper differs in its focus on exchange rate effects, energy and capital goods trade, and structural representation of energy production. Fornaro, Guerrieri and Reichlin (2024) studies the monetary policy implications of the energy transition focusing on sectoral reallocations and directed technical change.

[4] Jenkins et al. (2021) outline scenarios for the US to achieve net zero emissions by 2050 and Huppmann et al. (2023) compare net zero scenarios across a range of energy systems models for the National Climate Assessment.

This paper also relates to the literature considering the impacts of energy price volatility, energy trade, and geopolitical implications in the wake of Russia's invasion of Ukraine. Moll, Schularick and Zachmann (2023) studies the impact of Russia's natural gas embargo on the German economy. Bodenstein, Erceg and Guerrieri (2011) investigates the trade balance impacts of oil price shocks in a two-country model. Gagliardone and Gertler (2023) investigates the effect of oil price shocks on US inflation, building on an older literature investigating the effects of oil prices on the US economy (see, for example, Hamilton (1983), Bernanke et al. (1997), and Blanchard and Gali (2007)). This paper is also related to emerging literature on trade in energy and climate policy (see, for example, Kortum and Weisbach (2021) and Weisbach et al. (2023)).

Finally, we build on an extensive literature in macroeconomics and environmental economics that assesses climate policy. Nordhaus (1993) provided that first integrated assessment model (IAM) with subsequent updates of the DICE model in Barrage and Nordhaus (2023). Golosov et al. (2014) characterizes analytically and quantifies the optimal carbon tax in neoclassical growth model with damages from climate change. In these integrated assessment models, the mitigation (i.e. emissions reduction) process is modeled in reduced form and, typically, zero-emissions backstop technologies are introduced in the distant future to ensure the existence of a long-run steady state. Our approach differs by explicitly modeling the properties of clean technologies in power generation and transportation and taking account the implications of fossil energy trade.

2 Stylized Facts

In this section, we outline some of the key facts that motivate our modeling choices and highlight the contribution of small open economies to, the energy trade, global manufacturing and output and global emissions. We separately summarize the contribution of fossil fuel importers and exporters. Small open economies collectively account for a substantial portion of global emissions with several countries highly dependent on fossil fuel imports across all types of fuel: coal, crude oil and refined products, and natural gas.

2.1 Energy trade

Table 1 list the 15 largest fossil fuel importers by size. The US - a net energy exporter - is listed for comparison, as is the European Union (inclusive of the United Kingdom). The EU + UK as a bloc are the largest fossil fuel energy importer. The domestic production and consumption of three major fossil fuel categories (coal, natural gas, and crude oil/refined products) are aggregated based on energy content into quadrillion BTUs (10^15 British thermal units). Domestic production and consumption are taken from fossil fuel quantities data reported by the US Energy Information Administration (EIA), using 2018-2023 averages. Imports are defined as the difference between

	Fossil fuel (Quad BTUs)			Import share of fossil fuel consumption			
Country	Consumption	Production	Imports	All	Coal	Natural gas	Crude oil and refined products
European Union	51.8	13.6	38.2	0.7	0.3	0.8	0.9
US	84.1	87.4	-3.4	0.0	-0.1	-0.1	0.0
China	132.1	101.7	30.4	0.2	0.0	0.4	0.7
Japan	14.5	0.1	14.4	1.0	1.0	1.0	1.0
India	33.7	19.6	14.2	0.4	0.2	0.5	0.8
South Korea	9.7	0.1	9.6	1.0	1.0	1.0	1.0
Turkey	6.3	1.9	4.5	0.7	0.3	1.0	0.9
Taiwan	4.2	0.0	4.2	1.0	1.0	1.0	1.0
Singapore	3.5	0.0	3.5	1.0	1.0	1.0	1.0
Thailand	5.5	2.4	3.0	0.6	0.6	0.4	0.7
Mexico	7.3	5.4	1.9	0.3	0.5	0.7	-0.1
Pakistan	3.2	1.5	1.7	0.5	0.6	0.3	0.8
Vietnam	3.1	1.7	1.4	0.5	0.5	0.0	0.6
Philippines	1.8	0.4	1.3	0.8	0.6	0.0	1.0
Chile	1.2	0.1	1.1	0.9	1.0	0.8	1.0
Hong Kong	0.9	0.0	0.9	1.0	1.0	1.0	1.0
Ukraine	2.1	1.2	0.9	0.4	0.4	0.2	0.8
Average				**0.69**	**0.62**	**0.62**	**0.81**
Median				**0.72**	**0.61**	**0.73**	**0.90**

Table 1: Top 15 fossil energy importers

consumption and production.[5] As the table shows, most of the largest energy importers are advanced and emerging market Asian economies. The only Latin American economies that appear are Mexico and Chile. The only other non-Asian economy is Ukraine, partially reflecting disruptions from the war with Russia.

Most of the countries on this list also have negligible levels of domestic production of fossil energy as seen in the fifth column of Table 1 which shows the ratio of imported fossil fuels to domestic consumption. For Japan, Hong Kong, Taiwan, Singapore and South Korea, their ratio of imported fossil fuels to overall consumption is essentially 1. By contrast, China and India - the two largest fossil fuel importers next to Japan - produce significant levels of fossil fuels domestically and are not completely dependent on imports.

The last three columns of Table 1 show ratios of imports to consumption by the different major fossil fuel categories. Dependence on fossil fuels is typically high across all categories, particularly for advanced Asian economies. With the exception of Mexico and oil, each country is reliant on imports across all fuels. For countries like China and India that produce some fossil fuels domestically, their dependence is lowest for coal and highest for crude oil and refined products. The median importing country in Table 1 imports 60% of coal, 73% of natural gas, and 90% of crude oil/refined products that it consumes. Of the 230 geographical units listed in the EIA data, 172 are fossil fuel importers and 121 have a dependence of over 75% in terms of imports relative to fossil fuel consumption (aggregated by BTU).

Table 2 provides the analogous list of the largest fossil fuel exporters, calculated using the same

[5]In principle, countries may accumulate or decumulate inventories of fossil fuels. Taking an average over five years, we assume inventories remain relatively stable.

	Fossil fuel (Quad BTUs)			Export share of fossil fuel production			
Country	Consumption	Production	Exports	All	Coal	Natural gas	Crude oil and refined products
Nigeria	1.8	5.1	3.4	0.7	0.0	0.6	0.7
United States	84.1	87.4	3.4	0.0	0.1	0.1	N/A
Iran	13.2	16.7	3.4	0.2	0.0	0.1	0.4
Algeria	2.7	6.6	3.9	0.6	N/A	0.5	0.7
Kazakhstan	2.9	7.0	4.1	0.6	0.3	0.3	0.8
Kuwait	1.7	6.7	4.9	0.7	N/A	N/A	0.9
United Arab Emirates	4.2	10.4	6.2	0.6	N/A	N/A	0.8
Iraq	2.7	9.6	6.9	0.7	N/A	N/A	0.8
Qatar	2.2	9.9	7.8	0.8	N/A	0.7	0.9
Norway	0.7	8.5	7.8	0.9	N/A	1.0	0.9
Indonesia	8.5	17.5	9.0	0.5	0.7	0.4	N/A
Canada	10.0	19.0	9.0	0.5	0.6	0.3	0.6
Australia	6.0	16.2	10.1	0.6	0.8	0.7	N/A
Saudi Arabia	11.5	28.0	16.5	0.6	N/A	0.0	0.7
Russia	29.7	56.7	27.0	0.5	0.5	0.3	0.7
Average				**0.57**	**0.37**	**0.40**	**0.73**
Median				**0.59**	**0.37**	**0.34**	**0.75**

Table 2: Top 15 fossil energy exporters

data as for fossil fuel importers. Exports are the difference between domestic production and consumption, and the export share is defined as the ratio of exports to production. This list of 15 countries features mainly OPEC+ oil exporters along with a small number of non-OPEC producers such as Australia, Canada and Norway. The US is one the 15 largest fossil fuel exporters, but its exports are small relative to domestic production and consumption. The shift of the US to an energy exporter is a stark one, materializing only in the last decade. The US is also unique in being one of the few countries with relatively low fossil fuel openness (i.e. a high ratio of domestic consumption to production).

Exports are concentrated in crude oil and refined products, with 75% of domestic production exported by the top exporters. The N/A in Table 2 appear when the export ratio is either zero or the country is a net importer of the fuel. For many countries, fossil fuel exports tend to be concentrated in one product rather than across all products. Norway has a high export ratio of natural gas and oil, but is a net importer of coal. Most large fossil fuel exporters either have zero exports or are net importers of coal. These patterns are understandable given that natural gas is often coproduced with crude oil. While some countries exhibit high export dependence, the magnitude of dependence appears lower than that for the largest fossil fuel importers.

2.2 Energy shocks

Dependence on fossil fuel imports not only accounts for a sizable portion of fossil fuel energy use but also accounts for a sizable share of imports. For Japan and South Korea, fossil fuel imports are approximately 20% of the import bill. For India, fossil fuel imports are a quarter of the import bill. As a share of GDP, fossil fuel imports are significant: 4.6% for Japan, 2.8% for China, 6% for India and 10% for South Korea. The sizable share of fossil fuels in imports and relative to GDP makes

