# The Global Impact of the Shale Boom

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**Abstract**

The shale revolution more than doubled US oil production between 2005 and 2019. We quantify its global effects using a multi-country input-output trade model in which OPEC is a dominant producer facing a competitive fringe of heterogeneous oil producers. The model yields a closed-form expression for OPEC's markup, which declines with the fringe's market share and supply elasticity. Shale expansion therefore disciplines OPEC's market power, while input-output linkages propagate lower energy prices across sectors and countries. We estimate technology-specific supply elasticities using asset-level extraction data. The shale revolution lowered the world oil price by 5.4 percent, the coal price by 1.6 percent, and OPEC's Lerner index by 1.55 percentage points. Shale gas lowered the US gas price by about 43 percent but gas prices elsewhere by only about 1 percent. Real income rose by 0.65 percent in the United States and fell by 1.2 percent in OPEC countries, while global $CO_2$ emissions increased by about 740 million tons annually.

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**JEL Classification:** E23, F17, F18, L13, Q43, Q54

# 1 Introduction

The United States underwent a transformation in energy production between 2005 and 2019. Advances in horizontal drilling and hydraulic fracturing unlocked vast shale oil and gas reserves, raising US crude oil production from 5 million barrels per day to 13 million barrels per day and turning the United States from the world's largest oil importer into a net exporter. The same technology also expanded US natural-gas supply. This joint shock reshaped fossil prices, altered manufacturing costs across countries, and changed the balance of market power between OPEC and the competitive oil fringe.

Despite the magnitude of this shock, no paper has quantified its global general-equilibrium effects on energy market power, production location, real income, and emissions. The central trade question is where energy-intensive production locates when upstream fossil costs move. Oil and gas matter through different channels. Oil is close to a globally arbitraged strategic commodity, so shale oil works through terms of trade and OPEC market power. OPEC prices as a dominant firm over a competitive fringe and charges a markup that falls as the fringe becomes more elastic, so the shale revolution, by making fringe extraction more elastic, compresses that markup and transmits the lower oil price through input-output linkages into manufacturing costs and the location of production across countries. Gas and coal are modeled as competitive but origin-differentiated fossil inputs, so shale gas works through the energy-cost exposure of downstream sectors and the reallocation of production across countries, and the gas-price decline is concentrated where shale operated rather than arbitraged into a single world price. These forces require a trade model with global input-output linkages.

Figure 1 summarizes the upstream facts that motivate the counterfactual. The US share of global oil and gas production rose sharply after the mid-2000s, narrowing the gap with OPEC. Within the United States, the production increase came from shale/tight oil and shale/tight gas rather than conventional expansion. The model uses these facts to discipline a no-shale economy and then asks how the shock propagates through global input-output linkages.

This paper provides the first quantitative assessment of how the shale revolution affected global energy market power, manufacturing production, welfare, and emissions. The paper makes three contributions.

First, we build a multi-country general equilibrium trade model with three elements absent from standard trade frameworks: a dominant firm (OPEC) facing a competitive oil fringe with heterogeneous extraction technologies, competitive gas and coal markets, and input–output linkages across sectors. The model yields a closed-form equilibrium oil markup in which OPEC's market power depends on its market share, the elasticity of oil demand,

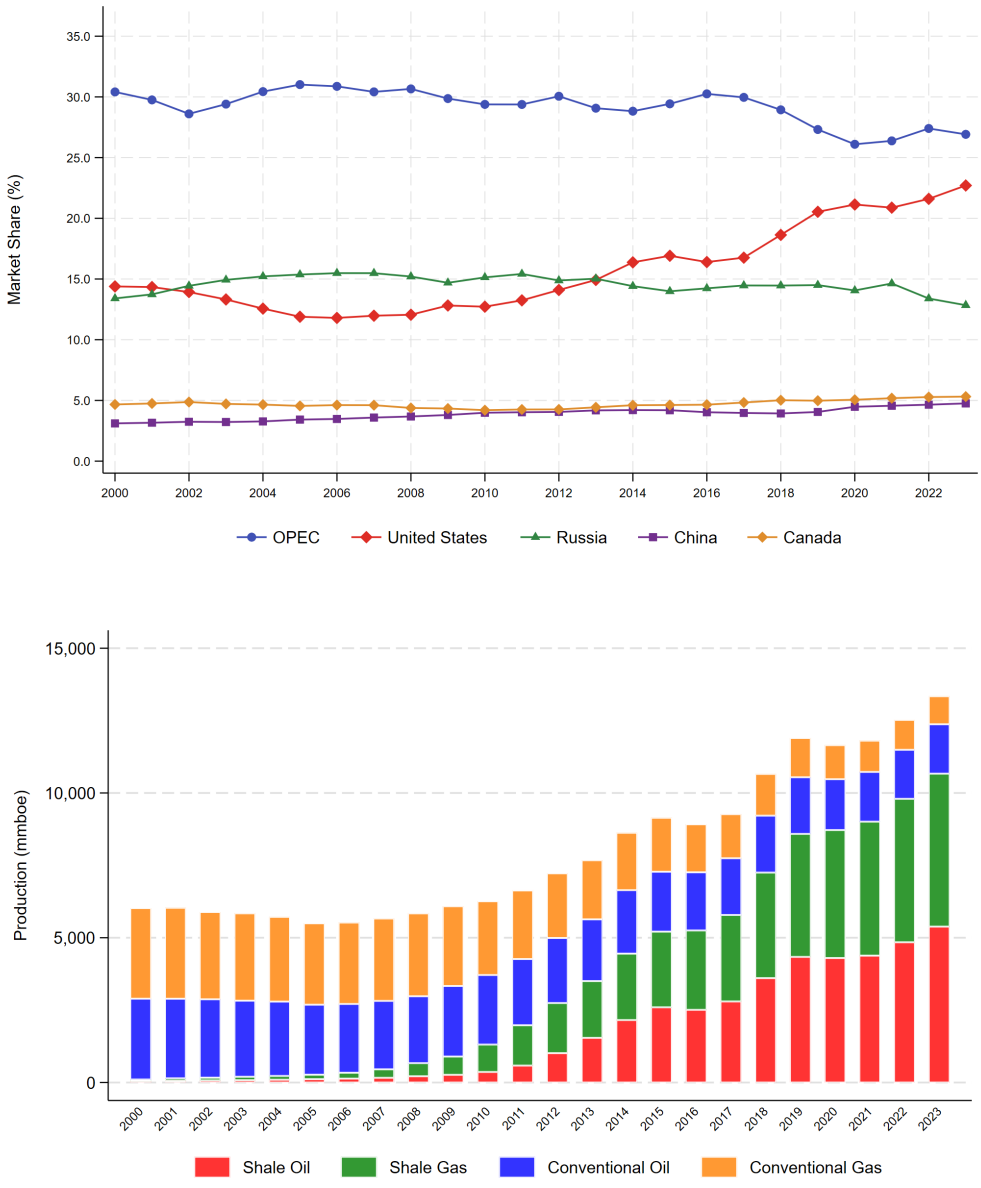



Figure 1: Motivating Facts: Market Structure and US Shale Production

*Notes:* The top panel plots global production shares of major oil and gas producers over time. The bottom panel decomposes US oil and gas production into conventional and shale/tight technology groups.

the competitive fringe's market share, and the local elasticity of fringe supply. The shale revolution enters through a quantity channel and an elasticity channel in oil, and through a competitive supply expansion in gas. The elasticity channel, in which technology entry raises the fringe's supply elasticity and compresses the markup, is the paper's distinctive mechanism, and we establish it as a comparative-statics proposition.

Second, we use field-level data from Rystad Energy to estimate the structural parameter governing supply elasticity, separately for oil and gas and for conventional and shale/tight extraction. The estimates exploit asset-level cost curves to recover long-run, capacity-inclusive elasticities of 1.32 for conventional oil, 1.79 for shale/tight oil, 1.74 for conventional gas, and 1.94 for shale/tight gas. The gap between the conventional and shale oil elasticities is the empirical micro-foundation of the market-power channel. Shale extraction is more elastic, so its entry into the fringe is what disciplines OPEC.

Third, we use the calibrated model to compare the observed 2019 world economy with a counterfactual in which the shale revolution did not occur, removing US shale capacity, reverting US extraction technology to conventional parameters, and solving for the new equilibrium using exact hat algebra.

Four findings emerge.

(1) The shale revolution lowered fossil prices through distinct oil and gas channels. In the baseline, observed 2019 oil prices are 5.37 percent lower than in the no-shale equilibrium and coal prices are 1.62 percent lower; gas is origin-differentiated, so the US gas price is about 43 percent lower while most other origins are near 1 percent lower (the trade-weighted world gas index is 8.47 percent lower). OPEC's oil Lerner index falls by 1.55 percentage points. Of the 5.37-percentage-point oil-price decline, the endogenous compression of OPEC's markup accounts for about 0.30 points, or roughly 6 percent, with the rest coming from the competitive-supply movement. This amplification gap, the difference between the price fall under an endogenous markup and under a fixed one, is the empirical signature of the market-power channel, and given the model's elastic oil demand it likely understates that channel.

(2) The oil and gas components move the economy through different mechanisms. The oil-only shock lowers the oil price by 3.26 percent and reduces the OPEC oil Lerner index by 1.36 percentage points. The gas-only shock lowers the gas price by 6.24 percent and has a much smaller direct effect on OPEC's oil markup. The quantity-only counterfactual accounts for most of the fossil-price movement, while the elasticity-only counterfactual is small for prices but still disciplines OPEC's markup.

(3) An exact decomposition of the welfare effect shows that the terms-of-trade channel dominates while the oil market-power channel, though a distinct welfare margin, is second

order. Net fossil exposure sorts the incidence between exporters that lose and importers that gain, and holding OPEC's markup fixed isolates the market-power margin, which is small, no more than about a tenth of a log point per country (OPEC −0.10, Russia +0.05), and operates as a transfer from OPEC to the competitive fringe.

(4) Production reallocates across countries and sectors along two margins, and the income and emissions effects are asymmetric. The genuinely fuel-intensive sector, refined petroleum, expands where shale fuel is cheap (USA +13.68 percent, Korea +8.14 percent), while the much larger set of low-fuel-share tradables moves the opposite way through real appreciation (USA basic metals −5.07 percent, USA computer and electronics −4.53 percent, with offsetting expansions in oil exporters such as Russia basic metals +4.82 percent and OPEC chemicals +4.96 percent). The US manufacturing declines reflect a real-appreciation channel rather than an energy-cost channel: the shale windfall raises US income and the US wage relative to the rest of the world, crowding out US low-fuel-share manufacturing, so the shock does not reshore all energy-intensive production to the United States. In the baseline calibration, the 14 OPEC market members are aggregated into a single OPEC bloc. The United States gains 0.65 percent, while the aggregate OPEC bloc loses 1.21 percent. Global $CO_2$ emissions rise by 738 $MtCO_2$ per year: oil emissions rise by 356 $MtCO_2$, gas emissions rise by 615 $MtCO_2$, and coal emissions fall by 233 $MtCO_2$.

**Related literature.** The literature on international trade with intermediate inputs, following Eaton and Kortum (2002) and Caliendo and Parro (2015), demonstrates how input-output linkages amplify the effects of cost shocks and create cascading comparative advantage. We extend this framework by introducing a dominant firm with market power in an upstream intermediate input market, where the competitive fringe has heterogeneous production technologies. This distinction matters because markups in a concentrated upstream market affect downstream manufacturing costs differentially across countries.

The energy economics literature has recognized the importance of market power in oil markets. Griffin (1985) tests models of cartel behavior; Asker et al. (2019) estimates misallocation from market power in oil extraction using field-level data; Bornstein et al. (2023) studies world oil market dynamics with heterogeneous fields. Our contribution is to embed the strategic oil market within a general equilibrium trade model, allowing us to trace how energy market structure affects manufacturing and welfare across countries through trade networks.

The industrial organization literature on oligopolistic competition provides our market structure. We adopt a dominant firm–competitive fringe market structure with heterogeneous technologies, following Encaoua and Jacquemin (1980). Our innovation is to derive how the

fringe's local aggregate supply elasticity enters the equilibrium markup and to show how technology entry (the shale revolution) disciplines market power through the supply elasticity channel.

Several papers study the shale revolution's economic effects. Feyrer et al. (2017) documents local economic effects of fracking; Kilian (2016) analyzes impacts on global oil markets; Newell and Prest (2019) documents productivity improvements in shale extraction; Balke et al. (2024) studies price effects. None of these papers embeds the shale revolution in a multi-country input-output trade model or quantifies how energy market power transmits into manufacturing production, welfare, and emissions across countries.

Finally, our paper relates to the literature on trade and the environment. Shapiro (2016) documents that trade policy implicitly subsidizes carbon emissions. We contribute a quantification of how a major energy shock redistributes emissions across countries through the reallocation of energy-intensive production.

The remainder of the paper proceeds as follows. Section 2 presents the model. Section 3 estimates the supply elasticities by fuel and technology from field-level cost data. Section 4 describes the calibration. Section 5 presents the quantitative analysis of the shale revolution. Section 6 concludes.

# 2 Model

The model places a strategic oil market inside a multi-country trade economy. OPEC is a dominant firm facing a competitive fringe of heterogeneous oil producers; gas and coal are competitive fossil inputs; and the non-energy economy has a standard Armington input-output structure. The purpose of this structure is to let a single concentrated upstream market transmit, through trade and input-output linkages, into manufacturing costs and the location of production across countries. We build on the Armington input-output framework of Garcia-Lembergman et al. (2025), inheriting their non-energy structure and departing from it in four ways: we split crude oil and natural gas into separate fossil inputs, replace competitive oil supply with the dominant-firm and competitive-fringe structure, model gas and coal as competitive markets, and set carbon taxes to zero. Oil, gas, and coal enter production through a CES energy bundle. We present a simple model first to convey the oil-market mechanism, then the full model.

## 2.1 A Simple Model

Before presenting the full model, we illustrate the core oil-market mechanism in a simplified setting with two types of oil producers (OPEC and a competitive fringe that includes the United States), $N$ countries that produce differentiated manufactured goods, one oil input, and one manufacturing sector.

**Oil production.** Each oil producer $i$ has technology $q_i = A_i m_i^{\nu_i} \ell_i^{1-\nu_i}$, yielding marginal cost

$$MC_i(q_i, w_i) = \frac{w_i}{(1-\nu_i) A_i^{1/(1-\nu_i)}} \left( \frac{q_i}{m_i} \right)^{\nu_i/(1-\nu_i)}. \tag{1}$$

OPEC chooses quantity strategically. All other producers, including the United States, take the world price as given and constitute the competitive fringe. Let $\mathcal{F}$ denote the set of fringe producers and define each producer's supply elasticity as $\epsilon_i = (1-\nu_i)/\nu_i$. Exact aggregate fringe supply is

$$Q_f(P_o, \{w_i\}_{i\in\mathcal{F}}) = \sum_{i\in\mathcal{F}} A_i^{1/\nu_i} m_i \left[ \frac{P_o(1-\nu_i)}{w_i} \right]^{(1-\nu_i)/\nu_i}. \tag{2}$$

The local aggregate fringe elasticity is

$$\varepsilon_f(P_o) \equiv \frac{\partial \ln Q_f(P_o)}{\partial \ln P_o} = \sum_{i\in\mathcal{F}} \frac{q_i(P_o)}{Q_f(P_o)} \frac{1-\nu_i}{\nu_i}. \tag{3}$$

For exposition, we sometimes summarize this local elasticity by the elasticity-equivalent representative parameter $\bar{\nu}_f(P_o) \equiv 1/[1+\varepsilon_f(P_o)]$. This object is not a production-weighted average of the primitive $\nu_i$'s.

**Manufacturing.** Country $n$ produces a differentiated good using labor and oil: $Y_n = A_n L_n^{\alpha} E_n^{1-\alpha}$. Unit cost is $c_n = A_n^{-1} w_n^{\alpha} P_o^{1-\alpha}$. Varieties are aggregated with CES elasticity $\sigma$.

**Equilibrium markup.** Rearranging OPEC's first-order condition gives the Lerner index:

$$\boxed{\frac{P_o - MC_O(q_O, w_O)}{P_o} = \frac{s_O}{\varepsilon_o + \varepsilon_f s_f}} \tag{4}$$

where $s_O$ is OPEC's market share, $s_f$ is the fringe share, $\varepsilon_f$ is the local aggregate fringe supply elasticity, and $\varepsilon_o$ is the oil demand elasticity. Equivalently, using the representative local shorthand, $\frac{1-\bar{\nu}_f}{\bar{\nu}_f} = \varepsilon_f$. With a single energy type and symmetric energy shares, world oil demand is unit elastic, $\varepsilon_o = 1$, because Cobb-Douglas manufacturing makes oil expenditure a

constant share of revenue, so quantity falls one-for-one with the price (Appendix E).

This Lerner index is the central object of the paper. OPEC has less room to price above marginal cost when its own share falls, the fringe share rises, or the fringe becomes more price elastic. The fringe is a collection of producers with heterogeneous technologies. Before the shale revolution, US production was conventional (high $\nu$), so fringe supply was relatively inelastic. When US producers adopt shale technology (low $\nu$ and high $(1-\nu)/\nu$), two margins move at once. Total fringe capacity expands, raising $s_f$ and lowering $s_O$; at the same time, the local aggregate fringe elasticity $\varepsilon_f$ rises. Both changes tighten the competitive constraint on OPEC and compress the markup. Figure 2 below illustrates this comparative static schematically, and Proposition 3 states it formally.

This simple model omits three features that matter quantitatively: multiple fossil inputs (which create substitution possibilities that affect $\varepsilon_o$), input-output linkages across manufacturing sectors, and cross-country heterogeneity in oil and gas intensity. The full model incorporates all three.

## 2.2 Environment

The world economy consists of $N$ countries indexed by $n, l \in \{1, \ldots, N\}$. OPEC, treated as a single player, acts as a dominant firm in the oil market. All non-OPEC oil producers, including the United States, are price takers in the competitive oil fringe. Gas and coal are supplied competitively. Each country has a representative household that supplies $\bar{L}_n$ units of labor inelastically.

Production occurs in energy sectors and non-energy sectors indexed by $k \in \{1, \ldots, K\}$. The fossil set is $\mathcal{S} = \{o, g, c\}$ for oil, gas, and coal, with world prices $(P_o, P_g, P_c)$. Manufacturing sectors produce differentiated goods where varieties from different countries are imperfect substitutes (Armington, 1969).

Each energy type $s \in \mathcal{S}$ has emission intensity $e_s$ (tons $CO_2$ per unit). Total global emissions are

$$\mathcal{E} = \sum_{n,k} \sum_{s} e_s E_{s,n,k} + \sum_{n} \sum_{s} e_s D_{s,n} \tag{5}$$

where $E_{s,n,k}$ is energy type $s$ used as an intermediate input in sector $k$ of country $n$, and $D_{s,n}$ is household direct consumption of fossil fuel $s$ in country $n$.

## 2.3 Households

The representative household in country $n$ has preferences

$$U_n = C_n - \delta_n \mathcal{E} \tag{6}$$

where $C_n$ is a consumption aggregate and $\delta_n \geq 0$ is the marginal damage from emissions. The consumption aggregate is Cobb-Douglas across manufactured goods and fossil fuels:

$$C_n = \prod_{k=1}^{K} C_{n,k}^{\beta_{n,k}} \prod_{s \in \mathcal{S}} D_{s,n}^{\mu_{n,s}}, \qquad \sum_k \beta_{n,k} + \sum_{s \in \mathcal{S}} \mu_{n,s} = 1 \tag{7}$$

where $C_{n,k}$ is consumption of manufactured good $k$, $D_{s,n}$ is direct household consumption of fossil fuel $s$, and $\beta_{n,k}$ and $\mu_{n,s}$ are expenditure shares.

Within each manufacturing sector, the household aggregates varieties from different countries using a CES aggregator:

$$C_{n,k} = \left[ \sum_{l=1}^{N} b_{l,k,n}^{1/\sigma_k} x_{l,k,n}^{(\sigma_k - 1)/\sigma_k} \right]^{\sigma_k/(\sigma_k - 1)} \tag{8}$$

where $\sigma_k > 1$ is the elasticity of substitution between varieties in sector $k$.

Household fossil fuel demand follows from Cobb-Douglas preferences:

$$P_{s,n}\, D_{s,n} = \mu_{n,s} X_n^C, \qquad s \in \mathcal{S}, \tag{9}$$

where $X_n^C$ is total final expenditure and $P_{s,n}$ is the price of source $s$ faced by country $n$. For oil this is the world price, $P_{o,n} = P_o$; for the origin-differentiated sources $s \in \{g, c\}$ it is the importer price index $P_{s,n}$ of equation (25). Household fossil fuel demand is unit-elastic with respect to both income and the price index it faces.

Total final expenditure in country $n$ is

$$X_n^C = w_n L_n + \Pi_n^o + \Pi_n^g + \Pi_n^c + T_n + \Lambda_n \tag{10}$$

where $w_n L_n$ is labor income, $\Pi_n^s$ is fossil-rent income from source $s$ (net of the government take), $T_n$ is the rebated government take defined in Section 2.4, and $\Lambda_n$ is the exogenous trade imbalance (calibrated from data as a residual).

Private real income in country $n$ is

$$W_n = \frac{X_n^C}{P_n} \tag{11}$$

where the ideal consumption price index is

$$P_n = \prod_k P_{k,n}^{\beta_{n,k}} \prod_{s \in \mathcal{S}} P_{s,n}^{\mu_{n,s}}, \tag{12}$$

with $P_{s,n}$ the source-$s$ price faced by country $n$ (the world oil price for $s = o$, the importer index of equation (25) for gas and coal). The corresponding indirect utility, including climate damages, is

$$V_n = W_n - \delta_n \mathcal{E}. \tag{13}$$

## 2.4 Government Take

Real fiscal regimes capture a large and heterogeneous share of resource revenue as *government take* (royalties, production-sharing, and resource taxes) that the state spends or saves rather than letting it accrue as private factor income. Each country $n$ and fuel $s$ levies a take $\tau_{n,s} \in [0, 1)$ on extraction revenue: the producer receives the net price $(1 - \tau_{n,s})P_{s,n}$ (as in the supply curves (20) and (24)), and the state rebates the take to that country's household,

$$T_n = \sum_{s \in \mathcal{S}} \tau_{n,s} \, P_{s,n} \, q_{n,s}, \tag{14}$$

where $q_{n,s}$ is country $n$'s output of fuel $s$. Each unit of fuel revenue $P_{s,n}q_{n,s}$ thus splits into government take $\tau_{n,s}$, producer rent $(1 - \tau_{n,s})\rho_{n,s}$, and extraction labor $(1 - \tau_{n,s})(1 - \rho_{n,s})$, where $\rho_{n,s} = \nu_{n,s} + \mu_{n,s}(1 - \nu_{n,s})$ is the rent share ($\mu_{n,s} = \mu_O$ for OPEC oil and zero for the competitive sources). The household receives producer rent *plus* the rebate, so its resource income from fuel $s$ is $[(1-\tau_{n,s})\rho_{n,s}+\tau_{n,s}]P_{s,n}q_{n,s}$. Because the take is a constant share, it does not enter any quantity response, the supply-elasticity identification, or the market-clearing prices. It re-routes *income* from the wage and the markup-leveraged rent toward the pure-revenue rebate, which raises resource exporters' exposure to the fuel-price swing the shale revolution drives.[1]

**Government take and the dominant-firm markup.** The take enters a price-taking producer and the dominant firm differently, and it is worth being explicit about the dominant

[1] A counterfactual that *changed* $\tau$ would reinstate a wedge in the supply response; the no-shale counterfactual holds $\tau$ fixed, so the take operates purely on the income margin.

firm. For a price taker (the competitive oil fringe and every gas and coal producer), a constant proportional take scales the net price to $(1-\tau)P$ and cancels from every quantity response, as above. For a dominant firm a genuine revenue tax would not cancel: were OPEC to face an external revenue tax $\tau_O$, its first-order condition would read $(1-\tau_O)\big(P_o+q_O\,dP_o/dQ\big) = MC_O$, and its Lerner index would be

$$\mu_O = \tau_O + (1-\tau_O)\,\frac{s_O}{\varepsilon_o + \varepsilon_f s_f}, \tag{15}$$

the sum of a fiscal wedge $\tau_O$ and the market-power wedge of Proposition 1. At the calibrated OPEC take this would raise the measured price–marginal-cost gap from 0.135 to 0.61 with no change in market power. We do not adopt this specification, because OPEC's take is not an external tax on an arm's-length producer: the national oil companies and the taxing state are the same sovereign, and the take is rebated to that same entity. OPEC therefore maximizes total sovereign revenue $P_o(Q)q_O - C_O$ with no net fiscal wedge, its effective take in the pricing problem is zero, and its Lerner index is the pure market-power wedge $\mu_O = s_O/(\varepsilon_o + \varepsilon_f s_f)$. The take we record for OPEC is an income-accounting split between rent and rebate, both of which accrue to the OPEC household, and does not distort its quantity choice. This is why the net-of-take price $(1-\tau)P$ enters the price-taking supply curves (20) and (24) but not OPEC's problem (34): the fringe are price takers facing a government, whereas OPEC is the government. We report $\mu_O = 0.135$ because it is OPEC's conduct markup, not a fiscal transfer the sovereign makes to itself. Either reading leaves the no-shale comparative static unchanged, since $\tau$ is held fixed and cancels in every hat.

## 2.5 Fossil Production with Heterogeneous Technologies

Each fossil producer $i$ combines reserves and labor according to

$$q_i = A_i m_i^{\nu_i} \ell_i^{1-\nu_i} \tag{16}$$

where $q_i$ is output (barrels of oil equivalent), $m_i$ is a fixed reserve or capacity endowment, $\ell_i$ is labor, $A_i$ is total factor productivity, and $\nu_i \in (0,1)$ is the reserve-intensity parameter.

The parameter $\nu_i$ governs the technology. Conventional extraction has higher $\nu_i$ and steeper marginal cost curves. Shale and tight extraction have lower $\nu_i$, making supply more responsive to price.

Cost minimization yields the cost function

$$C_i(q_i, w_i) = w_i \left(\frac{q_i}{A_i m_i^{\nu_i}}\right)^{1/(1-\nu_i)} \tag{17}$$

and marginal cost

$$MC_i(q_i, w_i) = \frac{w_i}{(1-\nu_i)A_i^{1/(1-\nu_i)}} \left(\frac{q_i}{m_i}\right)^{\nu_i/(1-\nu_i)}. \tag{18}$$

The supply elasticity with respect to price, holding wages fixed, is

$$\epsilon_{s,i} = \frac{1-\nu_i}{\nu_i}. \tag{19}$$

Technology heterogeneity, captured by differences in $\nu_i$, directly determines how responsive each producer is to price changes. The calibration maps Rystad elasticities into $\nu_i = 1/(1+\epsilon_i)$ separately for oil conventional, oil shale/tight, gas conventional, and gas shale/tight extraction.

## 2.6 Market Structure

The oil market has two types of producers.

**OPEC (dominant firm).** OPEC chooses quantity $q_O$ to maximize profit, taking into account its effect on the world price. Its technology parameter $\nu_O$ reflects conventional extraction.

**Competitive fringe.** All other producers, including the United States, take the world price as given. A fringe producer $f$ with technology $\nu_f$ supplies

$$q_f(P_o, w_f) = A_f^{1/\nu_f} m_f \left[\frac{(1-\tau_f)P_o(1-\nu_f)}{w_f}\right]^{(1-\nu_f)/\nu_f}, \tag{20}$$

where $(1-\tau_f)$ is the producer's net-of-take price share (Section 2.4).

Let $\mathcal{F}$ denote the set of fringe producers. Exact aggregate fringe supply is the sum of producer-level supplies:

$$Q_{fringe}(P_o, \{w_i\}_{i\in\mathcal{F}}) = \sum_{i\in\mathcal{F}} A_i^{1/\nu_i} m_i \left[\frac{(1-\tau_i)P_o(1-\nu_i)}{w_i}\right]^{(1-\nu_i)/\nu_i}. \tag{21}$$

This sum is generally not a single power function of $P_o$ when producers have different $\nu_i$'s. The relevant object for OPEC's pricing problem is the local aggregate fringe elasticity:

$$\varepsilon_f(P_o) \equiv \frac{\partial \ln Q_{fringe}(P_o)}{\partial \ln P_o} = \sum_{i\in\mathcal{F}} \frac{q_i(P_o)}{Q_{fringe}(P_o)} \frac{1-\nu_i}{\nu_i}. \tag{22}$$

When useful for exposition, define the elasticity-equivalent representative parameter

$$\bar{\nu}_f(P_o) \equiv \frac{1}{1+\varepsilon_f(P_o)}, \qquad \frac{1-\bar{\nu}_f(P_o)}{\bar{\nu}_f(P_o)} = \varepsilon_f(P_o). \tag{23}$$

Thus $\bar{\nu}_f$ is a local summary of the exact heterogeneous fringe supply curve, not a primitive average of the $\nu_i$'s.

The key feature of the fringe is that it contains producers with different technologies. Before the shale revolution, fringe production was predominantly conventional (high $\nu$ and low supply elasticity). After the shale revolution, a substantial share of fringe production uses shale technology (low $\nu$ and high supply elasticity), raising $\varepsilon_f$ and making aggregate fringe supply more elastic.