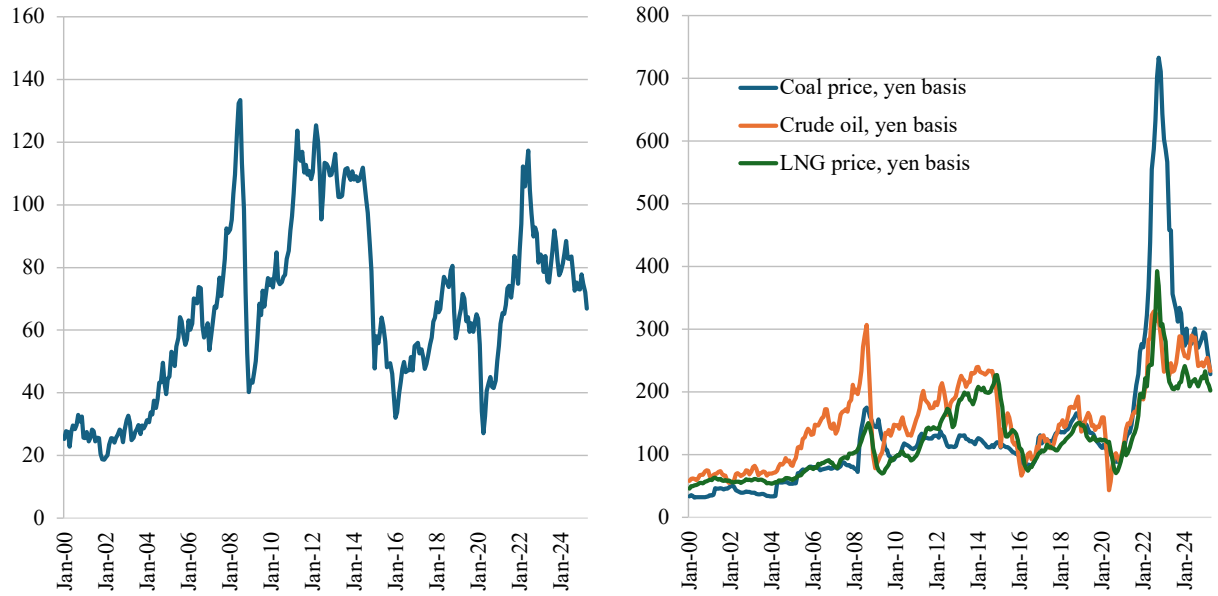


Figure 1: Energy prices: Brent oil price ($/bbl, LHS), Japan, import prices (RHS)

fossil fuel importers vulnerable to shocks in energy prices. The vulnerability to shocks to crude oil prices was obviously significant for the global economy in the late 1970s but has re-emerged after the Ukraine-Russia war and with recent hostilities in the Persian Gulf.

Figure 1 shows oil prices and Japanese import prices since 2000; the benchmark Brent oil price is shown on the left-hand side and Japanese fossil fuel import prices are shown on the right-hand side. Both series exhibit sharp increases around Russia's invasion of Ukraine and pronounced volatility in recent years. Coal prices (not shown) have also displayed volatility in the wake of the invasion. In addition to increased volatility, the price of oil in particular has risen sharply since 2000 and shown periods of elevated volatility even outside of war as high demand from developing economies and increased shale oil production have led to periods of under and over supply, along with boom and bust cycles in fossil fuel investment.

2.3 Emissions and mitigation

The largest fossil fuel importers are a sizable component of global CO_2 emissions. China and India are the largest and third-largest emitters respectively, with the European Union following as fourth. Japan and South Korea are the fifth and ninth largest emitters. Together the 15 largest fossil fuel importers (excluding the European Union) account for more than 50% of global emissions. Even excluding India and China, these countries have approximately the same level of emissions as the US. Figure 2 shows a pie chart of emissions by region, with the US and EU approximately equal to the emissions of top energy importers excluding China.

As Table 3 shows, the top energy importing countries are heterogenous in their emissions per

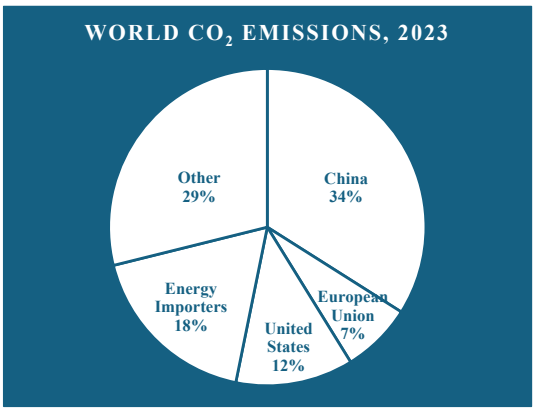


Figure 2: Distribution of global CO_2 emissions, 2023

capita and emissions intensity, reflecting large differences in economic development. Emissions data is reported by the European Commission's Emissions Database for Global Atmospheric Research (EDGAR). Emissions intensity is reported as tons per $1000 PPP-adjusted real GDP. The table both shows levels of emissions, emissions per capita, and emissions intensity in 2023 and the percentage change since 2000.

Developing economies like India, Pakistan and Vietnam have relatively low emissions per capita and have displayed large increases in emissions since 2000 due to high rates of economic growth. Per capita emissions have risen commensurately, and emissions intensity also appears elevated. China as well remains in a league of its own with high emissions intensity, higher than median emissions per capita, and a doubling of overall emissions and emissions per capita since 2000.

However, even restricting attention to relatively wealthier Asian energy importers shows important differences in emissions trends. Collectively, the advanced Asian economies of Japan, Hong Kong, Singapore, South Korea and Taiwan have emissions of approximately 2 gigatons and have reduced emissions only 3% since 2000. By comparison, the US lowered emissions by 21% and the EU lowered emissions by 30% over the same period. Progress in emissions reduction looks similarly slower on a per capita or emissions intensity basis. Emissions per capita fell 8% for advanced Asian economies; for the US and EU, per capita emissions fell by about 1/3. Emission intensity fell 40% for advanced Asian economies relative to a 50% reduction for the US.

To summarize, the largest fossil fuel importers are an important piece of overall global emissions, even if China and India are excluded. These countries have, on average, shown less progress in emissions reduction since 2000, though this is confounded by rapid economic growth, large populations, and starting from a low base. However, even limiting attention to countries to relatively prosperous Asian energy importers shows somewhat less progress in decarbonization than either the US or the European Union. As we will investigate, this may reflect external energy dependence and more challenging conditions for decarbonization.

	Emissions, 2023			Change relative to 2000		
Country	Total Mt CO2	Per capita Mt CO2/ person	Intensity Mt CO2/ $GDP	Total %	Per capita %	Intensity %
European Union	2814	5.7	0.10	-30	-32	-49
US	4682	13.8	0.19	-21	-34	-50
China	13260	9.2	0.42	262	223	-42
India	2955	2.1	0.23	197	119	-26
Japan	945	7.5	0.16	-24	-23	-35
South Korea	574	11.0	0.22	21	10	-45
Mexico	487	3.5	0.17	23	-10	-13
Turkey	438	5.1	0.15	93	43	-36
Vietnam	373	3.7	0.28	560	424	64
Taiwan	280	11.7	0.18	18	7	-47
Thailand	274	3.9	0.18	57	42	-24
Pakistan	201	0.9	0.15	79	13	-27
Philippines	161	1.4	0.14	117	48	-28
Ukraine	136	4.4	0.08	-62	-53	-61
Chile	84	4.5	0.15	56	26	-27
Singapore	57	9.4	0.08	25	-19	-54
Hong Kong	35	4.5	0.07	-17	-28	-55
Average		**6.0**	**0.17**	**80**	**45**	**-33**
Median		**4.5**	**0.16**	**25**	**10**	**-36**

Source: European Commission, EDGAR (Emissions Data for Global Atmospheric Research)

Table 3: Emissions for top energy importers

3 Analytical Model

We begin by presenting a neoclassical small open economy with clean and fossil fuel energy production. The model shown here follows standard real small open economy models, but incorporates the accumulation of clean and fossil fuel energy capital as outlined in Bistline, Mehrotra and Wolfram (2023) and Mehrotra (2024). In this section, we introduce the model, characterize the steady state and transition path, and derive an upper bound on the macroeconomic cost of the zero fossil fuel steady state.

3.1 Households' problem

A representative household maximizes the present discounted value of utility from consumption. Labor is supplied inelastically, and the household chooses investment into both clean and fossil

energy production. The representative household's optimization problem is given below:

$$\begin{aligned}
&\max \quad \sum_t \beta^t u\left(C_t\right) \\
\text{subject to } \; C_t + \sum_i p_{t,k}^i I_t^i + Q_t B_{t+1}^* &= \Pi_t + Q_t r_t^* B_t^* \\
&\quad + \sum_i W_t \bar{N} + \left(r_t^i + p_{t+1,k}^i \left(1-\delta_i\right)\right) K_t^i \\
I_t^i &= K_{t+1}^i - \left(1-\delta_i\right) K_t^i \\
K_t^i &\geq 0 \quad i \in c, f
\end{aligned}$$

where B_t^* represents the net foreign assets of the representative household denominated in units of the foreign good and Q_t is the exchange rate.

The optimal choice for capital stocks and foreign bonds are given by standard Euler equations:

$$\begin{aligned}
u_c\left(C_t\right) p_{t,k}^i &= \beta u_c\left(C_{t+1}\right)\left(r_{t+1}^i + p_{t+1,k}^i\left(1-\delta_i\right)\right) + \mu_{t+1}^i \\
u_c\left(C_t\right) Q_t &= \beta u_c\left(C_{t+1}\right) Q_{t+1} r_{t+1}^*
\end{aligned}$$

where μ_t^i is the Lagrange multiplier on the non-negativity constraint on the capital stock. We explicitly include non-negativity constraints given the assumption of perfect substitutability across clean and fossil fuel technologies (see next section).

3.2 Energy production

A representative firm produces energy by renting both fossil capital and clean energy capital from the representative household. Energy is used along with labor as an input into the production of the domestic tradable good. The representative energy producer must purchase fossil fuel in fixed proportions to the fossil fuel capital stock to produce energy (i.e. Leontif production). Energy produced via clean or fossil capital are perfect substitutes.

$$\begin{aligned}
&\max \quad p_t^e E_t - \left(p_t^x \kappa + r_t^k\right) K_t^f - r_t^c K_t^c \\
&\text{subject to } \; E_t = \theta_f K_t^f + \theta_c K_t^c
\end{aligned}$$

where K_t^i is the stock of power generation capital and r_t^i is the rental rate on for power generation capital i. p_t^x is the price of fossil fuel and κ is a production parameter for the quantity of fossil fuel that must be paired with a unit of fossil fuel capital to generate energy. Clean energy is assumed to have no fuel requirement (i.e. wind or solar).

Profit-maximization implies the following optimality conditions:

$$\begin{aligned}
p_t^e \theta_f &= p_t^x \kappa + r_t^f \\
p_t^e \theta_c &= r_t^c
\end{aligned}$$

The assumptions of perfect substitutability and constant returns across clean and fossil energy production deserve further discussion. First, these assumptions best capture the way energy systems modeling analyzes deep decarbonization scenarios (see, for example, Bistline et al. (2023)). In those models, a carbon-free pathway is specified for each distinct energy services (i.e. a carbon-free pathway for shipping, for space heating, etc.). The clean energy pathway may be more expensive but replicates the same service that is provided by the fossil fuel pathway.