## 2.7 Origin-Differentiated Gas and Coal Markets

Gas and coal are supplied competitively, but unlike oil they are *origin-differentiated* in trade: U.S. pipeline gas, Qatari LNG, and Australian coal are imperfect substitutes shipped under distinct logistics, and the shale revolution is, mechanically, a large change in *where* gas and coal are produced. We therefore model each as a CES Armington aggregate over producing origins rather than a single homogeneous world good. (Oil retains a single world price and the dominant-firm structure of Section 2.6; Section 2.11 shows the markup formula and oil-demand elasticity are invariant to this choice.)

**Notation and nesting.** Two prices appear for each origin-differentiated source, so we fix them at the outset. The *origin price* $P_{s,o}$ is what producing origin $o$ sells at; the *importer index* $P_{s,i}$ of equation (25) is the CES price importer $i$ buys at. They are distinct—a country that both produces and consumes sells at its origin price and buys at its importer index—and coincide only in the homogeneous limit $\sigma_s \to \infty$. In expressions carrying a single country subscript, context fixes which is meant: household fuel demand (9) and the consumption price index (12) use the importer (buy) price, whereas the government take (14) and the fossil rents use the origin (sell) price a country's own producers receive. Because Armington shares are expenditure shares, each origin's market clears in *value*, not quantity. Finally, the origin (Armington) nest sits *below* the oil–gas–coal energy nest, so the within-source elasticities $\sigma_s$ never enter oil's demand elasticity or the dominant-firm markup (Section 2.11).

**Supply.** Each producing origin $o$ in source $s \in \{g, c\}$ has the competitive technology $q_{o,s} = A_{o,s} m_{o,s}^{\nu_{o,s}} \ell_{o,s}^{1-\nu_{o,s}}$ and supplies against its *own* price $P_{s,o}$:

$$q_{o,s}(P_{s,o}, w_o) = M_{o,s} \left( \frac{(1-\tau_{o,s}) P_{s,o} (1-\nu_{o,s})}{w_o} \right)^{(1-\nu_{o,s})/\nu_{o,s}}, \qquad s \in \{g, c\}, \tag{24}$$

where $M_{o,s} = A_{o,s}^{1/\nu_{o,s}} m_{o,s}$ is the origin-source endowment and $(1-\tau_{o,s})$ is the producer's net-of-take price share (the government take $\tau_{o,s}$ is defined in Section 2.4).

**Demand and the importer price index.** Importer $i$ combines source-$s$ fuel from origins $o$ in a CES bundle with Armington elasticity $\sigma_s > 1$ and baseline bilateral expenditure shares $\pi_{s,oi}$ (row-stochastic over $o$, including the domestic diagonal $o = i$). The price index importer $i$ faces for source $s$ is

$$P_{s,i} = \left( \sum_o \pi_{s,oi} \left( P_{s,o}\, \tau_{s,oi}^{\mathrm{tr}} \right)^{1-\sigma_s} \right)^{1/(1-\sigma_s)}, \tag{25}$$

with $\tau_{s,oi}^{\mathrm{tr}}$ the bilateral (iceberg) trade cost. This $P_{s,i}$ is the price that enters $i$'s energy bundle, household fuel demand, and consumption price index in place of the scalar $P_s$. The expenditure share of origin $o$ in $i$'s source-$s$ purchases is $\pi'_{s,oi} = \pi_{s,oi} (P_{s,o} \tau_{s,oi}^{\mathrm{tr}})^{1-\sigma_s} / \sum_{o'} \pi_{s,o'i} (P_{s,o'} \tau_{s,o'i}^{\mathrm{tr}})^{1-\sigma_s}$.

**Per-origin market clearing.** Each origin's market clears in value: origin $o$'s sales revenue equals the expenditure all importers direct to it,

$$P_{s,o}\, q_{o,s} \;=\; \sum_i \pi'_{s,oi}\, X_{s,i}, \qquad s \in \{g, c\}, \tag{26}$$

where $X_{s,i} = P_{s,i}\, Q_{s,i}$ is importer $i$'s total source-$s$ expenditure and $Q_{s,i}$ its CES quantity. Summing (26) over $o$ recovers aggregate source-$s$ clearing; the homogeneous-good model of a single world price $P_s$ is the limit $\sigma_s \to \infty$ (or a single origin). The system is not over-determined: writing $P_{s,o} = P_s\, r_{s,o}$, a single scalar level $P_s$ clears the aggregate source-$s$ value balance while the level-free relative prices $\{r_{s,o}\}$—normalized to a unit baseline-weighted geometric mean—clear the cross-origin dispersion in (26), so each source pins down one price level and $|O| - 1$ relative prices (Appendix K.1). Fossil rents accruing to origin $o$ are $\Pi_{o,s} = \nu_{o,s}(1-\tau_{o,s}) P_{s,o} q_{o,s}$, net of the government take.

## 2.8 Manufacturing Production

Manufacturing firms in country $n$, sector $k$ use constant returns to scale technology:

$$Y_{n,k} = A_{n,k} L_{n,k}^{\gamma_{\ell,nk}} E_{n,k}^{\gamma_{E,nk}} \prod_{r=1}^{K} M_{r,n,k}^{\gamma_{r,nk}} \tag{27}$$

where $L_{n,k}$ is labor, $E_{n,k}$ is composite energy, $M_{r,n,k}$ is intermediate input from sector $r$, and $\gamma_{\ell,nk} + \gamma_{E,nk} + \sum_r \gamma_{r,nk} = 1$.

The composite energy input aggregates oil, gas, and coal using CES:

$$E_{n,k} = \left[ \sum_{s \in \mathcal{S}} \alpha_{s,n,k}^{1/\sigma_E} E_{s,n,k}^{(\sigma_E - 1)/\sigma_E} \right]^{\sigma_E/(\sigma_E - 1)} \tag{28}$$

where $\sigma_E$ is the elasticity of substitution between energy types.

Cost minimization yields the energy price index

$$P_{E,n,k} = \left[ \sum_{s \in \mathcal{S}} \alpha_{s,n,k} P_{s,n}^{1-\sigma_E} \right]^{1/(1-\sigma_E)} \tag{29}$$

energy demand by type

$$E_{s,n,k} = \alpha_{s,n,k} \left( \frac{P_{s,n}}{P_{E,n,k}} \right)^{-\sigma_E} E_{n,k} \tag{30}$$

where $P_{s,n}$ is the source-$s$ price faced by country $n$: the world oil price for $s = o$, and the origin-differentiated importer index of equation (25) for gas and coal. and unit costs

$$c_{n,k} = \frac{1}{A_{n,k}} w_n^{\gamma_{\ell,nk}} P_{E,n,k}^{\gamma_{E,nk}} \prod_r P_{r,n}^{\gamma_{r,nk}}. \tag{31}$$

The Cobb-Douglas share constants are absorbed into $A_{n,k}$, so they do not appear in level notation and cancel in hats.

The source-$s$ expenditure share within the energy bundle is

$$\omega_{s,n,k} \equiv \frac{\alpha_{s,n,k} P_s^{1-\sigma_E}}{\sum_{r \in \mathcal{S}} \alpha_{r,n,k} P_r^{1-\sigma_E}} = \frac{P_s E_{s,n,k}}{P_{E,n,k} E_{n,k}}. \tag{32}$$

## 2.9 Trade

Manufacturing goods are subject to iceberg trade costs $\tau_{l,k,n} \geq 1$. The expenditure share of country $n$ on sector $k$ goods from country $l$ is

$$\pi_{l,k,n} = \frac{b_{l,k,n}(c_{l,k}\tau_{l,k,n})^{1-\sigma_k}}{\sum_i b_{i,k,n}(c_{i,k}\tau_{i,k,n})^{1-\sigma_k}} = \frac{b_{l,k,n}(c_{l,k}\tau_{l,k,n})^{1-\sigma_k}}{P_{k,n}^{1-\sigma_k}} \tag{33}$$

where $P_{k,n} = [\sum_l b_{l,k,n}(c_{l,k}\tau_{l,k,n})^{1-\sigma_k}]^{1/(1-\sigma_k)}$ is the sectoral price index.

## 2.10 Dominant Firm Pricing and Markups

OPEC maximizes profit taking into account its effect on price:

$$\max_{q_O} \pi_O = P_o(Q) \cdot q_O - C_O(q_O, w_O) \tag{34}$$

where $Q = q_O + Q_{fringe}(P_o)$ is total supply.

The first-order condition, derived in Appendix D, yields a closed-form Lerner index, identical in form to the simple-model expression (4) but now with the demand elasticity $\varepsilon_o$ and the fringe elasticity $\varepsilon_f$ determined in the full general equilibrium.

**Proposition 1** (Dominant-firm markup)**.** *OPEC's profit-maximizing Lerner index is*

$$\mu_O \equiv \frac{P_o - MC_O}{P_o} = \frac{s_O}{\varepsilon_o + \varepsilon_f s_f}, \tag{35}$$

*where $s_O = q_O/Q$ is OPEC's market share, $s_f = Q_{fringe}/Q$ is the fringe share, $\varepsilon_o$ is the perceived price elasticity of oil demand determined in general equilibrium (Section 2.11, equation (42)), and $\varepsilon_f = (1 - \bar{\nu}_f)/\bar{\nu}_f$ is the local aggregate fringe supply elasticity (22). The index is a ratio of same-numeraire nominal magnitudes built from dimensionless shares and elasticities, hence homogeneous of degree zero in nominal prices and invariant to the choice of numeraire.*

The markup is increasing in OPEC's market share, decreasing in demand elasticity, decreasing in the fringe market share, and decreasing in the local fringe supply elasticity $\varepsilon_f$. The last property is the mechanism through which the shale revolution disciplines market power: the entry of low-$\nu$ shale capacity into the fringe raises $\varepsilon_f$, compressing OPEC's markup. Figure 2 makes this visual. As the dominant firm, OPEC does not face world oil demand directly but the *residual demand* that remains after the competitive fringe has supplied what it wishes at each price; it chooses the quantity where marginal revenue equals

marginal cost and reads the price off this residual curve, so the vertical distance from price to marginal cost is its markup (panel a). Taking the pre-shale world as the baseline, the shale boom adds elastic, low-$\nu$ capacity to the fringe, which moves OPEC's residual demand in two ways at once: the extra supply pulls the curve inward, and the more price-responsive barrels flatten it (panel b). A smaller and flatter residual demand is precisely what erodes a dominant firm's ability to hold price above marginal cost, so the markup wedge narrows once shale enters. These are the same two channels that, in equation (35), raise $\varepsilon_f$ and lower $s_O$ and thereby reduce $\mu_O$.

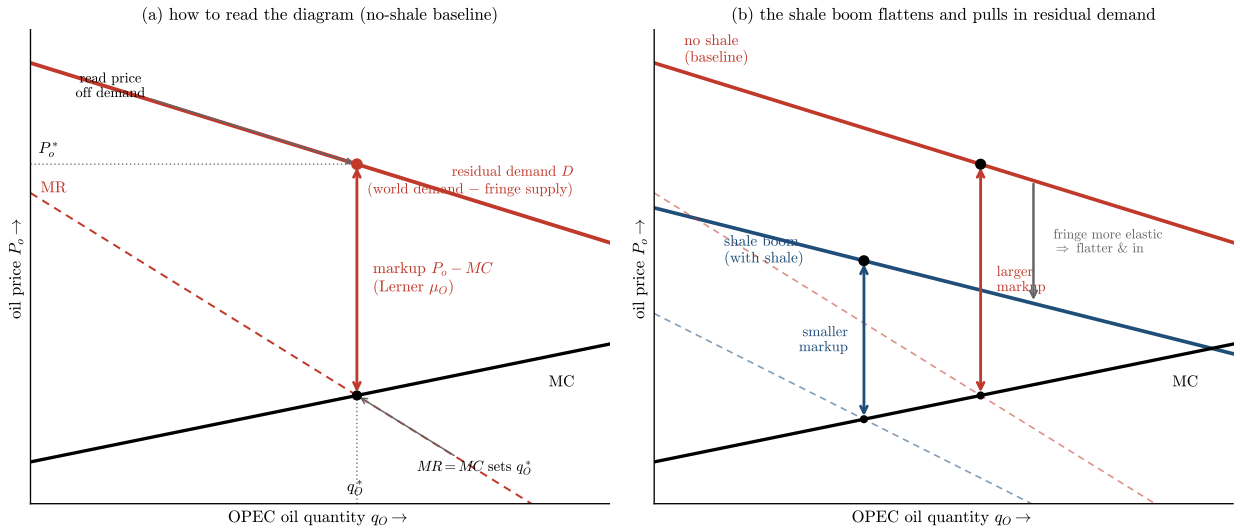



Figure 2: The Dominant-Firm Mechanism

*Notes:* Schematic; the axes are not to scale and no magnitudes are calibrated. As the dominant firm, OPEC faces a *residual demand* equal to world oil demand net of competitive-fringe supply. Panel (a): OPEC chooses the quantity at which marginal revenue (MR, dashed) equals marginal cost (MC) and reads the price off the residual demand curve above that quantity; the vertical gap between price and marginal cost is the markup $P_o - MC_O$, and the Lerner index is $\mu_O = (P_o - MC_O)/P_o$. Panel (b): starting from the pre-shale baseline, the shale boom adds low-$\nu$, high-elasticity capacity to the fringe, making fringe supply larger and more elastic, so OPEC's residual demand flattens and pulls in; the equilibrium price falls and the markup narrows. This is the comparative static in equation (35): a higher fringe elasticity $\varepsilon_f$, together with the lower OPEC share $s_O$ it induces, reduces $\mu_O = s_O/(\varepsilon_o + \varepsilon_f s_f)$.

**Conduct and the perceived demand elasticity.** OPEC is a price-maker in oil but a price-taker in every other market (labor, the competing fossil fuels, and non-energy goods), and treats aggregate wages $\{w_n\}$ and expenditures $\{X_{n,k}\}$ as given when choosing its quantity. The demand elasticity $\varepsilon_o$ in the markup (35) is accordingly the exact partial derivative of world oil demand with respect to $P_o$ at the equilibrium, holding the macroeconomic block fixed; it embeds within-energy substitution and cross-country trade reallocation (Section 2.11) but omits the income feedback that an oil-price change exerts through global incomes. This

is the subjective, perceived-demand conduct of the Cournot–Walras tradition (Negishi, 1961; Nikaido, 1975), with consistency between perceived and actual demand restored at the general-equilibrium fixed point. Because OPEC is a single large producer in a macro-relevant input rather than an atomistic firm in a continuum of sectors, we do *not* appeal to the "large in the sector, small in the economy" negligibility of Neary (2003, 2016) and Atkeson and Burstein (2008); the relevant precedent for a well-posed equilibrium with finitely many large, wage-taking firms and no continuum is d'Aspremont et al. (1989) and Nikaido (1975). OPEC's price-taking in labor is a separate assumption. Oil-extraction labor is a negligible share of any national labor market, so there is no monopsony wedge; we implement this by solving the oil oligopoly at given wages that subsequently clear.