Second, these assumptions allow for a zero-emissions steady state; the marginal cost curve is flat, though potentially substantially higher than that of fossil fuels. Third, there is no restriction placed on the magnitude of the price difference between the clean and fossil technology. Lastly, there is little reason to believe a priori that there is any underlying preference for fossil fuels relative to clean electricity as a fuel source or inherent limitations to scale. If anything, constant returns is more problematic for fossil fuels which are an exhaustible resource.

3.3 Goods production

A domestic representative firm produce a domestic tradable good that can be exported and is used as an input for a final good firm that combines this good with the foreign tradable good to produce the consumption aggregate. The domestic tradable good is produced using labor and energy via a Cobb-Douglas production and implying standard optimality conditions for input demand:

$$\begin{aligned} &\max \quad p_t^h Y_t^h - W_t N_t - p_t^e E_t \\ &\text{subject to} \quad Y_t^h = E_t^{\alpha_h} N_t^{1-\alpha_h} \end{aligned}$$

The problem of the representative final good firm is given below, where p_t^h is domestic price of the home tradable good and p_t^f is the domestic price of the foreign tradable good:

$$\begin{aligned} &\max \quad P_t Y_t - p_t^h Y_t^h - p_t^f Y_t^f \\ &\text{subject to} \quad Y_t = \left[\chi^{1-\theta} \left(Y_t^h \right)^{\theta} + (1-\chi)^{1-\theta} \left(Y_t^f \right)^{\theta} \right]^{1/\theta} \end{aligned}$$

where Y_t^f is domestic demand for the foreign tradable good. P_t is the price index for the domestic final good and will be normalized to unity.
Profit maximization implies the following demand curves for home and foreign traded good:

$$\begin{aligned} Y_t^h &= \chi Y_t \left(\frac{P_t^h}{P_t} \right)^{\frac{1}{\theta-1}} \\ Y_t^f &= (1-\chi) Y_t \left(\frac{P_t^f}{P_t} \right)^{\frac{1}{\theta-1}} \end{aligned}$$

where the elasticity of substitution between home and foreign tradable goods is $1/1-\theta > 0$.

3.4 Market clearing

The law of one price holds for both the home and foreign good and for fossil fuels: $p_t^i = Q_t p_t^{i*}$ $i \in h, f, x$. Foreign demand for the home tradable good is symmetric to domestic demand for the foreign good, implying the following demand schedule:

$$Y_t^{h*} = \chi^* \left(\frac{p_t^h}{p_t^f} \right)^{\frac{1}{\theta^* - 1}} Y_t^*$$

where θ^* determines the elasticity of substitution between the home and foreign tradable good and may differ from θ.

Market clearing for the home and foreign good imply the following conditions:

$$Y_t + Q_t r_t^* B_t^* = C_t + Q_t B_{t+1}^* + \sum_i p_{t,k}^i I_t^i$$

$$p_t^h Y_t^{h*} + Q_t r_t^* B_t^* = p_t^f Y_t^f + Q_t B_{t+1}^* + p_t^x \kappa K_t^f$$

The second equation represents the balance of payments, where the value of exports and earnings on foreign assets equals the value of imports and foreign investment. We assume a debt-elastic interest rate spread where the interest rate on foreign assets is a decreasing function of the net foreign asset position; higher foreign assets imply a lower spread to the constant world interest rate r^*.

3.5 Cost of zero fossil fuel steady state

Perfect substitutability between clean and fossil energy implies that, in steady state, only one type of capital is used to produce energy. Combining the Euler equations from the household's problem and capital demand from the energy producer, we obtain the following expressions for the steady state price of energy:

$$p_e = \frac{1}{\theta_f} \left(p^x \kappa + p_{k,f} \left(r + \delta_f \right) \right)$$

$$p_e = \frac{p_{k,c}}{\theta_c} \left(r + \delta_c \right)$$

These expressions give the steady state price of energy assuming strictly positive levels of capital. Outside the knife-edge case, one technology will imply a higher cost of electricity than the other and the non-negativity constraint on the capital stock will bind. It is also worth observing that these expressions are akin to the levelized cost of electricity (LCOE), which is the sum of fuel costs and an annualized capital charge adjusted for differences in capacity utilization.[6]

[6] Power generation from renewables like solar and wind have zero fuel cost but, generally, higher upfront capital costs $p_{k,c}$ and lower utilization rates θ_c relative to fossil power generation.

Assuming that fossil fuels imply a lower price of energy than the clean alternative, there exists a business-as-usual steady state with $K_c = 0$ and $p_{e,bau}$ given by the first levelized cost equation. Conversely under a carbon tax or other policy ruling out the use of fossil fuels, there exists a zero-emissions steady state with $K_f = 0$ and $p_{e,nz} \geq p_{e,bau}$. The long-run (i.e. steady state) macroeconomic cost of zero emissions has a straightforward definition as the difference between consumption between these steady states: $\Delta C = C_{nz} - C_{bau}$.

From the GDP equation, these long-run cost can be decomposed into an output cost and an investment cost. The output cost is the reduction in final good production from higher energy costs and unfavorable movements in the terms of trade. The investment cost reflects higher steady state investment expenditures for clean energy relative to fossil energy.

Under the assumption that the debt-elastic interest rate spread is such that $\beta r^* = 1$, $B^* = 0$, and we can derive a useful upper bound on the cost of zero emissions. In particular, a feasible allocation is one which there is a subsidy for clean energy such that energy production is constant. Under such a policy, real output of the domestic tradable good is unchanged. Without loss of generality, if we assume that depreciation rates and capacity factors are the same, we obtain the following expression for the difference in steady state consumption between zero emssions and business-as-usual:

$$\Delta C = (p_{h,nz} - p_{h,bau})\, Y_h + p_x \kappa K - (p_{k,c} - p_{k,f})\, \delta K$$

where δK is steady state investment in power generation and $p_{h,i}$ is the price of domestic tradable good. By construction, K and Y_h are the same across steady states since the price of energy and level of energy production is unchanged.

The first term reflects gains or losses from movements in the terms of trade. The reduction in the fossil fuel import bill will lead to a fall in the terms of trade to equate the balance of payments. The second term is positive and reflects savings from fuel imports that raises consumption in the zero emissions steady state. The third term is negative reflecting the higher capital cost of clean energy capital relative to fossil capital. In the special case of a single global good (i.e. $p_t^h = p_t^f$), the terms of trade are constant and only the second and third terms remain.

Dividing through by $p_{h,bau} Y_h$ provides an expression for the consumption cost of zero emissions as a share of domestic GDP. Maintaining the assumption of negligible terms of trade effects, an *upper* bound on the steady state cost of zero emissions is given below and is a generalization of Mehrotra (2024):

$$\Delta C/Y = \Delta p_x \kappa K/Y + \left(\frac{p_{k,c}}{p_{k,f}} - 1\right) I/Y$$

This equation states that the consumption cost of zero emissions is proportional to cost premium on green capital less fuel savings.

This equation is suggestive of why the macroeconomic costs of zero emissions are likely to be modest in the long run. First, given technological advances, the premium for clean capital

relative to fossil capital has closed substantially for major emitting sectors such as electric power generation and passenger vehicles. Second, investment in energy capital is a small share of overall investment. Therefore, even with a substantial capital premium for clean technologies, the consumption cost is limited by the low share of energy investment in the overall economy. Lastly, the cost of moving to zero emissions is offset by fuel savings; while expenditures on fossil fuels are also modest for advanced economies, they help offset the premium from clean technologies.

Strikingly, it is possible for the consumption gain to be *positive*. Maintaining the assumption of same depreciation rates and capacity factors, it is possible for the steady state cost of clean energy investment to be lower than the steady state cost for fossil investment, even though the price of energy is *higher* for clean relative to fossil. The following conditions show that it is simultaneous possible for the macroeconomic cost of clean energy to be lower than that of fossil energy, but the price of energy from clean capital to be higher:

$$p_{k,c}\delta K \leq p_{k,f}\delta K + \kappa p_x K$$
$$p_{e,nz} = p_{k,c}\left(r+\delta\right) \geq p_{k,f}\left(r+\delta\right) + \kappa p_x = p_{e,bau}$$

These conditions are more likely to simultaneous obtain when the interest rate r is high and the fuel cost is a relative large part of the price of fossil energy.[7]

3.6 Exchange rate effects

A transition to zero emissions can have long run effects on the real exchange rate via effects on the terms of trade and the import bill from reduction in fossil fuel use. To illuminate the mechanisms that determine the real exchange rate, it is helpful to consider two case: the case on no traded good and imperfect substitutability between home and foreign traded goods, the case of a non-traded good and perfect substitutability between the home and foreign traded good (i.e. single traded good). The latter case eliminates terms of trade effects from the transition to zero emissions.

In the first case of no traded good (and assuming balanced trade in steady state), the terms of trade $S \equiv p_h/p_f$ is given by the following expression:

$$E^{\alpha_h} = \frac{\chi}{1-\chi}\left(SY_h^* - p_x^* F\right) S^{1/(\theta-1)} + Y_h^*$$

where the left-hand side is production of the home traded good, the first-term on the right-hand side is consumption of the foreign good from the trade balance equation and the second-term is foreign demand for the home traded good. An increase in the price of electricity lower energy

[7]The notion that steady state consumption could rise under zero emissions is counterintuitive but analogous to a capital subsidy in the neoclassical growth model. Under dynamically efficient conditions, the planner's steady state level of capital will be strictly below that of the Golden rule level of capital. A small capital subsidy would transition the economy to a new steady state with higher capital and higher consumption, the return on capital would be suboptimally low.

use and lowers production of the home traded good. This reduction in the supply of the home good must be met by reduction by some combination of domestic and foreign demand. The relative price of the home good must rise - a real appreciation - to reduce both home and foreign consumption of the traded good.

The fossil fuel import bill $p_x^* F$ enters into the determination of the steady state terms of trade. In a zero emissions steady state, this term disappears, which increases desired consumption of the home good (since consumption of the foreign good rises). Therefore, for a given change in the price of electricity, the larger the fossil fuel import bill, the larger the appreciation required in the real exchange rate to maintain external balance.