Two consequences follow. First, the Lerner index $\mu_O = (P_o - MC_O)/P_o = s_O/(\varepsilon_o + \varepsilon_f s_f)$ is a ratio of same-numeraire nominal magnitudes built from dimensionless shares and elasticities; it is homogeneous of degree zero in nominal units and hence invariant to the choice of numeraire, so the numeraire-dependence that afflicts objective-demand oligopoly (Gabszewicz and Vial, 1972; Ginsburgh, 1994) does not affect the reported markup, even though equilibrium price *levels* do depend on it. Second, the omitted income (Ford) feedback (d'Aspremont et al., 1989; Azar and Vives, 2021) is a deliberate approximation, and the object that matters is its effect on the *shale comparative static* we report, not on the *level* of the markup. The level of any objective-demand markup is in fact numeraire-dependent, an instance of the Gabszewicz–Vial pathology, so we do not report one; the perceived-demand Lerner index, which rises from 13.5% to 15.0% when shale is removed, is the numeraire-invariant conduct primitive. To check that the income feedback does not overturn this comparative static, we trace OPEC's objective residual demand by re-solving the full general equilibrium under perturbed conduct, and we recompute the shale effect on its Lerner index under eight distinct numeraires and deflators: the US, Chinese, OPEC, German, and Japanese wages; a wage-bill-weighted world wage index; and the world and OPEC consumption price indices. Under every normalization the objective-conduct shale effect (1.9 to 2.5 percentage points) exceeds the perceived-demand effect (1.55 percentage points): the income feedback amplifies, and never reverses, shale's erosion of OPEC's market power. This is intuitive, since oil is scarcer and a larger share of world income once shale is removed, which strengthens the feedback precisely in the no-shale world. The perceived-demand conduct we adopt is therefore conservative, in that it understates the market power that shale erodes, and because the markup feeds the oil price, our headline real effects are conservative for the same reason.

## 2.11 Oil Demand Elasticity

In the full model with multiple energy types and trade, the oil demand elasticity $\varepsilon_o$ that enters the markup formula is endogenous. It depends on within-energy substitution, the energy share in manufacturing costs, and the competitive reallocation of manufacturing across countries. This section derives the formula; the complete step-by-step algebra is in Appendix E.

A key feature of the model is that oil trades at a single world price $P_o$. When $P_o$ changes, the unit costs of all countries move simultaneously. The output response of any country therefore depends on how that country's energy intensity compares with its trade competitors', not on its absolute energy intensity alone.

### 2.11.1 Definitions

Let total oil demand be

$$Q_o^d = \sum_{n,k} E_{o,n,k} + \sum_n D_{o,n}. \tag{36}$$

Throughout this subsection, the aggregation weights are shares of total oil demand:

$$\varphi_{o,nk}^{prod} \equiv \frac{E_{o,n,k}}{Q_o^d}, \qquad \varphi_{o,n}^{HH} \equiv \frac{D_{o,n}}{Q_o^d}, \qquad \sum_{n,k} \varphi_{o,nk}^{prod} + \sum_n \varphi_{o,n}^{HH} = 1. \tag{37}$$

Let $H \equiv \sum_n \varphi_{o,n}^{HH}$ denote the household share of total oil demand.

Define the oil expenditure share within the energy bundle from equation (32). For destination market $i$ in sector $k$, the import-weighted average oil intensity is

$$\Gamma_{k,i} \equiv \sum_l \pi_{l,k,i} \gamma_{E,lk} \omega_{o,l,k}. \tag{38}$$

This measures how the price index in market $(k,i)$ responds to $P_o$: $d\ln P_{k,i}/d\ln P_o = \Gamma_{k,i}$.

For origin country $n$ in sector $k$, the export-destination-weighted competitor intensity is

$$\bar{\Gamma}_{n,k} \equiv \sum_i \frac{R_{n,k,i}}{R_{n,k}} \Gamma_{k,i} \tag{39}$$

where $X_{i,k}$ is destination $i$'s total expenditure on sector $k$ goods, $R_{n,k,i} = \pi_{n,k,i} X_{i,k}$ is country $n$'s revenue from selling sector $k$ goods to destination $i$, and $R_{n,k} = \sum_i R_{n,k,i}$ is total sector $k$ revenue. The difference $\gamma_{E,nk}\omega_{o,n,k} - \bar{\Gamma}_{n,k}$ measures how much more (or less) oil-intensive country $n$ is relative to its competitors in sector $k$.

### 2.11.2 Matrix Form

Index country-sector cells by $m = (n, k)$. Let $\boldsymbol{\varphi}_o^{prod}$, $\boldsymbol{\omega}_o$, $\boldsymbol{\gamma}_E$, and $\boldsymbol{\sigma}$ denote cell-level vectors, with $\boldsymbol{\sigma}_{(n,k)} = \sigma_k$, and define direct oil exposure $\mathbf{x} \equiv \boldsymbol{\gamma}_E \odot \boldsymbol{\omega}_o$. The matrix $B$ maps direct oil exposure into export-weighted competitor exposure:

$$B_{(n,k),(l,r)} \equiv \mathbf{1}\{r = k\} \sum_i \frac{R_{n,k,i}}{R_{n,k}} \pi_{l,k,i}. \tag{40}$$

Thus $B\mathbf{x} = \bar{\boldsymbol{\Gamma}}$ and $(I - B)\mathbf{x}$ is relative oil exposure. Holding wages, expenditure, other energy prices, and sectoral price indices fixed, the production contribution to oil demand elasticity is

$$\varepsilon_o^{prod} = (\boldsymbol{\varphi}_o^{prod})' \left[\sigma_E \mathbf{1} - (\sigma_E - 1)\boldsymbol{\omega}_o + (\boldsymbol{\sigma} - \mathbf{1}) \odot (I - B)(\boldsymbol{\gamma}_E \odot \boldsymbol{\omega}_o)\right]. \tag{41}$$

The first two terms capture within-energy substitution and Cobb-Douglas energy expenditure. The last term captures trade reallocation toward less oil-intensive suppliers. Since the production weights are normalized by total oil demand, $\varepsilon_o^{prod}$ is already scaled by the production-demand share $1 - H$. Household oil demand is Cobb-Douglas and unit-elastic, so the aggregate elasticity is

$$\boxed{\varepsilon_o = \varepsilon_o^{prod} + \mathbf{1}'\boldsymbol{\varphi}_o^{HH}.} \tag{42}$$

Appendix E gives the cell-level derivation of equation (41).

### 2.11.3 Special Cases

Two limiting cases bracket the economics of the formula; two further nesting checks, which confirm that it recovers familiar structures, are deferred to Appendix E.

*Single energy type with symmetric intensity* ($\omega_{o,n,k} = 1$ for all $n, k$, $H = 0$). Within-energy substitution vanishes, the expenditure effect contributes 1, and competitive reallocation is zero: $\varepsilon_o = 1$. This is the simple model of Section 2.1.

*Perfect energy substitutes* ($\sigma_E \to \infty$). If a positive share of total oil demand comes from production cells with $\omega_{o,n,k} < 1$, firms can substitute away from oil toward gas and coal with arbitrarily large elasticity. In that limit, $\varepsilon_o$ diverges and oil market power disappears, apart from the knife-edge case in which all oil demand is household demand or production demand with $\omega_{o,n,k} = 1$.

The markup of Proposition 1, with the demand elasticity fully expanded, is

$$\mu_O = \frac{s_O}{\varepsilon_o(\sigma_E, \{\sigma_k\}, \{\omega_{o,n,k}\}, \{\gamma_{E,nk}\}, \{\bar{\Gamma}_{n,k}\}, H) + \varepsilon_f s_f} \tag{43}$$

revealing how demand-side substitution (through $\sigma_E$ and $\sigma_k$), household demand (through $H$), cross-country heterogeneity in energy intensity (through $\bar{\Gamma}$), and supply-side technology heterogeneity (through the local aggregate fringe elasticity $\varepsilon_f$) jointly determine equilibrium market power.

**Invariance to origin-differentiated gas and coal.** The markup formula and the elasticity $\varepsilon_o$ are unchanged by the origin-differentiation of gas and coal (Section 2.7). Three features account for this. First, the origin (Armington) nest sits *below* the oil–gas–coal energy nest: oil substitutes against the gas and coal aggregates, so the within-source elasticities $\sigma_{\text{gas}}, \sigma_{\text{coal}}$ never enter $\varepsilon_o$, which depends only on oil's expenditure share $\omega_{o,n,k}$ within the bundle and on $\sigma_E$. Second, $\varepsilon_o$ is the perceived residual-demand elasticity, derived holding the other energy prices fixed; the one place origin-differentiation could enter is the general-equilibrium response of the gas and coal price indices to the oil price, which is what this elasticity holds fixed. Third, the trade-reallocation term runs on the *goods* trade shares $\pi_{l,k,i}$ and elasticities $\sigma_k$, a different nest from energy origin. Every input to $\varepsilon_o$ is therefore evaluated where the origin indices equal one, so the baseline $\varepsilon_o$ and Lerner index are numerically identical to the homogeneous-good model, and in the counterfactual the markup moves only second order, through oil's energy-expenditure share at the new gas and coal indices (the no-shale Lerner effect is 1.55 points, against 1.62 in the homogeneous model). This invariance relies on oil remaining a single world market; differentiating oil by origin would instead add the oil-origin elasticity to OPEC's residual demand and modify the markup formula.

## 2.12 Equilibrium and Welfare

An equilibrium consists of wages $\{w_n\}$, fossil prices $(P_o, P_g, P_c)$, manufacturing prices $\{P_{k,n}\}$, sectoral expenditures and outputs $\{X_{n,k}, Y_{n,k}\}$, fossil quantities, and trade shares such that households optimize, firms minimize costs, OPEC satisfies its first-order condition, competitive fossil producers set price equal to marginal cost, and all markets clear.

Let $X_{n,k}$ denote country $n$'s total absorption of sector-$k$ goods. It is the sum of final expenditure and intermediate demand:

$$X_{n,k} = \beta_{n,k} X_n^C + \sum_r \gamma_{k,nr} c_{n,r} Y_{n,r}. \tag{44}$$

For each origin $l$ and sector $k$, goods-market clearing requires

$$c_{l,k} Y_{l,k} = \sum_n \pi_{l,k,n} X_{n,k}. \tag{45}$$

Labor markets clear country by country:

$$\bar{L}_n = \sum_k L_{n,k} + \ell_n^o + \ell_n^g + \ell_n^c, \tag{46}$$

where $\ell_n^s$ is labor used in fossil source $s$ by producers located in country $n$. The oil market clears at the strategic price:

$$q_O + Q_{fringe}(P_o, \{w_i\}_{i\in\mathcal{F}}) = \sum_{n,k} E_{o,n,k} + \sum_n D_{o,n}. \tag{47}$$

Gas and coal are competitive fossil markets:

$$\sum_j q_{j,s}(P_s, w_j) = \sum_{n,k} E_{s,n,k} + \sum_n D_{s,n}, \qquad s \in \{g, c\}. \tag{48}$$

Final expenditure satisfies the income identity in equation (10), with fossil rents accruing to the countries that own each source and the trade-imbalance wedge $\Lambda_n$ held fixed in counterfactuals. These level conditions, together with household demand, firm cost minimization, and the OPEC first-order condition, define the economy. Appendix G gives the associated optimization details and Appendix H gives the exact-hat system used for computation.

We report two welfare-related objects. The first is private real income:

$$W_n = \frac{X_n^C}{P_n} = \frac{w_n L_n + \Pi_n^o + \Pi_n^g + \Pi_n^c + \Lambda_n}{\prod_k P_{k,n}^{\beta_{n,k}} \cdot P_o^{\mu_{n,o}} \cdot P_g^{\mu_{n,g}} \cdot P_c^{\mu_{n,c}}} \tag{49}$$

where $\Lambda_n$ is the exogenous trade imbalance. The second is indirect utility including climate damages:

$$V_n = W_n - \delta_n \mathcal{E}. \tag{50}$$

The private real-income change from a counterfactual is

$$\frac{W_n'}{W_n} = \frac{\hat{X}_n}{\hat{P}_n} \tag{51}$$

where hats denote counterfactual-to-baseline ratios and $\hat{P}_n = \prod_k \hat{P}_{k,n}^{\beta_{n,k}} \cdot \hat{P}_o^{\mu_{n,o}} \cdot \hat{P}_g^{\mu_{n,g}} \cdot \hat{P}_c^{\mu_{n,c}}$.

Logarithmically differentiating equation (49) gives an exact decomposition of the real-

income change into an income side and a cost-of-living side:

$$d\ln W_n = \underbrace{\lambda_n^w\, d\ln w_n + \sum_{s\in\{o,g,c\}} \theta_n^s\, d\ln \Pi_n^s}_{\text{income: wage and fossil rents}} - \underbrace{\sum_k \beta_{n,k}\, d\ln P_{k,n}}_{\text{non-energy cost of living}} - \underbrace{\sum_{s\in\{o,g,c\}} \mu_{n,s}\, d\ln P_s}_{\text{fossil cost of living}}, \quad (52)$$

where $\lambda_n^w$ and $\theta_n^s$ are the shares of labor income and source-$s$ fossil rents in absorption, $\beta_{n,k}$ and $\mu_{n,s}$ are consumption shares, and the trade imbalance $\Lambda_n$ is held fixed. Each non-energy price index $P_{k,n}$ is a CES aggregate of domestic and imported varieties, so the term $d\ln P_{k,n}$ separates exactly into a domestic-cost component and an import-price (terms-of-trade) component. Equation (52) is the exact first-order welfare decomposition; Table 13 reports its finite-change counterpart, with each term evaluated at the counterfactual equilibrium.

Two features of these income shares shape the welfare incidence. First, the model has a single composite primary factor, so $w_n L_n$ is value added, the combined return to labor and capital, rather than a narrow wage bill. We set the household's labor-income share $\lambda_n^w$ equal to the production-side value added that clears the factor market, so the same composite-factor income that the wage $\hat{w}_n$ prices in the labor market is the income that enters the budget. Second, the fossil-rent shares $\theta_n^s$ are the model's own structural mining rents, the scarcity rent $\nu_s$ of each producer's revenue plus OPEC's markup, so the rent the household receives equals the rent the production side generates and the residual $\Lambda_n$ is the country's trade imbalance. These structural rent shares are smaller than the World Bank's natural-resource rents, which are a broader series that also includes coal, mineral, and forest rents; we use that series only as an external cross-check, not as a calibration target. A robustness specification that instead anchors the rent shares to the external series, holding the labor alignment fixed, deepens the losses of the oil and gas exporters but leaves the price, markup, and reallocation results unchanged.

Substituting out the endogenous wage and rents with factor-market clearing gives equation (52) a sharper reading: welfare moves with the country's net trade positions, and a single distortion survives the world aggregation.