To gauge the importance of the terms of trade effect, it is worth considering the alternative where the home country's traded good is perfectly substitutable for the foreign traded good. This case comes closer to capturing policymakers' concerns that a zero emissions target may damage the competitiveness of energy-intensive manufacturing. A similar set of equations now obtains for determining the real exchange rate:

$$E^{\alpha_{tr}} = \frac{\omega}{1-\omega} Y_n \left(Q/p_n\right)^{1/(\eta-1)} + p_x^* F + \sum_i p_k^i \delta_i K_i$$

$$1 = \omega Q^{\eta/\eta-1} + (1-\omega)\, p_n^{\eta/\eta-1}$$

where we assume that α_i is the energy share of production for tradables $i = tr$ and non-tradables $i = n$ respectively and Q is the real exchange rate. In this case, the terms of trade are fixed and the real exchange rate is the price of the tradable good. Under the assumption that $\alpha_n = 0$, non-traded output and consumption is unchanged in the zero emissions steady state.[8] The higher energy price lowers output of the tradable good. The real exchange rate may now appreciate or depreciate depending on the change in the import bill (inclusive of capital costs for energy). If the resource cost of producing clean energy falls relative to fossil energy (capital + fuel cost), then the traded good is relatively more plentiful and a real appreciation is needed for external balance.

It is useful to consider the knife edge case where the steady state resource cost of zero emissions is the same as in the business-as-usual, but the price of electricity is strictly higher. In this case, the second term in the market clearing condition above is zero and any adjustment in traded goods consumption only comes via prices. In this case, higher electricity prices lower production of the traded good, raising its price, depreciating the real exchange rate. As we will argue, the transition to zero emissions is likely to lower aggregate resource costs needed for energy production even if the price of energy rises. Combined with standard terms of trade effects if traded goods are imperfectly substitutable, this suggests the real exchange rate is likely to appreciate.

The model considered here can be straightforwardly modified to allow for consideration of

[8] An additional assumption is that energy capital is traded in world markets and unaffected by changes in the real exchange rate.

other trade policies that have been widely considered or adopted in the context of the energy transition. Many countries have expressed concern about Chinese dominance in clean energy capital goods and becoming overly dependent on Chinese imports. The US IRA, for example, imposed domestic sourcing requirements on electric vehicles and clean power generation in an effort to promote US clean energy manufacturing. In the context of this model, domestic sourcing has two effects: 1) it enters into the market-clearing conditions for the traded good, 2) it raises the price of clean energy capital $p^c_{t,k}$. Consider the case of only traded and non-traded goods. To the extent that the domestic sourcing implicitly raises the price of capital goods, the price of energy is higher as is the resource cost. This makes the traded good less plentiful, resulting in a real depreciation. Conversely, with a home and foreign traded good, domestic sourcing raises lowers production of the home good (via higher energy prices), lowers the quantity of home goods available domestically, and raises the quantity of foreign goods available. These effects all result in a strong real appreciation.

The EU recently imposed a carbon border adjustment mechanism to equalize the treatment of domestic and foreign manufactured goods, since the EU imposes a carbon tax (via the EU emissions trading scheme). A carbon border adjustment tax raises the price of the traded good as perceived by producers and consumers, but leaves the underlying market clearing conditions unchanged. The foreign traded good has price $p^f_t = (1+\tau)\, Q_t p^*_f$ where the foreign price can be normalized to unity. How does a CBAM affect the exchange rate? In the case of only traded and non-traded goods, a CBAM lowers Q implying either less depreciation or greater appreciation of the real exchange rate.[9] In the case of only home and foreign traded goods, the CBAM limits the degree of real appreciation since the CBAM is already partially changing the terms of trade.

3.7 Transition path to zero emissions

The transition to zero emissions may entail further costs that are not present in simply analyzing the business-as-usual and clean energy steady states. In particular, the transition may be costly by leading to large changes in consumption along the transition path or irreversibility in capital investment may result in stranded assets. The policy discussion has often emphasized the latter - achieving zero emissions over a relatively short horizon may require mothballing capital investments before the end of their usable life.

In general, it will be difficult to characterize the transition paths for output, consumption and capital stocks analytically without strong assumptions. However, to illustrate the key forces at work in the transition, I consider the special case of a single global good such that $p^h_t = p^f_t$. In this case, the impact of the transition on the path of consumption can be understood from the

[9] Our maintained assumption is that price of energy capital goods are unaffected.

household's Euler equation for foreign assets and capital and the economy's resource constraint:

$$Y_t + r_t^* B_t = C_t + B_{t+1} + p_f \kappa K_t^f + \sum_i p_{t,k}^i \left(K_{t+1}^i - (1-\delta_i) K_t^i \right)$$
$$u_c(C_t) p_{t,k}^i = \beta u_c(C_{t+1}) \left(r_{t+1,k}^i + p_{t+1,k}^i (1-\delta_i) \right)$$
$$u_c(C_t) = \beta u_c(C_{t+1}) r_t^*$$

As noted in Mehrotra (2024), a policy-induced energy transition operates like the combination of two shocks: an anticipated negative productivity shock and an anticipated negative capital shock. If capital is reversible or the transition is sufficiently far into the future, then the energy transition is an anticipated negative productivity shock. At some point in the future, energy production occurs only via clean capital, implying a higher price for energy and lower production. The representative households wish to insure against lower future income by accumulating net foreign assets along the transition path.

We can obtain a simple analytical characterization of the transition path with a constant foreign interest rate $r_t^* = 1 + \bar{r}$ and $\beta(1+\bar{r}) = 1$. In this case, the capital stock immediately adjusts to its steady state value after the zero emissions date T_{nz} when fossil fuel capital can no longer be used. For all $t \geq T_{nz}$, output and clean energy capital are given by:

$$Y_{nz} = (\theta_c K_c)^{\alpha_h} \bar{N}^{1-\alpha_h}$$
$$p_{k,c}(\bar{r} + \delta) = \alpha_h \theta_c^{\alpha_h} K_{nz}^{\alpha_h - 1}$$

with $K_t^f = 0$ for $t \geq T_{nz}$. For $t < T_{nz}$, $Y_t = Y_{bau} > Y_{nz}$ - prior to the zero emissions date, energy is produced via cheaper fossil fuel. Under the assumption of a constant world interest rate, the level of domestic consumption will be constant. Let C_{bau} and C_{nz} be the steady state levels of consumption using fossil and clean technologies respectively. Then long-run consumption is given by:

$$C_t = C_0 = C_{nz} + \bar{r} \left(B_0 + \sum_{t<T_{nz}} C_{bau} - C_{nz} \right)$$

This expression for consumption has a natural interpretation. A zero emissions target lowers long-run consumption due to higher energy prices, but there is a transition period during which the economy continues to produce using cheaper fossil capital. This higher income along with any initial foreign assets are invested in foreign assets yielding a stream of income $\bar{r}$.

A similar derivation can be made in the case of irreversibility. To fix ideas, assume capital irreversibility, that the price of energy capital is comparable $p_{k,c} = p_{k,f} + \epsilon$, and assume fuel costs are zero. In this case, the price of energy from fossil fuel capital is comparable to the price of energy from clean capital. In steady state, output, consumption and the capital stock will be comparable across the business-as-usual and zero emissions steady states. However, the cost of stranding the

fossil fuel capital stock must be incorporated into consumption. Therefore, if the capital stock K_f is stranded at the zero emissions date: T_{nz}, consumption for all $t \geq 0$ is given by:

$$C_t = C_0 = Y_{nz} + \bar{r}\left(B_0 - p_{k,f}K_f\right)$$

As before, this equation has a natural permanent income interpretation. After the zero emissions date, the clean energy capital stock jumps to its steady state level, along with output. Consumption jumps to a constant long-run level that equals long-run production plus interest income on initial foreign assets, less the interest cost on foreign borrowings to pay for replacing the stranded fossil fuel capital stock. Intuitively, households borrow from international capital markets to replace the fossil capital stock that is stranded at time T_{nz}. They lower their consumption initially to build up foreign assets to pay for cost of installing the clean energy capital stock.

More generally, given any arbitrary path of losses from stranded assets, consumption will be equal to output plus interest income on initial foreign assets less interest cost on replacing stranded assets. The dynamics of the net foreign asset position reflect some initial accumulation in foreign assets (current account surplus) followed by a large deficit as international capital is used to invest in the clean energy capital stock.

While these calculations assumed the case of a constant world real interest rate, we can characterize qualitatively the transition path with a debt-elastic interest rate. Mehrotra (2024) shows that, in a closed economy, the transition path will generically feature a declining consumption path between date 0 and the zero emissions date T_{nz}. The real interest rate and rate of return on capital will also generically fall since consumption growth is negative. In an open economy, this decline in the interest rate will be tempered by the ability to acquire foreign assets to buffer the long-run decline in consumption. Between date 0 and the zero emissions date, the net foreign asset position will rise and the open economy will temporarily run a current account surplus.

4 Quantitative Model and Calibration

In this section, we present the full quantitative model used to analyze decarbonization of power generation in Japan. Relative to the analytical model, the quantitative model features three distinct types of power generation capital and non-energy capital that is allocated to domestic production of the tradable and non-tradable good. Labor is supplied inelastically but is employed in both sectors. Investment in all types of capital is subject to capital adjustment costs. This section also describes in some detail how electric power generation is represented in the model, and the relationship between our modeling approach and the approach used in energy systems models.

4.1 Power generation

The representative household's problem is generalized here from the previous section to account for capital adjustment costs. A representative household maximizes the discounted present value of consumption while receiving labor and capital income and investing in various types of physical capital and foreign assets. The household's problem is given below:

$$\begin{aligned} & \max \sum_{t=0}^{\infty} \beta^t u\left(C_t \bar{D}\right) \\ C_t + Q_t B_{t+1} + \sum_i p_{t,k}^i I_t^i + S\left(I_t^i, K_t^i\right) &= \Pi_t + Q_t r_t^* B_t^* \\ & \quad + W_t \bar{N} + \sum_i \left(r_t^i + p_{t+1,k}^i \left(1-\delta_i\right)\right) K_t^i \\ K_{t+1}^i &= I_t^i + \left(1-\delta_i\right) K_t^i \end{aligned}$$

There are four types of productive capital: unabated fossil fuel capital K_t^f, abated fossil fuel (carbon capture) capital K_t^{ccs}, clean energy capital K_t^c, and non-energy capital K_t^{ne}. Each capital stock has a relative price given by $p_{t,k}^i$ and is subject to capital adjustment costs given by the function $S_i\left(I_t^i, K_t^i\right)$. $\bar{D}$ is the representative household's use of the end-use durable discussed further in the next section. Capital accumulation equations for each type of capital are standard but capital may differ in depreciation rates. Electricity production is a function of the three types of energy capital discussed in the next section:

The optimality conditions for the planner's problem are given below:

$$\begin{aligned} u_c\left(C_t\right) &= \lambda_t \\ \mu_t^i &= \lambda_t \left(p_{t,k}^i + S_1\left(I_t^i, K_t^i\right)\right) \\ \mu_t^i - \beta \mu_{t+1}^i \left(1-\delta_i\right) &= \beta \lambda_t \left(r_{t+1}^i + p_{k,t+1}^i \left(1-\delta_i\right)\right) - S_2\left(I_{t+1}^i, K_{t+1}^i\right) \\ \lambda_t Q_t &= \beta \lambda_{t+1} Q_{t+1} r_{t+1}^* \end{aligned}$$

where μ_t^i are the Lagrange multipliers on the capital accumulation equation for capital types i and λ_t is the Lagrange multiplier on the household's budget constraint. The quantitative model simplifies to the analytical model considered earlier if adjustments costs are zero and there is no non-energy capital or abated fossil energy capital.

In the quantitative model, we allow for the production of a non-traded domestic good. This good is combined with a composite traded good to create the domestic final good that is used for consumption and investment, and the price index of the final good is normalized to unity. Like the traded good, the non-traded good is produced via a Cobb-Douglas production function with non-energy capital, labor and electricity as inputs. For brevity, the full set of equilibrium conditions are relegated to the appendix.

4.2 Transportation

Households have inelastic demand for transportation services $\bar{D}$. These transportation services can be provided by internal combustion vehicles that require imported fossil fuels or by electric vehicles. The household chooses between a fossil fuel and electric capital to replace the fraction δ_d of capital that is depreciating in the current period. The fraction of the fossil fuel option chosen depends on a comparison of the lifecycle cost differences between the fossil fuel and electric option and on an idiosyncratic cost shock that is normally distributed with mean zero and standard deviation σ. We define operating costs for the fossil fuel and electric capital stock recursively, and define z_t as the expected difference in lifecycle cost between the electric and fossil fuel vehicle:

$$
\begin{aligned}
V_t^f &= \left(p_{f,t} + \tau_t^f + \nu_f\right) + \frac{1-\delta_d}{1+r_{t+1}} V_{t+1}^f \\
V_t^e &= p_t^e + \nu_e + \frac{1-\delta_d}{1+r_{t+1}} V_{t+1}^e \\
z_t &= p_{d,t}^e + \eta_e V_t^e - p_{d,t}^f - \eta_f V_t^f + \mu \\
I_t^f &= \Phi\left(z_t/\sigma\right) \delta_d \bar{D} \\
I_t^e &= \delta_d \bar{D} - I_t^f
\end{aligned}
$$

where V_t^j is the depreciation adjusted present value of price of fuel j, and the carbon tax is τ_t^f. The parameters ν_f and ν_e are wedges that reflect the retail cost of delivery of fuels and electricity (i.e. the wedge between wholesale prices and residential prices). Since emissions vary across fuels, the carbon tax is fuel specific. z_t^i is the premium for the electric option (its capital cost and expected fuel cost) relative to the fossil fuel option. Given this lifecycle price premium, investment shares are translated from a standard normal distribution. μ is a cost-shifter to capture both monetary and non-monetary differences between electric and fossil fuel capital services such as charging network concerns or taste. All things equal, with low variation σ, the electric option will only be chosen if the price premium is low or negative and investment will rapidly shift based on the lower price option. With higher variation, households will continue to purchase electric or fossil fuel vehicles even with substantial lifecycle price differences.

4.3 Electricity production

In the quantitative model, we now seek to model electricity production instead of energy. Solar and wind power represent the least costly zero carbon sources of electric power generation. These sources of power generation are fundamentally different that fossil fuel power generation due to their intermittent nature. By contrast, fossil fuel power sources are dispatchable - power generation from these sources can be adjusted up or down to meet fluctuations in demand. Our model of electric power generation must capture the intermittency penalty associated with solar and wind power.

Following Mehrotra (2024), we adopt a variable elasticity of substitution production function to represent aggregate electric power generation. The variable elasticity of substitution production function is due to Revankar (1971) and used in modeling the energy transition in Fries (2023). Usable electric power is a variable elasticity of substitution aggregate of intermittent E_t^{int} and dispatchable power E_t^{dis}:

$$E_t = \left(E_t^{dis}\right)^{\alpha} \left(E_t^{int} + \alpha\rho E_t^{dis}\right)^{1-\alpha}$$

where ρ is the key parameter that determines how the elasticity of substitution varies as the share of dispatchable generation falls.

As shown below, an increase in intermittent power generation relative to dispatchable generation lowers the elasticity of substitution when $\rho > 0$.

$$\sigma_t = \left(1 + \rho \frac{E_t^{dis}}{E_t^{int}}\right)$$

Our power generation function has constant returns to scale, decreasing returns to each type of power generation, and the characteristic that intermittent power generation is not essential for production (i.e. $E_t^{int} = 0$, $E_t > 0$ is feasible). This can also be seen by looking at the expression for the elasticity of substitution σ_t, which has the property that $\sigma_t \to \infty$ as $E_t^{dis}/E_t^{int} \to \infty$.

In steady state, the share of intermittent and dispatchable power will depend on relative prices. Assume that dispatchable power is unabated fossil energy and intermittent power is clean energy. In steady state and with constant returns, a simple relationship between the relative price of fossil versus clean energy and their share in power generation can be derived:

$$\frac{p_f}{p_c} = \frac{\theta_f}{\theta_c} \frac{\alpha}{1-\alpha} \left(\frac{E_{int}}{E_{dis}} + \rho\right) - \tilde{\mu}_c$$

where $\tilde{\mu_c}$ is a Lagrange multiplier on the constraint that clean energy capital must be non-negative. When $\rho > 0$, the Lagrange multiplier is binding if capacity-adjusted clean energy capital $p_c/\theta_c > p_f/\theta_f$. Intuitively, clean energy generation will only be utilized if its price is less than dispatchable generation because of the intermittency penalty. As clean energy capital becomes cheaper, more intermittent energy is utilized but its market penetration is limited by a rising intermittency penalty.

In our quantitative application, we assume that clean energy is a composite of solar and wind that provides intermittent power generation. Dispatchable power is a CES composite of power from fossil fuel and power from a more expensive "clean-firm" alternative. Electricity generated from unabated fossil fuel power generation and from the clean-firm alternative are assumed to be highly substitutable, reflecting the fact that by definition clean-firm power sources generate dispatchable power. Clean-firm power sources include natural gas or coal power with carbon capture technologies, nuclear, geothermal or hydro power.[10] Increasingly, batteries can be paired

[10]The ability for nuclear and hydro power to ramp in response to demand fluctuations is more limited than natural gas or coal.

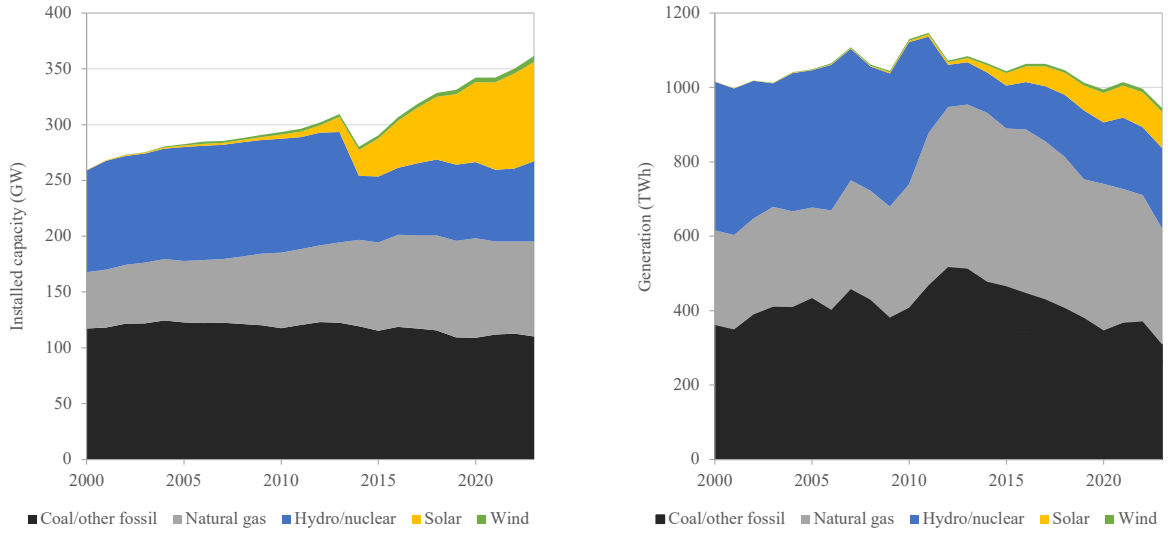


Figure 3: Nameplate capacity and generation by technology

with solar or wind to provide dispatchable power generation.

The production function for dispatchable power is shown below:

$$E_t^{dis} = G^{dis}\left(K_f, K_{ccs}\right) = \left(\eta_e \theta_f K_f^{\epsilon} + \left(1-\eta_e\right)\left(\theta_{ccs} K_{ccs}\right)^{\epsilon}\right)^{\frac{1}{\epsilon}}$$

4.4 Data

Calibration of the model requires choosing key parameters such as the relative price of energy capital, the productivity of energy capital, and the parameters in the variable elasticity of substitution production function. We use historical data on installed capacity and power generation for Japan along with projections for future technology cost of both intermittent renewables and clean-firm power sources.