**Proposition 2** (Terms of trade and the single distortion)**.** *The exact first-order welfare change* (52) *reorganizes, country by country, into terms-of-trade revaluations plus a competitive wage residual,*

$$d\ln W_n = \underbrace{-\sum_k \mathrm{nm}_{n,k}\, d\ln P_{k,n}^{\mathrm{imp}}}_{\textit{goods terms of trade}} + \underbrace{\sum_{s\in\{o,g,c\}} \mathrm{nx}_{n,s}\, d\ln P_{s,n}}_{\textit{fossil terms of trade}} + \underbrace{\left(\lambda_n^w - \tilde{\beta}_n^{\mathrm{VA}}\right) d\ln w_n}_{\textit{wage residual}},$$

*where* $\mathrm{nm}_{n,k}$ *is country* $n$*'s net non-energy import share of absorption,* $\mathrm{nx}_{n,s} = \Theta_n^s - \mu_{n,s}$ *is its net fossil-export share with fuel-revenue exposure* $\Theta_n^s = [(1-\tau_{n,s})\rho_{n,s} + \tau_{n,s}]P_{s,n}q_{n,s}/X_n^C$ *and rent share* $\rho_{n,s} = \nu_s + \mu_{n,s}(1-\nu_s)$*,* $P_{k,n}^{\mathrm{imp}}$ *is the imported-variety component of the sectoral price index, and* $\tilde{\beta}_n^{\mathrm{VA}}$ *is the input–output-adjusted value-added cost share. The two terms-of-trade blocks are pure international transfers: weighted by absorption and summed across countries, they cancel up to the fixed imbalances* $\{\Lambda_n\}$*, and the only component that does not cancel is the oil markup,*

$$\sum_n X_n^C \, d\ln W_n \;=\; \mu_O \, P_o \, dq_O, \qquad \mu_O = \frac{s_O}{\varepsilon_o + \varepsilon_f s_f},$$

*with* $dq_O$ *the change in OPEC's output.*

The decomposition isolates three features of the welfare incidence. The government take $\tau_{n,s}$, held fixed, contributes no efficiency term: it cancels in every quantity and market-clearing hat and enters welfare only through the income weight $\Theta_n^s$. The scarcity rents $\nu_s$ enter only as a revaluation of the fixed reserve endowment inside $\mathrm{nx}_{n,s}$. The wage residual $(\lambda_n^w - \tilde{\beta}_n^{\mathrm{VA}})\, d\ln w_n$ vanishes under balanced trade with a single mobile factor and is otherwise carried explicitly. The lone efficiency term $\mu_O P_o \, dq_O$ is the welfare counterpart of the market-power channel in Proposition 3: removing shale raises $\mu_O$ and restricts OPEC's output, the same output restriction that Corollary 1 measures as the markup-amplification gap.

**Remark 1.** Proposition 2 is a structural reorganization of the exact identity, not a closed-form sufficient statistic: it does not collapse to the formula $\hat{W}_n = \lambda_{nn}^{-1/\varepsilon}$ of Arkolakis et al. (2012). The oil markup has no domestic-trade-share representation, fixed-factor fossil rents make the net fossil position first-order, oil clears at a single world price with no domestic oil share, and input–output linkages with imbalanced trade keep the wage residual alive. Equation (52) is the exact first-order decomposition; Table 13 reports its finite-change counterpart, evaluated at the counterfactual equilibrium.

For the climate-damage utility, the natural counterfactual object is a level change rather than a ratio:

$$\Delta V_n = W_n(\hat{W}_n - 1) - \delta_n(\mathcal{E}' - \mathcal{E}). \tag{53}$$

## 2.13 Counterfactuals in Exact Hats

We solve counterfactuals using exact hat algebra. Hats denote counterfactual-to-baseline ratios, $\hat{x} \equiv x'/x$. The objects taken from the baseline economy are expenditure shares, cost shares, trade shares, energy shares, income shares, and physical fossil-supply shares. The objects solved in each counterfactual include wages, sectoral outputs, fossil prices and quantities, OPEC's markup, oil demand elasticity, and the local fringe elasticity.

The core manufacturing hats are standard:

$$\hat{c}_{n,k} = \hat{A}_{n,k}^{-1} \hat{w}_n^{\gamma_{\ell,nk}} \hat{P}_{E,n,k}^{\gamma_{E,nk}} \prod_r \hat{P}_{r,n}^{\gamma_{r,nk}}, \qquad \hat{P}_{E,n,k} = \left( \sum_{s \in \mathcal{S}} \omega_{s,nk} \hat{P}_s^{1-\sigma_E} \right)^{1/(1-\sigma_E)}, \tag{54}$$

$$\pi'_{l,k,n} = \frac{\pi_{l,k,n} (\hat{c}_{l,k} \hat{\tau}_{l,k,n})^{1-\sigma_k}}{\sum_i \pi_{i,k,n} (\hat{c}_{i,k} \hat{\tau}_{i,k,n})^{1-\sigma_k}}, \qquad \hat{W}_n = \frac{\hat{X}_n}{\hat{P}_n}. \tag{55}$$

The oil block is recomputed at counterfactual prices:

$$\mu'_O = \frac{s'_O}{\varepsilon'_o + \varepsilon'_f s'_f}. \tag{56}$$

Thus $s'_O$, $s'_f$, $\varepsilon'_o$, $\varepsilon'_f$, and $\mu'_O$ are equilibrium objects, not parameters held fixed from the baseline. The no-shale shock changes US shale/tight oil and gas capacity and technology assignments; the equilibrium then updates fossil supply, demand, wages, trade shares, and income consistently. Appendix H reports the full exact-hat system, including goods and labor clearing, fossil profit hats, the counterfactual oil-demand elasticity update, and the numerical fixed-point algorithm.

## 2.14 Technology Entry and Market Power

The following assumption and propositions characterize how technology heterogeneity shapes equilibrium outcomes. We work locally around the oil-market equilibrium under standard regularity.

**Assumption 1** (Local regularity)**.** At the oil-market equilibrium: (i) oil demand is downward sloping, $\varepsilon_o > 0$; (ii) fringe supply is upward sloping, $\varepsilon_f > 0$; (iii) OPEC's marginal cost is nondecreasing in $q_O$ and is not shifted up by fringe entry; and (iv) OPEC's second-order condition holds, so its residual marginal revenue cuts marginal cost from above and the equilibrium is locally unique and stable.

**Proposition 3** (Technology Entry, Prices, and Market Power)**.** *Let Assumption 1 hold and let a marginal mass of shale capacity enter the competitive fringe with local supply elasticity $\varepsilon_h > \varepsilon_f$. Then, to first order around the equilibrium:*

1. Elasticity channel: *the local aggregate fringe elasticity rises, $\varepsilon_f^{new} > \varepsilon_f$;*
2. Price channel: *the equilibrium oil price falls, $P'_o < P_o$, because entry shifts OPEC's residual demand inward and makes it more elastic, and OPEC's marginal cost does not rise;*

*3.* Market-power channel: *OPEC's Lerner index falls, $\mu_O' < \mu_O$, whenever*

$$\frac{s_O'}{s_O} < \frac{\varepsilon_o' + \varepsilon_f' s_f'}{\varepsilon_o + \varepsilon_f s_f}, \tag{57}$$

*which holds in the shale mechanism because entry lowers OPEC's share ($s_O' < s_O$) while raising the competitive constraint ($\varepsilon_f' s_f' > \varepsilon_f s_f$).*

**Corollary 1** (Markup amplification)**.** *Let $dP_o^{\text{fix}}$ denote the equilibrium oil-price change induced by entry when OPEC's markup is held at its baseline value, and $dP_o^{\text{endog}}$ the change when the markup adjusts as in Proposition 3. Under Assumption 1, $|dP_o^{\text{endog}}| > |dP_o^{\text{fix}}|$: the endogenous decline in OPEC's markup amplifies the price fall, because a lower markup moves OPEC's effective supply outward at any given price. The fixed-markup counterfactual in Section 5.2 measures exactly this amplification gap.*

Proposition 3 and Corollary 1 are proved in Appendix I. The proof updates the heterogeneous fringe through its local supply elasticity rather than a production-weighted average of the primitive $\nu$'s, which is generally inconsistent with the exact aggregate supply curve.

**Proposition 4** (Output Response in a World Market)**.** *Holding destination-sector expenditures, wages, other energy prices, and non-energy input price indices fixed, the local output response of country $n$ in sector $k$ to a change in $P_o$ is*

$$\frac{d \ln Y_{n,k}}{d \ln P_o} = -\sigma_k \gamma_{E,nk} \omega_{o,n,k} + (\sigma_k - 1)\bar{\Gamma}_{n,k}. \tag{58}$$

*The first term is the direct cost effect. The second offsets it by competitors' average cost response. Only the relative cost change moves trade shares.*

*Proof.* See Appendix F. □

# 3 Estimating Supply Elasticities by Technology

The fossil-supply block is disciplined by direct, field-level estimates of supply elasticities. This is the paper's empirical contribution: rather than calibrating a single fossil-supply elasticity from external references, we estimate the elasticity separately for conventional and shale/tight extraction, and separately for oil and gas, from the marginal-cost curves of essentially the universe of producing assets. These four elasticities are the same objects that map into the reserve-intensity parameters $\nu_i$, the local aggregate fringe elasticity $\varepsilon_f$, and, through the dominant-firm first-order condition, OPEC's equilibrium markup. Because the shale

revolution enters the model as a shift in the technology composition of supply, estimating how much more elastic shale extraction is than conventional extraction is what gives the counterfactual its quantitative content.

## 3.1 From Cost Curves to the Model's Supply Elasticity

The extraction technology in equation (16) implies the constant supply elasticity $\epsilon_i = (1-\nu_i)/\nu_i$ in equation (19). In that technology, marginal cost in equation (18) rises in the producer's own *production-to-reserve intensity* $q_i/m_i$ at the log-linear rate $\nu_i/(1-\nu_i) = 1/\epsilon_i$, so the structurally exact regressor for the slope $\beta = \nu_i/(1-\nu_i)$ is $\ln(q_i/m_i)$. We instead recover this slope from a field-level cost curve, sorting assets from lowest to highest extraction cost and tracing how marginal cost rises with cumulative output. Under the interpretive assumptions stated in Section 3.3 the cost-curve slope equals $1/\epsilon_i$; it is the reduced-form counterpart of the intensity regression, standard in the field-level cost-curve literature, and we adopt it because cumulative production along the sorted cost curve is directly observed for essentially the universe of producing assets.

Concretely, within each fuel–technology group we estimate

$$\ln(\text{Marginal Cost}_g) = \beta \ln(\text{Cumulative Production}_g) + \gamma_r + u_g, \qquad \widehat{\epsilon} = \frac{1}{\widehat{\beta}}, \qquad \widehat{\nu} = \frac{\widehat{\beta}}{1+\widehat{\beta}}, \tag{59}$$

where $g$ indexes cost bins formed by ranking assets on marginal extraction cost, $\gamma_r$ are region fixed effects, and the supply elasticity is the reciprocal of the estimated cost-curve slope. A flatter cost curve (smaller $\beta$) corresponds to a more elastic, lower-$\nu$ technology. We estimate equation (59) four times: conventional oil, shale/tight oil, conventional gas, and shale/tight gas.

## 3.2 Data and Estimation

**Data.** We use field/asset-level production and cost data from Rystad Energy's UCube, which covers essentially all producing oil and gas fields worldwide. The cost variable is the marginal extraction cost (Rystad `ap_costofprod4_1`), which is *capital inclusive*: it comprises facility capex, well capex, abandonment cost, production opex, and SG&A opex, and excludes transport costs, taxes, and royalties. Using a capex-inclusive concept rather than cash operating cost alone is important for shale, whose responsiveness operates largely through drilling and completion capital; it ensures the estimated curvature reflects the full-cycle cost of expanding output rather than only short-run lifting costs. Assets are classified as

shale/tight or conventional from Rystad's resource-segment labels, and oil and gas are kept as separate fuel components in a common energy unit (barrels of oil equivalent). The baseline uses the 2019 cross-section, matching the model's calibration year.

**Cost-curve construction.** Within each year × fuel × region × technology cell, assets are sorted by marginal extraction cost and compressed into 20 production-weighted cost bins, yielding the binned vertices of the supply curve. For each bin we compute the average marginal cost and cumulative production, and take logs. Binning on production weights ensures that the estimated slope reflects where output actually is on the cost curve rather than the density of small marginal fields.

**Identification of the slope.** To purge cross-regional differences in resource quality, infrastructure, and fiscal regime, we use a two-step residualization: we first regress $\ln(\text{Marginal Cost}_g)$ and $\ln(\text{Cumulative Production}_g)$ on region dummies and retain the residuals, then regress the residualized cost on residualized cumulative production. The second-stage slope is $\widehat{\beta}$. This preserves within-region cost-curve variation while removing systematic level differences across regions.

**Sample construction.** We drop assets with missing, zero, or negative cost or production; aggregate to the asset level using the median to smooth annual fluctuations; trim outliers with a combination of the three-standard-deviation rule and P2–P92 winsorization; and retain only cells with at least 20 distinct assets. Table 2 reports the resulting field sample and the binned cost-curve vertices used in estimation, and Table 3 summarizes the underlying field-level cost and production distributions, both of which are strongly right-skewed.

## 3.3 What the Elasticity Measures

The object in equation (59) is a *long-run, capacity-inclusive* supply elasticity: it measures how the marginal cost of the marginal unit of output rises as the industry moves up its full-cycle cost curve. This is the relevant object for the model, whose counterfactual compares two long-run equilibria with and without shale capacity, and it is distinct from, and larger than, the short-run behavioral elasticities estimated from high-frequency price and quantity variation, which are damped by drilling lags and capacity rigidities. The cost-curve interpretation rests on three assumptions, which we state explicitly: (i) cumulative production along the sorted cost curve approximates the quantity available at or below a given marginal-cost threshold; (ii) the ranked marginal-cost curve approximates the inverse supply schedule relevant for the long-run extraction decision; and (iii) region fixed effects absorb the confounders (resource

endowment, infrastructure, fiscal regime) that would otherwise contaminate the cost–quantity slope. Under these assumptions the cost-curve slope identifies the model's reserve-intensity parameter $\nu_i$. The structurally exact alternative regresses log marginal cost directly on the log production-to-reserve intensity $\ln(q_i/m_i)$ of equation (18), recovering the same slope $\beta = \nu_i/(1-\nu_i)$ without assumptions (i) and (ii); we adopt the cost-curve slope as the baseline because it is the standard field-level object and does not require an asset-by-asset reserve measure, and the direct intensity regression is a natural sharpening of the identification. Subsection 3.4 benchmarks the estimates against both cost-curve and behavioral studies, and the no-shale counterfactual is reported under both the production-flow and the reserve-stock cost-curve concepts as a robustness check on this interpretation.

## 3.4 Results

**Baseline estimates.** Table 1 reports the four baseline supply elasticities. Within both fuels, shale/tight extraction is more elastic than conventional extraction, and the implied reserve-intensity parameter $\nu_i = 1/(1+\epsilon_i)$ is correspondingly lower for shale. For oil, the conventional elasticity is 1.32 and the shale/tight elasticity is 1.79, so shale oil supply is about 36 percent more elastic than conventional oil supply. For gas, the conventional and shale/tight elasticities are 1.74 and 1.94, an 11 percent gap. All four cost-curve slopes are significant at the 1 percent level, with robust standard errors small relative to the coefficients (Table 1). The oil gap is the larger of the two, which is why the oil elasticity channel disciplines OPEC's market power in the quantitative model, while the gas channel operates mainly through competitive supply and downstream energy costs.

**Interpretation.** A more elastic shale supply curve means output expands with a smaller increase in marginal cost. Economically, this reflects the "manufacturing-like" character of shale extraction, with its short drilling cycles, modular and repeatable capital deployment, and steep learning curves, relative to the long lead times and geological constraints of conventional fields. In the model, the entry of low-$\nu$ shale capacity into the competitive fringe raises the local aggregate fringe elasticity $\varepsilon_f$ (equation (22)); through the markup formula (35), a higher $\varepsilon_f$ compresses OPEC's Lerner index. The estimated oil elasticity gap is thus the micro-foundation of the market-power channel: it is what turns the shale revolution into a discipline on OPEC conduct rather than merely a shift in competitive supply.

**Mapping to the model.** The four estimates map to reserve-intensity parameters $\nu_{\text{oil,conv}} = 0.43$, $\nu_{\text{oil,shale}} = 0.36$, $\nu_{\text{gas,conv}} = 0.36$, and $\nu_{\text{gas,shale}} = 0.34$. Each producer's observed local

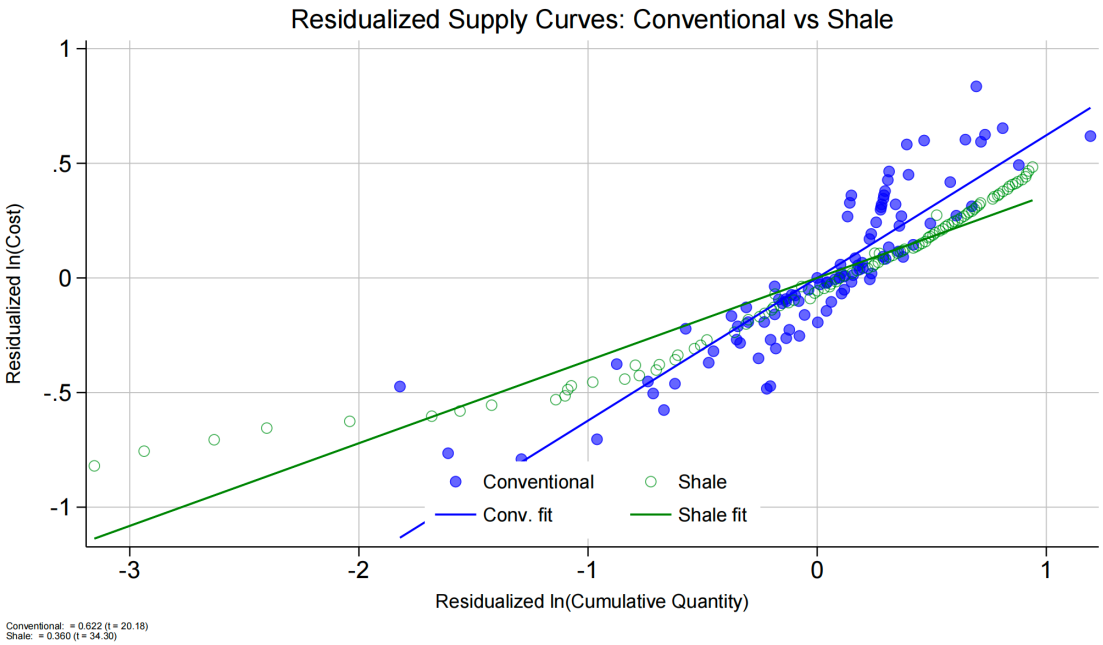



Figure 3: Residualized Supply Curves by Technology Group

*Notes:* Residualized field-level cost–quantity relationships for conventional and shale/tight production, after removing region fixed effects. The flatter slope for shale/tight extraction is the graphical counterpart of its higher estimated supply elasticity in Table 1.

elasticity is constructed as a production-weighted average of the technology-specific elasticities (not of the primitive $\nu$'s), consistent with the aggregation in equation (22).

**Benchmarking.** Table 4 places the estimates against the literature. They sit squarely within the range of studies that, like ours, recover supply elasticities from field- or deposit-level cost curves: Bornstein et al. (2017) obtain oil elasticities of 1.2–1.8 from deposit-cost curves, and Garcia-Lembergman et al. (2025) obtain 1.5 for oil and 2.9 for gas from cost-tier cumulative regressions. Our estimates are larger than the short-run instrumental-variables estimates (e.g. Abuin, 2024, gas 0.24) and than the gas elasticity in the CGE calibration of Boeters and Bollen (2012) ($\approx 1.0$). This is as expected, since the IV estimates identify a short-run behavioral response damped by capacity adjustment, whereas the cost-curve method identifies the long-run schedule that is the relevant object for our comparative-static counterfactual.

**Robustness.** The estimates are robust to the number of cost bins (50, 150), to the trimming rule (P5–P95), and to including basin fixed effects. As a robustness check on the cost concept, Table 1 also reports a reserve-stock specification that replaces cumulative production with cumulative recoverable reserves along the cost curve, following the stock-cost concept of

Welsby et al. (2021). The reserve-based estimates are close to the baseline for conventional oil but about 18 to 20 percent lower for the gas groups, and the shale-oil estimate falls from 1.79 to 1.06; the full no-shale counterfactual is reported under both concepts in Section 5.7.[2]

Table 1: Baseline Supply Elasticity Estimates by Fuel and Technology

| | Conv. oil | Shale oil | Conv. gas | Shale gas |
|---|---|---|---|---|
| *Panel A. Production-flow (baseline)* | | | | |
| Cost-curve slope $\widehat{\beta}$ | 0.759 | 0.560 | 0.574 | 0.515 |
| | (0.051) | (0.094) | (0.076) | (0.106) |
| Supply elasticity $\widehat{\epsilon} = 1/\widehat{\beta}$ | 1.317 | 1.787 | 1.742 | 1.942 |
| Reserve intensity $\widehat{\nu}$ | 0.432 | 0.359 | 0.365 | 0.340 |
| $R^2$ | 0.649 | 0.601 | 0.621 | 0.683 |
| Vertices $N$ | 290 | 49 | 278 | 38 |
| Regions | 19 | 6 | 19 | 5 |
| *Panel B. Reserve-stock (robustness)* | | | | |
| Cost-curve slope $\widehat{\beta}$ | 0.795 | 0.944 | 0.700 | 0.647 |
| | (0.055) | (0.149) | (0.049) | (0.162) |
| Supply elasticity $\widehat{\epsilon} = 1/\widehat{\beta}$ | 1.258 | 1.059 | 1.428 | 1.546 |
| $R^2$ | 0.554 | 0.593 | 0.550 | 0.514 |
| Vertices $N$ | 276 | 51 | 258 | 41 |

*Notes:* Each column estimates equation (59) within a fuel × technology group on binned cost-curve vertices, with region fixed effects. $\widehat{\beta}$ is the cost-curve slope, with robust standard errors in parentheses, all significant at the 1 percent level; the supply elasticity is its reciprocal; $\widehat{\nu} = \widehat{\beta}/(1+\widehat{\beta})$ is the model's reserve-intensity parameter. Panel A (baseline) uses cumulative 2019 annual production along the cost curve; Panel B (robustness) uses cumulative 2P reserves. Cost is the capex-inclusive marginal extraction cost (Rystad `ap_costofprod4_1`); $N$ is the number of binned vertices.

Table 2: Estimation Sample and Cost-Curve Vertices, 2019

| Fuel | Technology | Field-level obs. | Binned vertices | Regions | Production |
|---|---|---|---|---|---|
| Oil | Conventional | 13,458 | 290 | 19 | 25,255 |
| Oil | Shale/tight | 1,554 | 49 | 6 | 3,976 |
| Gas | Conventional | 8,212 | 278 | 19 | 15,541 |
| Gas | Shale/tight | 1,667 | 38 | 5 | 4,324 |

*Notes:* Field-level observations are the cleaned 2019 production-flow field sample; binned vertices are the production-weighted cost-curve points used to estimate equation (59) (Table 1). Production is in million barrels of oil equivalent. Shale/tight resources span fewer regions (six for oil, five for gas), reflecting the geographic concentration of shale extraction rather than a data restriction.

[2]The production-flow concept is the baseline because it captures the active-margin responsiveness for which shale extraction is known; the reserve-stock concept measures a different, longer-horizon object and compresses the shale oil premium.

Table 3: Descriptive Statistics for Production-Flow Field Points

| Fuel | Technology | Obs. | Mean | Median | Std. dev. | P10 | P90 |
|---|---|---|---|---|---|---|---|
| *Panel A. Marginal extraction cost (USD/boe)* | | | | | | | |
| Oil | Conventional | 13,458 | 156.922 | 11.973 | 5,755.645 | 3.773 | 52.178 |
| Oil | Shale/tight | 1,554 | 37.648 | 10.650 | 382.356 | 3.908 | 51.959 |
| Gas | Conventional | 8,212 | 85.725 | 8.940 | 1,975.669 | 3.202 | 32.798 |
| Gas | Shale/tight | 1,667 | 9.758 | 7.132 | 25.250 | 3.732 | 13.053 |
| *Panel B. Annual production (mmboe)* | | | | | | | |
| Oil | Conventional | 13,458 | 1.877 | 0.107 | 13.025 | 0.002 | 2.922 |
| Oil | Shale/tight | 1,554 | 2.559 | 0.560 | 5.742 | 0.030 | 7.028 |
| Gas | Conventional | 8,212 | 1.892 | 0.076 | 12.780 | 0.001 | 2.619 |
| Gas | Shale/tight | 1,667 | 2.592 | 0.472 | 8.284 | 0.019 | 5.789 |

*Notes:* Field-level production-flow points before the production-weighted binning, by fuel and technology. Cost is the capex-inclusive marginal extraction cost (Rystad `ap_costofprod4_1`) in US dollars per barrel of oil equivalent; annual production is in million barrels of oil equivalent. Both distributions are strongly right-skewed, with mean costs far above medians, which is why the cost-curve vertices are constructed on production weights rather than treating each field equally.

Table 4: Estimates in the Context of the Supply-Elasticity Literature

| Study | Method | Key estimates |
|---|---|---|
| Arora (2014) | Calibration meta-analysis | U.S. gas: 0.1–6.0 |
| Boeters and Bollen (2012) | CGE calibration | Gas $\approx$ 1.0; coal $\approx$ 4.0 |
| Farrokhi and Lashkaripour (2023) | National-accounts back-calibration | Resource share 0.31–0.49 |
| Abuin (2024) | IV (short-run) | U.S. gas 0.24; coal 0.77 |
| Bornstein et al. (2017) | Deposit-cost-curve | Oil 1.2–1.8 |
| Cruz and Rossi-Hansberg (2024) | Deposit-cost curves | Coal 2.5–3.5 |
| Garcia-Lembergman et al. (2025) | Cost-tier cumulative regression | Oil 1.5; gas 2.9; coal 3.1 |
| **This paper** | **Cost-curve, by technology** | **Oil** 1.32/1.79**; gas** 1.74/1.94 |

*Notes:* "This paper" reports conventional/shale–tight production-flow estimates for oil and gas. Estimates from cost-curve methods (Bornstein et al., 2017; Garcia-Lembergman et al., 2025) bracket ours; short-run IV estimates (Abuin, 2024) identify a different (behavioral, short-run) object.

# 4 Calibration

The remaining model inputs are calibrated to match the 2019 world economy. The country dimension is $N = 76$: 74 individually covered OECD ICIO countries plus an aggregate OPEC bloc and a residual rest-of-world aggregate. There are $K = 48$ non-energy sectors. The fossil set is $\mathcal{S} = \{o, g, c\}$ for oil, gas, and coal. Table 5 reports the main primitive inputs and no-shale shock targets. Baseline oil-market shares, oil demand elasticity, local fringe elasticity, and the OPEC Lerner index are computed equilibrium objects rather than externally imposed parameters.

Table 5: Main Calibration Inputs

| Block | Parameter or object | Value | Source |
|---|---|---|---|
| Trade | Sectoral Armington elasticities $\sigma_k$ | 1.8–8.8 | Sector-level trade-elasticity calibration |
| Energy demand | Energy substitution elasticity $\sigma_E$ | 3.0 | Baseline energy-CES calibration |
| Oil supply | Conventional oil supply elasticity | 1.317 | Rystad production-based estimate |
| Oil supply | Shale/tight oil supply elasticity | 1.787 | Rystad production-based estimate |
| Gas supply | Conventional gas supply elasticity | 1.742 | Rystad production-based estimate |
| Gas supply | Shale/tight gas supply elasticity | 1.942 | Rystad production-based estimate |
| No-shale shock | Oil quantity target | 0.568 | 2005 B06 benchmark and non-shale oil share |
| No-shale shock | Gas quantity target | 0.351 | 2005 B06 benchmark and non-shale gas share |
| Emissions | Oil, gas, coal emission factors | 3.00; 2.00; 3.81 | $tCO_2$/toe calibration |
| Robustness | Reserve-based elasticity concept | cumulative reserves | Rystad reserve-based estimates |

*Notes:* The table reports the main primitive and shock inputs. Country-sector cost shares, trade shares, fossil-use shares, and income shares are calibrated from the adjusted 2019 input-output accounts. Baseline oil-market shares, oil demand elasticity, local fringe elasticity, and the OPEC Lerner index are equilibrium objects computed from the calibrated model, not externally imposed parameters.

**OPEC aggregation.** The calibration collapses all 14 OPEC market members in 2019 into a single aggregate OPEC bloc: AGO, ARE, COG, DZA, ECU, GAB, GNQ, IRN, IRQ, KWT, LBY, NGA, SAU, and VEN. The starting ICIO table directly identifies AGO, ARE, NGA, and SAU and embeds the remaining members in ROW. We use the 2015 full Eora country detail to split the ICIO ROW block into a ROW-embedded OPEC slice and residual ROW, then recompute OPEC and ROW production, expenditure, trade-share, income-share, and fossil-demand objects. This calibration maps all 14 OPEC market producers to OPEC income and assigns OPEC's counterfactual wage $\hat{w}_O$ from the aggregate OPEC labor-market clearing condition.