The capital stocks K_t^i for different types of energy capital and the capacity factors of these technologies are taken from historical data on electric power generation capacity and generation data from the Energy Information Administration. Figure 3 displays the evolution of installed capacity and generation in Japan since 2000. Capacity is a quantity measure of the capital stock K_t^i, representing the rated (nameplate) output for a technology (measured in gigawatts); generation $E_t^i = \theta_i K_t^i$ is the electric power output over a year (measured in terawatt hours). Renewables like solar and wind differ from fossil fuel generation in typically have lower capacity factors. Observed data shows that capacity factors θ_i for solar and wind power in Japan are quite low (10-20%).[11]

[11] For example, a gigawatt of installed wind power could theoretically generate 8760 = 365 x 24 gigawatt hours (8.8 terawatt hours) of electric power over the course of a year with constant maximum wind speed and no downtime. Of course, in reality, wind speeds are variable and therefore realized power generation is 2-3 terawatt hours.

As Figure 3 shows, installed capacity has increased but power generation has remained mostly flat and now falling in recent years. Capacity and generation from renewables has risen substantially in Japan, particularly in the last decade. Installed solar capacity in 2023 was approximately 90 GW in 2023, exceeding natural gas capacity and closing in on coal capacity. However, it's low capacity factor means that solar's contribution to power generation is still more modest, accounting for about 10% of power generation in 2023. Wind power has been rising but accounts for a very small share of both capacity and generation.

The other clear effect visible in 3 is the sharp decline in nuclear capacity and generation after the Fukashima nuclear accident in 2011. In the wake of the accident, Japan scaled down power generation from it nuclear power plants, relying on coal and natural gas to make up the difference. In recent years, Japan has restarted some of its nuclear fleet but has yet to restore generation from nuclear back to it's pre-Fukashima level. Some further restarts on the nuclear power fleet are expected through the end of the decade.

Finally, we collect data on the current and projected costs of different power generation technologies. Table 4 shows the current and projected capital cost of different types of generation technology, including the full range of intermittent and dispatchable sources of power generation likely to be used in a zero emissions transition for Japan. Levelized cost of electricity is a measure of the breakeven price of electricity needed to recoup the initial capital expenditure and fixed and variable costs, including fuel costs over the lifetime of a project. Table 4 is sorted from lowest to highest current levelized cost. Technology cost data is obtained from the National Renewable Energy Laboratories (NREL) Annual Technology Baseline and are reported in constant 2023 dollars.[12] While NREL's estimates are projections for US construction costs, we assume that capital costs are comparable in Japan.

The rising but small share of renewables in Japan's power generation reflects the particular challenges Japan faces in scaling up renewable power generation. Japan is not particularly well suited for either solar or onshore wind power relative to some other countries. Solar potential is lower in Japan, akin to solar potential in the northeastern US as opposed to the southwest US. Elevation and density also make Japan less suited for onshore wind development. Relative to Europe, Japan faces challenges in relying on offshore wind because it lacks shallow waters close to the coast. Therefore, Japan must develop floating-bottom offshore wind resources - a more expensive option than either onshore wind or fixed-bottom offshore wind.

Table 4 shows that solar and onshore wind are currently the cheapest sources of power generation. Fixed bottom offshore wind that has been deployed extensive in Europe is significantly more expensive but expected to become more economical over time. Floating bottom offshore that has

[12]NREL Annual Technology Baseline is available from https://atb.nrel.gov/electricity/2023/technologies under a moderate assumption for capital cost reductions and the most conservative assumptions for capacity factors for solar and wind.

		Levelized cost of electricity ($/MWh)		Capital cost ($2023/kW)	
Technologies	**Emissions**	**2023**	**2050**	**2023**	**2050**
Solar	0	65	26	1611	683
Natural gas	+	45	39	1487	1191
Onshore wind	0	77	45	2490	1463
Geothermal (conventional)	0	70	59	7097	5735
Natural gas with CCS	0	83	64	2913	2199
Offshore wind (fixed bottom)	0	121	64	6579	3358
Nuclear	0	84	67	7616	5012
Geothermal (enhanced)	0	92	71	9367	6834
Offshore wind (floating)	0	148	73	9016	4164

Table 4: Electric power generation, technology costs

yet to be deployed in scale is even more expensive than offshore wind. In our quantitative projections, we assume that clean power will be mostly solar with some reliance on fixed and floating bottom offshore wind; onshore wind is expected to make a negligible contribution.

Capital costs and levelized cost are projected to fall across all technologies in 2050, with solar showing the biggest drop in capital cost. As noted earlier, other zero emissions dispatchable sources of power - nuclear, conventional geothermal, and enhanced geothermal - are as or more expensive than the cheapest form of natural gas with carbon capture.[13] Offshore wind costs are projected to fall but remain considerably higher than solar or onshore wind through 2050, with floating offshore wind the most expensive option.

4.5 Calibration strategy

The calibration strategy uses historical data, technology cost projections, and energy systems modeling projections to choose the parameters of the quantitative model. Current and future capital costs for different power generation technologies - shown in Table 4 - are used to obtain paths for the relative price of energy capital p_t^i.

For electricity generation, we choose the price of fossil electric generation in the baseline to match the share of electricity investment in GDP and to match the share of power generation in clean energy (defined as solar and wind). Coal, hydro and nuclear are assumed to be exogenous sources of power generation that depreciate on a fixed schedule (some nuclear that was taken offline after Fukashima is assumed to return to service). The dispatchable form of electricity gen-

[13] Enhanced geothermal use fracturing techniques from oil and gas drilling to inject and heat water to drive power generation. By contrast, conventional geothermal uses hot water created in natural geological formations relatively close to the surface, limiting its scaling potential.

eration is natural gas that is either unabated or abated (i.e. carbon capture).

Using historical data on the value and volume of coal and natural gas imports and power generation from these sources, we determine the price of these imports, capacity factors, and fuel intensities (i.e. $p_f, \kappa_i, \theta_i, K_i$). Lifetimes for power generation capital are assumed to be 30 years. The depreciation rate for non-energy capital is chose to match the investment to GDP ratio, and the relative price of non-energy capital goods is chosen to be unity. The overall investment to GDP ratio for Japan is 25.1%, taken as the five year average of fixed investment to GDP in the national accounts. Fossil fuel coal and natural gas imports are 0.21% of GDP and 0.9% of GDP, taken from Japanese trade data. Implicit fuel prices are inferred from import values and fuel quantities.

The baseline is calibrated so K_c matches capacity of solar and wind, K_{exo} matches the sum of hydro, nuclear, and coal/oil, K_{ng} matches the capacity of natural gas. Carbon capture is assumed to start at 1% of natural gas capacity. Capacity factors θ_i are chosen for each type of power generation to match observed generation shares for the period 2019-2023. We allow for some increase in the capacity factors for solar and wind technologies based on NREL's projections. The price of fossil fuel capital is chosen to match the steady state level of electric power investment to GDP - 0.74% for Japan.

The parameters ρ and α in the variable elasticity of substitution electric power production function are chosen to match the share of intermittent (clean) power generation in the business-as-usual scenarios from an range of energy systems models. Specifically, we use the equation below to estimate values of α and ρ to fit energy systems model projections of intermittent energy share, capital costs, and capacity factors:

$$\frac{p_f}{p_c} = \frac{\theta_f}{\theta_c} \frac{\alpha}{1-\alpha} \left(\frac{E_{int}}{E_{dis}} + \rho \right) \tag{1}$$

We use business-as-usual projections for intermittent power generation from energy systems models. These models are based on projections for the US (see, for example, Bistline et al. (2023)), but we apply the same parameters to power generation in Japan. The variable elasticity of substitution parameters are estimated by minimizing the deviations between projected renewable energy share from US energy systems models and that share implied by equation 1.

Transportation end-use is separated into two distinct capital stocks: residential and commercial surface transportation. The stock is set at 62.3 million and 14.6 million vehicles respectively, with annual depreciation rates δ_d of 6.4% and 5.8% respectively to match data on the total stock of Japanese vehicles and annual vehicle sales from the Japanese Automobile Manufacturing Association. Data on total vehicle kilometers traveled and total fuel use are used to derive annual kilometers traveled (8029 km and 4990 km respectively) drawn from the Automotive Consumption Fuel Survey. We draw on calibrations from **?** to find the electricity needed to deliver an equivalent service demand (i.e. same annual kilometers traveled). EVs for residential and com-

mercial use are assumed to have an efficiency of 188 Wh/km and 1063 Wh/km respectively.[14] Retail and commercial prices of electricity and gasoline/diesel are used as fuel costs. The capital cost of EVs is assumed to be a 40% and 180% premium on fossil fuel vehicles for residential and commercial segments respectively. The standard deviation σ is chosen to match the interquartile range for annual kilometers traveled.

The capital, electricity and labor share are chosen for the non-tradables and tradables sector are chosen to match cost shares (on a value-added and value-added + electricity basis) for service-providing and goods-producing industries. Specifically, the labor share and electricity share are 43.9% and 4.6% for the tradables (manufacturing) sector and 52.2% and 2.0% for the non-tradables (service) sector. These values are taken from Japan's input-output tables.[15] We choose consumption shares for traded and non-traded goods so that the traded (manufacturing) sector accounts for 19.2% of Japan's value added.

The share of services in GDP is chosen to target the weight of non-tradables in the final output basket. The share of the foreign good in the tradables basket is set to match net exports ex energy trade. We assume that foreign trade share and elasticity of substitution is symmetric across the home and foreign economies. The elasticity of substitution between home and foreign tradables is set at 2, implying a moderate degree of substitutability. By contrast, the elasticity of substitution between tradables and non-tradables is set at 0.5, implying a moderate degree of complementarity. Both elasticities are broadly consistent with the literature. Share parameter for domestic demand for the foreign good and vice versa are choose to match the value of Japanese exports and Japanese imports relative to the traded good sector (59.4% and 62.8% respectively).

We take the debt elasticity μ from the literature and assume log consumption. We target a net international foreign asset position for Japan of 60% of GDP and a trade deficit of 0.6% of GDP. The rate of time preference is set so that the real interest rate is 2% annually. Capital adjustment costs γ_i are assumed to be symmetric for all types of capital and are set at $\gamma_i = 2$, consistent with business cycle estimates of quadratic capital adjustment costs (see, for example, Canzoneri et al. (2006)).The remaining functional forms for the quantitative model are given below:

$$
\begin{aligned}
u(C) &= \ln(C) \\
F(K_{ne}, E, N) &= K_{ne}^{\kappa} E^{\nu} N^{1-\kappa-\nu} \\
\text{or} \quad F(K_{ne}, E, N) &= \left(\eta E^{\nu} + (1-\eta)\left(K_{ne}^{\kappa} N^{1-\kappa}\right)^{\nu}\right)^{\frac{1}{\nu}} \\
G^{dis}(K_f, K_{ccs}) &= \left(\eta_e \theta_f K_f^{\epsilon} + (1-\eta_e)\left(\theta_{ccs} K_{ccs}\right)^{\epsilon}\right)^{\frac{1}{\epsilon}} \\
S_i(I, K) &= \frac{\gamma_i}{2}\left(\frac{I - \delta K}{K}\right)^2 K
\end{aligned}
$$

[14] We draw on calculations from **?** to find the electricity needed to deliver an equivalent service demand (i.e. same annual kilometers traveled).

[15] Industries 66-134 are defined as non-traded.

	Baseline (2016-2020)	BAU (2050)	Net zero - CCS (2050)	Net zero - nuclear (2050)	No technological progress (2050)	Clean energy subsidy (2050)
	(1)	(2)	(3)	(4)	(5)	(6)
Aggregates:						
Output (% dev. from baseline)	0.0	0.9	-0.9	1.0	-0.5	4.0
Consumption (% dev. from baseline)	0.0	0.9	-0.6	0.8	-0.9	0.4
Investment rate (% of GDP)	25.1	25.1	24.9	25.3	25.3	27.7
Power generation:						
Elec. investment rate (% of GDP)	0.7	0.8	0.9	1.1	1.3	3.2
Fossil capital price (2020 = 100)	100	77	77	77	100	77
Clean capital price (rel. to 2020 fossil)	182	92	92	92	182	92
Emissions (% dev. from baseline)	0	-16	-99	-99	-99	-99
Electricity production (% dev. from baseline)	0	11	-28	-8	-30	96
Renewables share (% of generation)	7	23	62	26	14	21
Clean firm share (% of generation)	15	24	37	74	85	79
External:						
Trade balance (% of GDP)	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6
Fossil fuel imports (% of GDP)	0.7	0.5	0.2	0.0	0.1	0.0
Real exchange rate (% dev. from baseline)	0.0	0.9	2.8	3.5	4.1	3.0
Terms of trade (% dev. from baseline)	0.0	0.5	5.4	4.5	7.3	0.6

Table 5: Steady state macro and energy outcomes

5 Results

In this section, we present the quantitative effects of a zero emissions target for macroeconomic aggregate and power generation for Japan. Our key is result is that the transition to zero emissions involves a modest consumption cost of roughly 0.2-2% of steady state consumption depending on elasticities and available decarbonization technologies. At the low end, incurring these costs can be largely justified on the grounds of benefits from reductions in conventional (non-CO_2) air pollutants.

5.1 Steady state

Table 5 summarizes a comparison of steady state macroeconomic aggregates and power generation indicators under various technological scenarios. In the baseline calibration, we assume a moderate degree of complementarity between electricity and non-electricity inputs in the production of the domestic tradable good and the domestic non-tradable good. Column (1) shows the baseline steady state calibrated to match key pre-pandemic moments for Japan's economy. In our calibration, renewable energy accounts for 7% of generation while clean-firm sources (nuclear and hydropower) account for an additional 15% of generation. We estimate that the capital price of solar and wind is 82% higher than natural gas fossil generation. Fossil fuel imports are 0.7% of GDP, meaning the trade deficit is in balance absent fossil fuel imports.

Column (2) shows the business-as-usual steady state - the model steady state assuming the

capital cost declines shown in the previous section.[16] Price declines in solar and wind imply a sizable increase in power generation from renewables to 23%. Clean firm power also increases to 24% of generation due to the restart of nuclear power plants. However, a significant fraction of generation remains in fossil fuels. Lower coal and natural gas imports, however, lower the import bill and result in a modest real appreciation. The fall in power generation costs mainly due to cheaper solar and wind result in an 11% increase in electricity consumption and higher output and consumption. Investment in power generation rises slightly to 0.8% of GDP.

Columns (3) and (4) show two scenarios to achieve zero emissions by 2050. In the first scenario, the clean-firm power generation sources is assumed to be natural gas with carbon capture; in the second scenario, we assume that the clean-firm power source is nuclear power. As 4 shows in the previous section, both natural gas with CCS and nuclear currently have similar levelized cost of electricity with similar levels of technological progress by 2050. However, an important difference is that the initial capital cost for CCS is much lower than that for nuclear power. Their respective levelized costs turn out to be similar because of higher fuel costs for CCS. Moreover, given Japan's experience, the political acceptability of new nuclear power generation remains an open question.

As a result, the long-run consumption cost of zero emissions is quite different across the two scenarios. Under CCS, output rises just 0.3% and consumption fall 0.9%. Relative to business-as-usual, the consumption cost of zero emissions is 1.5%. The large reduction in emissions comes with some savings in terms of fuel costs; fossil fuel imports fall to 0.2% of GDP and renewables account for 62% of generation. Relative to the business-as-usual case, electricity production falls 28% on higher electricity prices. The reduction in fossil fuel imports along with the higher cost of producing the home tradable good appreciate the real exchange rate by roughly 3%.

In the zero emissions scenario with nuclear power, the price increase in electricity (relative to BAU) is mitigated. Electricity production falls 8% with 74% of power generated from clean firm sources and the remainder from renewables. Output rises relative to BAU because of higher levels of steady state investment. The reliance on nuclear power and renewables eliminates fossil fuel imports and allows for more imports of the foreign tradable good. As a result, consumption falls by much less than under the CCS case. As a result, the fall in consumption is just 0.2% relative to BAU. This is comparable to the magnitudes in Mehrotra (2024) but seems to be drive by different reasons. Relative to the US, renewables prices fall by less and renewables share is far more limited in a zero emissions scenario. However, relative to the US case, Japanese consumption is supported by less need for fossil imports.

Column (5) considers the case of no technological progress. In this case, investment in both nuclear and carbon capture is allowed, but prices for all energy capital are fixed at their 2020 level. Moreover, the implicit subsidy to renewables is removed. The zero emissions target implies that

[16] We also assume that coal-fired power generation is not replaced due to depreciation, hydropower is maintained, and that all nuclear power plants outside Fukashima are restarted.

the renewables share rises but to just 14% of generation. Clean firm sources - mostly nuclear - are required to make up the difference. Energy investment is significantly higher in the case as are prices, with production falling 30%. The consumption cost of zero emissions using currently technologies is around 1% or similar to the zero emissions with CCS scenario. The fact that the consumption cost is lower reflect the important role of nuclear in decarbonization.

Lastly column (6) considers the case of using only a subsidy to achieve zero emissions in power generation. A subsidy based approach requires a sharp increase in power generation investment that also increases overall investment. A subsidy approach significantly raises power generation (nearly doubles) and, therefore, boost output and production of the domestic tradable good. This limits the terms of trade and exchange rate appreciation relative to other scenarios. Lower electricity prices and higher output raises consumption, but by less than in the case of a fossil fuel tax. The subsidy leads to high a share of renewables in generation and excessively high levels of investment in steady state.

5.2 Transition path

Figure 4 shows the transition path of key macroeconomic aggregates and power generation in the BAU and zero emissions. The transition path is shown for the case of moderate complementarity and zero emissions using either nuclear power or carbon capture with CCS. The red line shows the transition path under the optimal climate policy subject to a zero emissions date and emissions target. The transition involves large increases in clean energy capital but declines in energy services provided to industry as electricity prices rise. The sharp discontinuities in energy prices and energy use occur around the zero emissions date - this is a function of modeling the zero emissions date as a constraint in time. The planner optimally accepts a more volatile path of energy prices and energy use.

Both consumption and gross value added fall by more than their long-run values, suggesting that the transition costs are first-order in comparison to the steady state costs. However, the magnitude of the fluctuations in both consumption and gross value added are modest. The real exchange rate appreciates relative to the BAU transition path, with the appreciation gradually increasing along the transition path as fossil fuel imports decline.

For this transition path, we compute the Lucas consumption-equivalent welfare cost. We know that the long-run cost of zero emissions is quite low - just 0.2% of BAU consumption. Both the BAU and zero emissions paths have consumption below their long-run, steady state level. As noted the zero emissions path in 4 involves a slow convergence of consumption to its long-run steady state. However, prior to the zero emissions date, levels of consumption are comparable across both transition paths. Therefore, the transition path welfare cost is *lower* than the long-run cost - just 0.1% of BAU consumption. The longer-run differences in consumption paths are relatively more

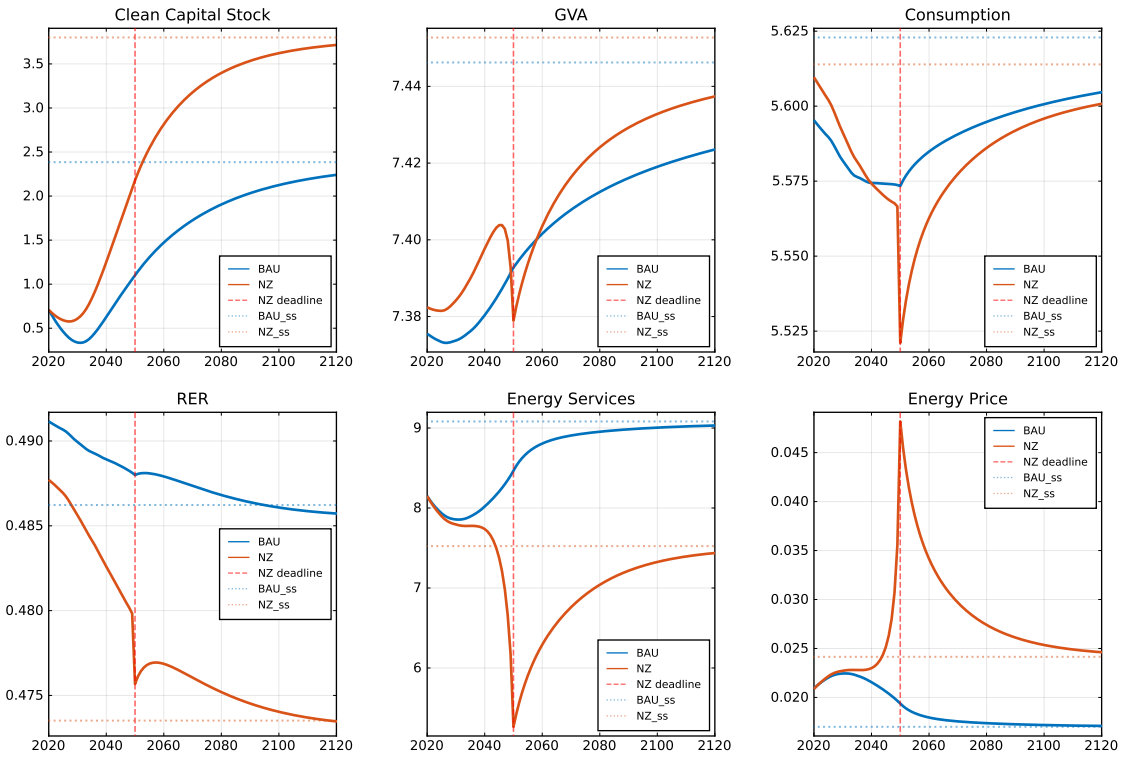


Figure 4: Transition path to zero emissions

highly discounted, further lowering the consumption cost.