**Input-output and energy shares.** Sectoral cost shares $\gamma_{\ell,nk}$, $\gamma_{E,nk}$, $\gamma_{r,nk}$ and bilateral trade shares $\pi_{l,k,n}$ are computed from the adjusted OECD ICIO tables. The mining sectors B05 and B06 are removed from the Armington sector set and treated as homogeneous fossil inputs. B05 maps to coal. B06 is split into oil and gas using physical production, final-demand, and rent information so that household shares $\mu_{n,o}$, $\mu_{n,g}$, and $\mu_{n,c}$ and energy-bundle shares $\omega_{o,nk}$, $\omega_{g,nk}$, and $\omega_{c,nk}$ sum to the corresponding ICIO fossil totals. Purchases of refined petroleum and electricity remain non-energy IO inputs and enter through the

intermediate-input coefficients.

**Market structure.** OPEC's oil-market share $s_O$ and the fringe share $s_f$ are baseline equilibrium shares computed from model-consistent oil quantities for the validated OPEC oil-market coalition and all non-OPEC producers. The local aggregate fringe elasticity $\varepsilon_f$ is computed from the exact heterogeneous fringe supply curve using equilibrium production weights. Gas and coal use competitive supply curves by country and source.

**Income and rents.** Fossil rents are split into oil, gas, and coal components and normalized by final absorption $X_n^C$, the denominator in the exact-hat income equation. Thus $\lambda_n^w + \theta_n^o + \theta_n^g + \theta_n^c + \theta_n^{\text{roy}} + d_n = 1$ by construction, where $\theta_n^{\text{roy}}$ is the rebated government-take share defined below and $d_n$ is the trade-imbalance wedge. The real-income decomposition in the quantitative section uses these split rent shares.

**Origin-differentiated gas and coal trade.** The origin-differentiated gas and coal markets of Section 2.7 require baseline bilateral expenditure shares $\pi_{s,oi}$, which we build from 2019 reporter-by-partner gas and coal trade. Because bilateral flows cover only cross-border trade, the domestic own-share $\pi_{s,ii}$ (home-produced fuel consumed at home) is anchored to each country's model fuel balance, one minus net import penetration from the model's own production-versus-consumption accounting, and the foreign residual is allocated by observed bilateral shares. The resulting diagonals are sensible: China sources about 82% of its coal at home and Japan essentially none, with Japan's coal sourced from Australia (0.58), Indonesia (0.12), and Russia (0.10). We set the Armington elasticities $\sigma_{\text{gas}} = \sigma_{\text{coal}} = 1.8$, a standard fossil value, and hold the bilateral trade-cost hats at unity so the no-shale counterfactual isolates origin differentiation in baseline sourcing rather than counterfactual shifts in pipeline-versus-LNG or Pacific-versus-Atlantic wedges. Oil retains a single world price.

**Government take.** We set the take $\tau_{n,s}$ to the 2019 government take as a share of fuel revenue, from asset-level fiscal economics (Rystad UCube), aggregated to model countries by summing take and revenue across assets and taking the ratio (coal take is set to zero). Government take is substantial and heterogeneous: revenue-weighted oil rates run from about 0.25 in the United States, where private mineral rights leave a low federal take, to roughly 0.5–0.55 for OPEC, Russia, and Norway, with gas rates somewhat lower. Holding the fuel-revenue share of absorption fixed, the take re-derives the income shares as $\theta_{n,s}^{\text{new}} = (1-\tau_{n,s})\theta_{n,s}$, a rebated-take share $\theta_n^{\text{roy}} = \sum_s \tau_{n,s}\sigma_{n,s}$, and a labor share net of the take, all summing to

one; the rebated-take share is largest for the concentrated exporters (Brunei 0.14, OPEC 0.13, Russia 0.11, Norway 0.07). These are fiscal-model statutory takes rather than realized receipts; we adopt them as the best available cross-country measure of the wedge between resource revenue and private factor income, and report a no-take specification as a robustness check in Section 5.7.

**Counterfactual shocks.** The no-shale counterfactual removes US shale/tight oil and gas capacity and applies the corresponding conventional extraction curvature. The baseline production-based concept uses current production along the Rystad cost curve. The reserve-based robustness concept uses cumulative reserves along the cost curve. In both concepts, oil shocks enter through the oil fringe and the OPEC first-order condition; gas shocks enter through competitive gas supply. Table 6 reports the resulting no-shale oil and gas quantity targets, alongside the calibrated supply-elasticity inputs estimated in Section 3.

**External validation of the market-power moments.** Because OPEC's Lerner index, the oil demand elasticity, and the fringe elasticity are equilibrium objects rather than imposed parameters, they serve as over-identifying checks against the literature. The baseline OPEC Lerner index of 13.5% describes real but bounded marginal market power, a price-cost margin at the active extraction margin rather than the textbook monopoly wedge or the large average gap between price and the lowest-cost barrel. It is consistent with Asker et al. (2019), who attribute roughly 14 to 22 percent of the $744 billion in global crude-oil misallocation over 1970–2014 to market power, and with Asker et al. (2024), who find that this market power materially curtails extraction and the associated emissions. The computed oil demand elasticity $\varepsilon_o \approx 2.0$ is, by contrast, considerably more elastic than the values used in single-good world-oil models. Bornstein et al. (2023) calibrate an oil demand elasticity of 0.15, so that a one-percent rise in output lowers the price by about seven percent, and reduced-form estimates place the short-run price elasticity of oil demand near 0.1 and the long-run elasticity below one. This gap is structural rather than a discrepancy. Our $\varepsilon_o$ is the long-run, general-equilibrium elasticity of world oil demand, which allows inter-fuel substitution (governed by $\sigma_E$) and cross-country manufacturing reallocation. Reduced-form estimates and single-good models hold these margins fixed, but a long-run no-shale counterfactual must incorporate them. The direction of the difference is moreover conservative for our central mechanism: a more elastic residual demand implies a smaller markup, so adopting an inelastic, Bornstein et al. (2023)-style demand would raise the implied baseline Lerner index from 13.5% to roughly 38%. We therefore do not overstate the level of OPEC market power, and the same logic of long-run versus short-run elasticities that justifies our supply-side estimates (Section 3.4)

applies on the demand side.

Table 6: Split Oil and Gas Supply Elasticity Inputs

| Fuel | Technology | Supply elasticity |
|---|---|---|
| Oil | Conventional | 1.317 |
| Oil | Shale/tight | 1.787 |
| Gas | Conventional | 1.742 |
| Gas | Shale/tight | 1.942 |
| No-shale oil quantity target | Ratio to observed 2019 | 0.568 |
| No-shale gas quantity target | Ratio to observed 2019 | 0.351 |

*Notes:* Supply elasticities are the baseline production-based Rystad estimates. The no-shale targets allocate the 2005 B06 fossil benchmark between oil and gas using 2019 non-shale oil and gas production shares.

# 5 Quantitative Analysis: The Shale Revolution

## 5.1 Counterfactual Definition

We compare two equilibria that share the same 2019 baseline data. The observed equilibrium is the 2019 world economy. The no-shale counterfactual removes US shale/tight oil and gas capacity, replaces the affected extraction elasticities with the corresponding conventional parameters, and solves for a new global input-output equilibrium. All reported numbers are observed 2019 minus the no-shale counterfactual. Positive real-income effects therefore mean that the shale equilibrium has higher real income than the no-shale equilibrium.

The baseline production-based specification includes five full-GE counterfactuals: the full no-shale counterfactual, a quantity-only run, an elasticity-only run, an oil-only run, and a gas-only run. The reserve-based full counterfactual is reported as a robustness check.

The analysis follows the mechanism in sequence. We first establish the effect on the oil price and OPEC's markup, then contrast the strategic oil channel with the competitive gas channel, trace how the shock reallocates production across countries, measure the welfare incidence, and report the change in emissions.

## 5.2 The Oil Market and OPEC's Markup

Removing the shale revolution raises the world oil price by 5.37 percent and lifts OPEC's oil Lerner index by 1.55 percentage points; equivalently, the shale revolution lowered the oil price

by 5.37 percent and compressed OPEC's markup by 1.55 percentage points (Table 7). This is the first link of the mechanism. Shale entry expands the competitive fringe and raises its local supply elasticity $\varepsilon_f$, which through the markup formula (35) lowers OPEC's equilibrium markup, and removing shale reverses both margins. Figure 2 traces this comparative static at the calibrated equilibrium.

Table 7: Split Fossil-Market Effects of the Shale Revolution

| Scenario | Oil price (%) | Gas price (%) | Coal price (%) | Oil Lerner (pp) |
|---|---|---|---|---|
| Full no-shale | -5.38 | -8.48 | -1.62 | -1.55 |
| Oil only | -3.36 | -1.25 | -0.88 | -1.38 |
| Gas only | -1.83 | -7.06 | -0.67 | -0.14 |
| Quantity only | -5.16 | -8.05 | -1.54 | -1.37 |
| Elasticity only | -0.04 | -0.01 | -0.01 | -0.20 |

*Notes:* Entries are observed 2019 minus the no-shale counterfactual. Price effects are percent changes; the oil Lerner effect is in percentage points. The production-based elasticity estimates define the baseline.

The markup compression is a distinct part of the price decline, and the model measures it by solving the no-shale counterfactual twice: once letting OPEC re-optimize its markup (row i of Table 8), and once holding the markup at its observed 2019 value (row ii). Reading across the columns makes the experiment concrete. The oil-price column is the no-shale price relative to the observed equilibrium: removing shale raises the oil price to 1.0537 when OPEC re-optimizes, but only to 1.0507 when its markup is frozen. The OPEC-Lerner column is the markup *level*: without shale the competitive fringe is less elastic, so OPEC's optimal Lerner index rises from the observed 13.5 percent to 15.0 percent, whereas row (ii) holds it at 13.5 by construction. The two quantity columns show how the supply side responds, again as no-shale-to-observed ratios: OPEC, exploiting the higher markup, restricts its own output to 1.046 rather than the 1.067 it would choose at a fixed markup, a 2.1 percent additional cut, while the fringe expands marginally on the slightly higher price.

The difference between the two oil-price entries (the bottom row of the table) isolates the market-power channel. OPEC's endogenous markup increase accounts for $1.0537 - 1.0507 = 0.0030$ of the no-shale price rise, that is, about 0.30 of the 5.37-percentage-point oil-price decline from shale, or roughly 6 percent; the remaining 5.07 points are the competitive-supply contraction itself. The mechanism behind that 0.30-point gap is visible in the quantity columns: the higher no-shale markup is achieved by the extra OPEC output restriction. This amplification gap is the empirical measurement of Corollary 1 and the signature of the dominant-firm mechanism: shale disciplines OPEC, and removing it lets OPEC re-exercise

market power by holding back output. Because the model's oil demand is elastic, the gap is a conservative estimate of that channel: a less elastic demand would imply a larger markup and a wider gap.

Table 8: Decomposing the No-Shale Oil-Price Rise: Competitive Supply versus OPEC Market Power

| Counterfactual | Oil price (hat) | OPEC Lerner (level, %) | OPEC quantity (hat) | Fringe quantity (hat) |
|---|---|---|---|---|
| (i) Endogenous markup | 1.0537 | 15.04 | 1.0461 | 0.9280 |
| (ii) Fixed observed markup | 1.0507 | 13.49 | 1.0673 | 0.9244 |
| Market-power channel, (i)−(ii) | +0.0030 | +1.55 | −0.0212 | +0.0036 |

*Notes:* Both counterfactual rows are no-shale values relative to the observed 2019 equilibrium. The oil-price and quantity columns are hats (no-shale divided by observed); the OPEC Lerner column is the markup *level* in percent (observed = 13.49). Row (i) lets OPEC re-optimize its markup; row (ii) re-solves the same no-shale full-GE counterfactual with the markup held at its observed value. The bottom row, (i) minus (ii), isolates the market-power channel: of the 5.37-point no-shale oil-price rise, OPEC's endogenous markup increase contributes 0.30 points (about 6 percent), achieved by restricting OPEC output a further 2.1 percent.

The scenario rows of Table 7 separate the competitive-supply movement from the markup channel. The quantity-only run, which removes shale capacity while holding the extraction elasticities fixed, carries most of the price movement, lowering the oil price by 5.16 percent and the Lerner index by 1.37 percentage points. The elasticity-only run, which reverts only the extraction elasticities, has almost no price effect, −0.04 percent, but still moves the Lerner index by 0.20 percentage points, isolating the pure markup channel that the dominant-firm mechanism predicts.

## 5.3 Oil versus Gas: Strategic and Competitive Channels

Gas and coal prices fall as well, but reach the economy through a different channel from the oil price, and unlike oil through origin-differentiated trade. The shale revolution lowers the United States gas price by about 43 percent while leaving most other origins' gas prices nearly unchanged (roughly 1 percent), so the trade-weighted world gas index falls by 8.47 percent and coal by 1.62 percent (Table 7). The decline an importer experiences scales with how much of its gas it sources from the United States (Korea −8.1, Japan −4.6, India −2.6, China and Germany −0.8 percent). This concentration matches the observed decoupling of US Henry Hub prices from European and Asian benchmarks over the period, which a single world gas price cannot produce. Gas is a competitive fossil input, so shale gas works through the energy costs of downstream sectors rather than through a strategic markup. The

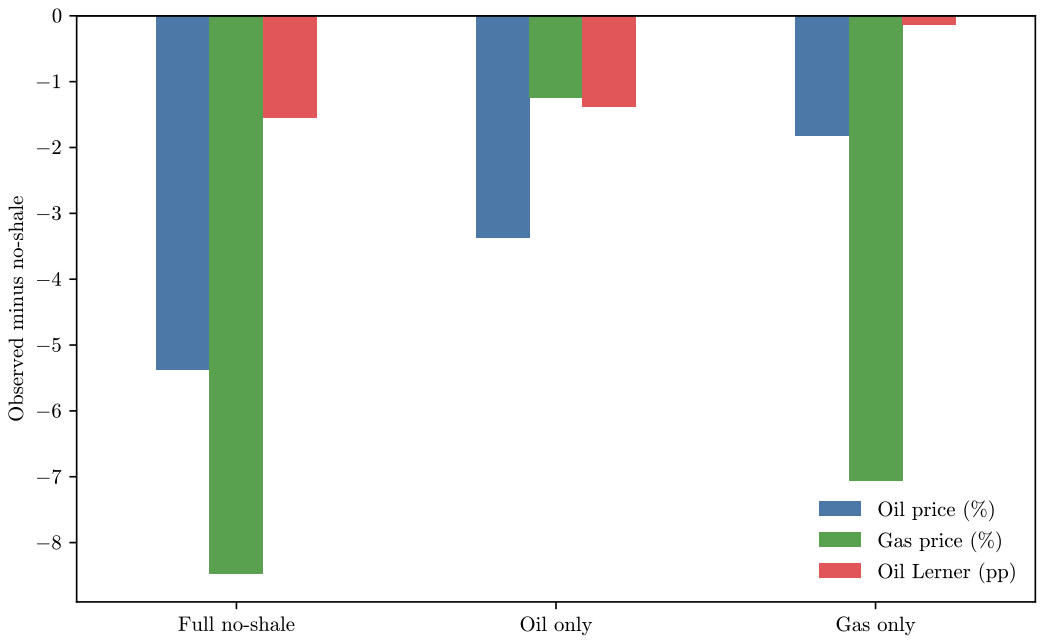



Figure 4: Fossil-Market Effects Across Counterfactual Scenarios

*Notes:* Bars report observed 2019 minus the no-shale counterfactual for the full, oil-only, and gas-only runs. Oil and gas price effects are percent changes; the oil Lerner effect is in percentage points.

contrast is sharp in the single-source runs: the gas-only shock lowers the world gas index by 7.06 percent yet moves OPEC's oil Lerner index by only 0.14 percentage points, whereas the oil-only shock lowers the oil price by 3.36 percent and the Lerner index by 1.38 points. This asymmetry is why the model treats oil as a dominant-firm market with a competitive fringe while gas, like coal, is competitive.