It is worth underscoring that at these consumption costs, decarbonization of power generation may pass the cost-benefit test simply on based on conventional (non-greenhouse gas) air pollution abatement. Studies in the US estimate premature mortality of approximately 1600 persons per year as of 2021 due to coal power generation. Japan has a higher share of generation from coal. If per capita mortality rates are similar and with a conventional value of statistical life of $1-$10 million, decarbonization of power generation could save $800 million to $8 billion. For reference, Japan's PPP adjusted GDP is approximately $6 trillion, with consumption of approximately $4 trillion. A consumption cost of 0.1% of GDP falls within this range of estimated benefits.

5.3 Fossil fuel shocks

Table 6 shows the effects of fossil fuel price volatility on consumption and output volatility and the associated welfare effects. Energy price shocks are mitigated in the business-as-usual and zero emissions scenarios via lower exposure to volatile fossil fuel imports. In the BAU case, the falling price of solar and wind energy lowers the standard deviation of consumption by 30% as power generation becomes less dependent on coal and natural gas. It is worth emphasizing that fossil fuel shocks have large effects on both the import bill and electricity prices. We estimate that a one

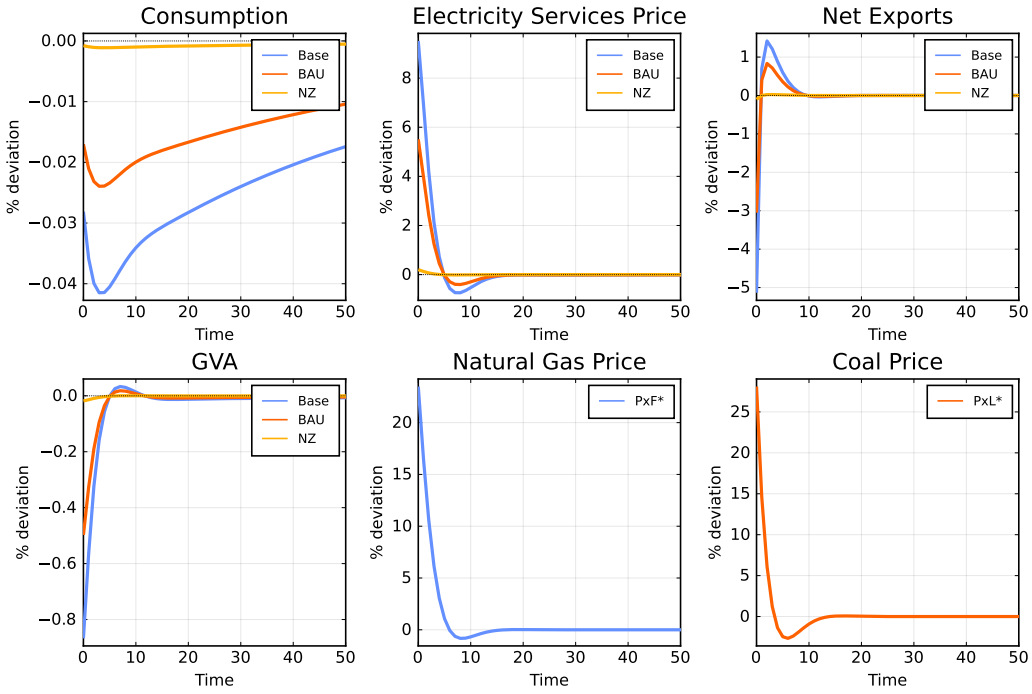


Figure 5: Impulse response to fossil fuel energy shock

standard deviation global energy shock raises natural gas and coal prices by about 25%. In the baseline (2020) calibration, this raises electricity prices by 8% and generates a modest recession (gross value added falls by 0.9% on impact). When nuclear power is fixed at its current level, natural gas consumption remains larger as carbon capture is used to complement renewables.

Figure 5 shows the impulse response of consumption, gross value added, electricity prices and exports to an estimated energy price shock. The large increase in the price of coal and oil leads to sizable increases in electricity prices; the effects on consumption are fairly persistent but quite small as exports are used to buffer the overall decline in domestic consumption of the home good. Even absent any policy-induced energy transition, electricity price sensitivity to a fossil fuel price shock is cut by about 1/3.

Under the business as usual case, exposure to natural gas falls and electricity prices become less sensitive. Under zero emissions scenarios, this sensitivity falls to nearly zero. Fossil fuel price shocks still have an effect since some substantial generation in the zero emissions case is being satisfied using natural gas with CCS. The reductions in consumption volatility are substantial relative to the BAU scenario. Under zero emissions with nuclear power, consumption volatility falls by 89% and under zero emissions with carbon capture, volatility falls by 64% as seen in Table 6.

These reductions in consumption volatility however generate only small welfare gains, with welfare losses largely dominated by lower long-run consumption. The reason welfare gains are

		Net zero	
	BAU	Nuclear	CCS
Consumption (% dev. from baseline)			
Non-stochastic	0.8	0.7	-0.6
E(C)	0.9	0.8	-0.5
Std(C)	-30.0	-89.0	-63.7
Welfare			
Transition cost (relative to BAU)		-0.1	-0.5
Gain from lower volatility		0.19	0.01

Table 6: Consumption volatility and welfare

small is because consumption volatility is already quite small in response to energy price shocks. In the model, households are able to buffer against energy shocks by increasing imports of the foreign consumption good. Moreover, as is standard in business cycle and consumption-based finance models, typically utility functions imply only modest costs of business cycle fluctuations. A utility function with energy in the consumption function or with increased curvature due to habits or Epstein-Zin preferences would imply more quantitatively significant welfare gains.

6 Conclusion

In this paper, we study the macroeconomic and energy security implications of the energy transition for a fossil fuel dependent small open economy. We characterize changes in output, consumption, exchange rates, trade balance and energy prices in a zero emissions steady state relative to a business-as-usual steady state that relies on fossil fuels in a real small open economy model. We also characterize the implications of the energy transition for the interest rate and current account along the transition path. We build a small open economy model with energy for both power generation and transportation to consider the quantitative implications of declining prices for renewable energy.

We show that a large number of countries are highly dependent on fossil fuel imports across the full range of fossil fuels. Fossil fuel imports are a significant share of the import bill and expose these countries to sizable energy price shocks like the 2022 energy price spike that occurred in the wake of Russia's invasion of Ukraine. Highly dependent fossil fuel importers include several advanced economies like Japan, South Korea, and Taiwan that collectively contribute significantly to global carbon dioxide emissions and that have made less progress in reducing emissions relative to the US or European Union.

Using our analytical model, we characterize the difference between a zero emissions and fossil fuel economy. The long-run cost of zero emissions can be decomposed into losses from higher investment and lower output, partially offset by lower fossil fuel costs. Terms of trade effects may further work to mitigate the long-run cost of achieving zero emissions. Changes in the real ex-

change rate are ambiguous, but the increased scarcity of the domestically produced goods along with the lower import bill for fossil fuels will tend to appreciate the real exchange rate. We establish a useful bound on long-run consumption losses; this bound helps illustrate why the long-run costs of zero emissions may be low. We even show the possibility that long-run consumption losses may be *negative*.

The analytical model can also be used to characterize the economy's transition path. We establish that a zero emissions target is akin to an anticipated productivity shock and an anticipated capital shock. Both of these shocks imply a reduction in future income. Households adjust by gradually lowering consumption and buffering future income losses by accumulating foreign assets. Thus, the energy transition has the property that the current account initially improves despite an increase in investment demand from the replacement of the fossil capital stock with the clean capital stock.

We enhance our model to better capture salient features of electric power generation and differences between clean and fossil power generation. In particular, we show how a variable elasticity of substitution production function can capture the difficulty of scaling renewable power generation from intermittent sources like solar and wind to generate electricity. We calibrate our model to match macroeconomic moments and data for electric power generation in Japan, and use technology projections for key carbon-free power generation technologies. We also introduce energy end-use for transportation to model the transition from internal combustion to electric vehicles as a major source of fossil fuel demand is for transportation.

Using our calibrated model, we find moderate costs of transitioning to net zero for Japan's electric power sector. Steady state consumption falls 1.7%, an order of magnitude larger than the decline in consumption for the US projected in Mehrotra (2024). This difference is driven primarily by lower solar and wind potential in Japan and higher reliance on more expensive clean-firm power sources. Relative to the business-as-usual case, fuel imports remain sizable in the net zero scenario since natural gas with carbon capture is the cheapest clean-firm power source. Both the business-as-usual and the zero emissions target feature large decreases in output and consumption volatility. The welfare cost is lower over the transition path due to discounting. The model finds welfare gains due to lower consumption volatility, but these gains are modest relative to the consumption cost of the zero emissions steady state.

We leave to future work consideration of the economic and geopolitical consequences of decarbonization for energy trade. As we showed earlier, energy production is highly concentrated among a small set of producers, who already collude to manage the price of oil. Decarbonization in advanced economies may have significant ramifications for global prices for oil, natural gas and coal (see, for example, Bistline et al. (2024)). For OPEC, global decarbonization undercuts current and future export earnings, and these producers may have incentives to increase their extraction rate and keep prices lower to maximize the intertemporal value of their rents. Conversely, as de-

carbonization technologies become cheaper, importers may seek to hasten the transition to lower their dependence on external energy. These strategic considerations appear a promising avenue for further work.

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