Table 9 compares the full counterfactual with the quantity-only, elasticity-only, oil-only, and gas-only scenarios. In the full counterfactual, observed oil quantity is 2.66 percent higher and observed gas quantity is 8.99 percent higher than in the no-shale equilibrium. The oil-only shock raises oil quantity and lowers gas quantity, while the gas-only shock raises gas quantity and slightly lowers oil quantity. This cross-source substitution is one reason a combined fossil block hides the economic channel.

Table 9: Oil and Gas Channel Decomposition

| Scenario | Oil quantity (%) | Gas quantity (%) | USA income (%) | OPEC income (%) | Emissions ($MtCO_2$) |
|---|---|---|---|---|---|
| Full no-shale | +2.65 | +8.99 | +0.65 | -1.21 | +738 |
| Quantity only | +2.61 | +8.62 | +0.66 | -1.18 | +717 |
| Elasticity only | +0.07 | -0.02 | -0.05 | +0.03 | +6 |
| Oil only | +4.67 | -0.81 | +0.30 | -0.76 | +471 |
| Gas only | -2.14 | +9.68 | +0.33 | -0.39 | +248 |

*Notes:* Quantity effects and income effects are observed 2019 minus no-shale. The oil-only and gas-only rows isolate the two shale shocks in the split model.

The country incidence also differs by source. In the oil-only run, OPEC loses because lower oil prices and a lower oil markup reduce fossil-rent income. In the gas-only run, the United States gains mainly through the competitive gas-supply channel and the associated consumption-price response, while OPEC still loses through general-equilibrium income and price-index effects rather than through a large direct oil-markup shock.

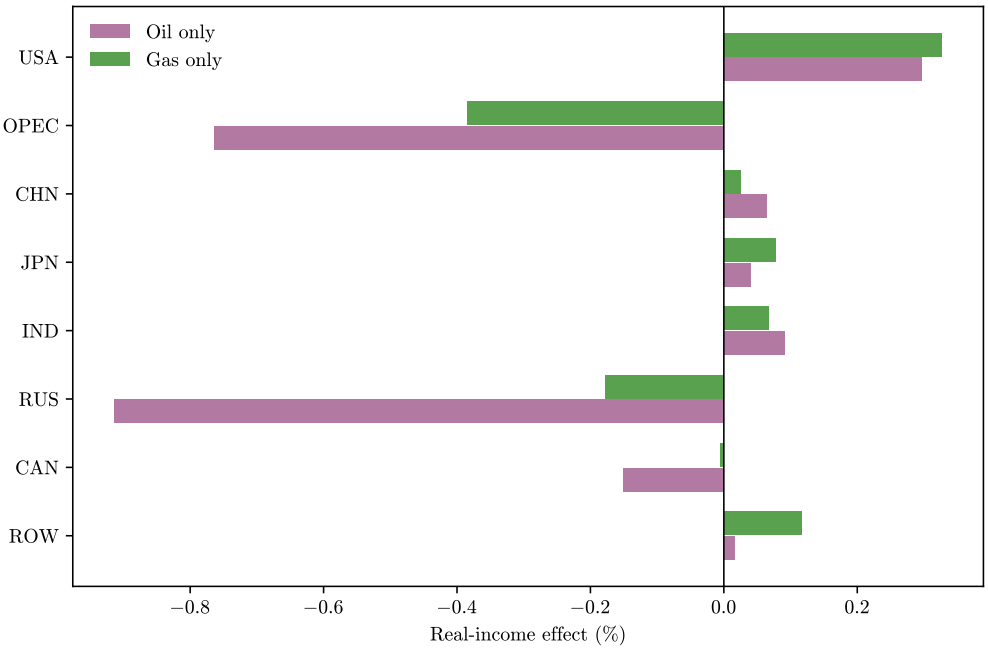



Figure 5: Oil-Only and Gas-Only Real-Income Effects

*Notes:* Bars report private real-income effects, observed 2019 minus no-shale, for the oil-only and gas-only counterfactual runs. Countries shown are the focal economies used throughout the quantitative section.

Figure 6 summarizes the distinction: oil shale works mainly through the world oil price and the OPEC markup, while gas shale works mainly through the local gas price and downstream

input costs.

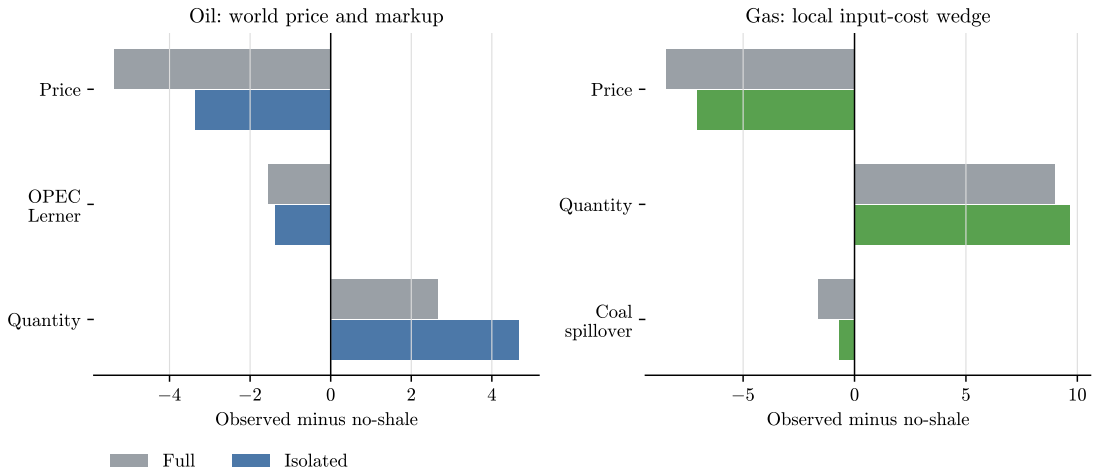



Figure 6: Oil and Gas Enter the Mechanism Through Different Margins

*Notes:* Bars report observed 2019 minus no-shale. Price and quantity effects are percent changes; the OPEC Lerner effect is in percentage points. The oil panel compares the full and oil-only counterfactuals; the gas panel compares the full and gas-only counterfactuals.

## 5.4 Production Reallocation

The shale revolution reallocates production across countries and sectors along two distinct margins. Table 10 ranks country-sector cells by absolute output effect, and they sort cleanly. The first is a *direct cheap-input* margin: the most fuel-intensive sector, refined petroleum, expands sharply in the United States (+13.68 percent, with a fossil-energy cost share of 0.52) as cheap shale oil and gas lower its input costs, with similar expansions in other refiners. The second is a *real-appreciation* margin that moves the much larger set of low-fuel-share tradables in the opposite direction: US basic metals fall 5.07 percent and computer and electronics 4.53 percent, while the same sectors expand in oil exporters (Russia basic metals +4.82 percent, OPEC chemicals +4.96 percent). This second pattern is paradoxical at first sight: because the shale revolution lowers US energy costs, US manufacturing should expand, yet it contracts. The reason, developed below, is that for sectors with negligible fossil shares the reallocation operates through a real-exchange-rate channel rather than a direct energy-cost channel; only the genuinely fuel-intensive sectors such as refining follow the direct-cost logic.

Table 10: Largest Country-Sector Output Reallocations in the Split Model

| Country | Sector | Shale effect (%) | Energy share |
|---|---|---|---|
| USA | refined petroleum | +13.67 | 0.521 |
| KOR | refined petroleum | +8.14 | 0.627 |
| CAN | refined petroleum | -6.18 | 0.637 |
| GRC | refined petroleum | +5.92 | 0.749 |
| SWE | refined petroleum | +5.74 | 0.624 |
| ISR | refined petroleum | -5.29 | 0.038 |
| USA | basic metals | -5.09 | 0.002 |
| OPEC | chemicals | +4.96 | 0.156 |
| RUS | basic metals | +4.83 | 0.003 |
| ROW | refined petroleum | -4.78 | 0.413 |
| USA | computer and electronics | -4.55 | 0.000 |
| KOR | chemicals | +4.40 | 0.047 |

*Notes:* Sector names replace ICIO sector codes. Positive effects mean observed output is higher than in the no-shale counterfactual.

For the United States, the shale revolution is a domestic resource windfall. It raises US real income (Section 5.5) and, with it, the US wage relative to the rest of the world. The shale revolution raises the US nominal wage by 0.88 percent relative to the output-weighted world-average wage, while the wages of oil exporters fall relative to the United States (Russia −2.13, OPEC −1.97, Norway −1.84 percent) and those of oil-importing manufacturers fall more modestly (China −1.05, Germany −1.09, Japan −0.93 percent). This real appreciation raises US unit production costs by about one percentage point relative to the world average, and it does so roughly uniformly across tradable sectors.

A decomposition of the US unit-cost change confirms that for the contracting sectors this relative-cost movement, not energy cost, drives the reallocation. Using the cost-hat identity $\ln \hat{c}_{n,k} = \gamma_{\ell,nk} \ln \hat{w}_n + \gamma_{E,nk} \ln \hat{P}_{E,n,k} + \sum_r \gamma_{r,nk} \ln \hat{P}_{r,n}$, for the largest US output declines the direct fossil-energy contribution to the change in unit cost is negligible, since these sectors have negligible direct fossil-input shares, whereas the US relative-cost gap is about one percentage point. These low-fuel-share sectors contract not because their energy costs rose, since those fell slightly through cheaper purchased inputs, but because the shale windfall made the United States a relatively expensive place to produce tradables. This is a Dutch-disease pattern operating alongside the direct cheap-input expansion of genuinely fuel-intensive sectors such as refining: the United States gains as a consumer, with real income rising 0.65 percent (Section 5.5), while its low-fuel-share tradable manufacturing contracts through real

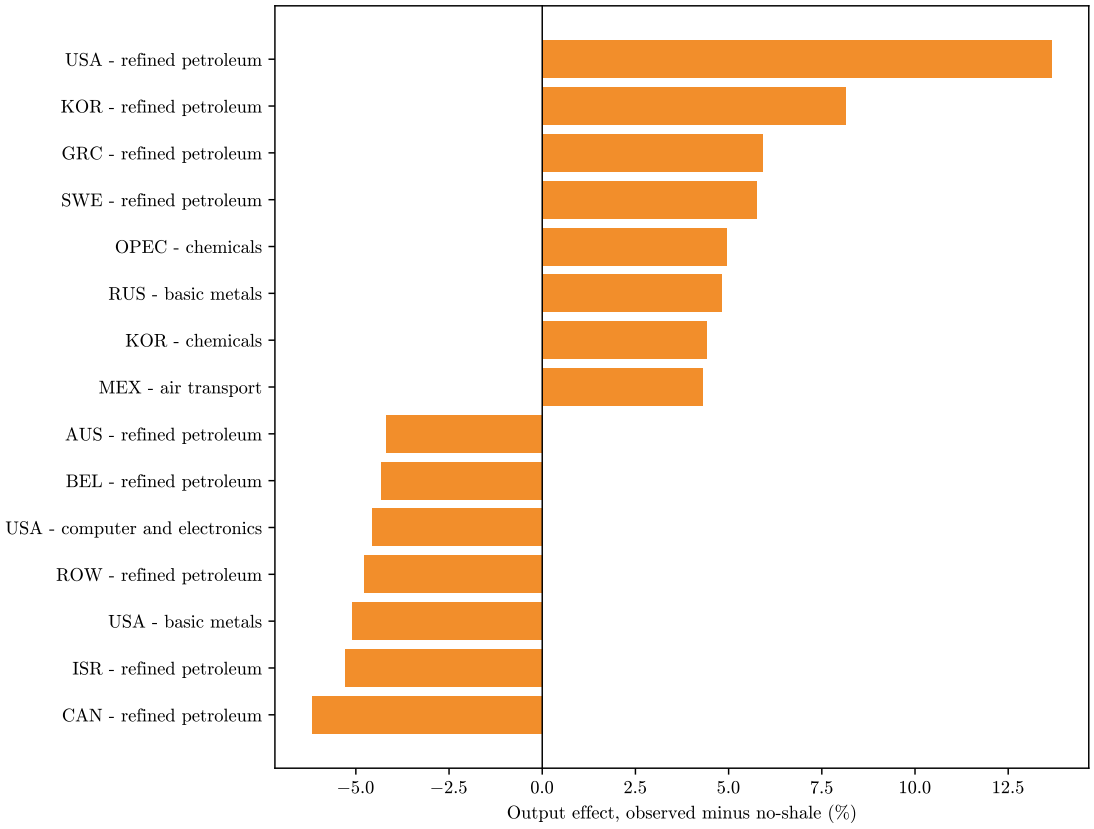



Figure 7: Largest Country-Sector Output Reallocations

*Notes:* Bars rank country-sector cells by gross-output effects in the full no-shale comparison. Effects are observed 2019 minus no-shale, in percent. Sector labels use descriptive ICIO names rather than sector codes.

appreciation. The shale revolution should therefore not be read as a straightforward reshoring of all energy-intensive production to the United States.

Consistent with the two-margin interpretation, Figure 8 shows that the largest US *contractions* occur in sectors with negligible direct fossil-input shares, the real-appreciation margin, an economy-wide relative-cost movement rather than a local energy-cost disadvantage, while the largest *expansion* is concentrated in the most fuel-intensive sector, refining, where the direct cheap-input advantage dominates the real-appreciation drag.

## 5.5 Welfare Incidence

The shale revolution raises United States real income by 0.65 percent and lowers the aggregate OPEC bloc's real income by 1.21 percent (Table 11). China, Japan, and India gain modestly from lower fossil prices, while Russia (−1.14 percent) and Canada (−0.17 percent) lose because lower fossil-rent and wage-income components dominate the consumer-price gain.

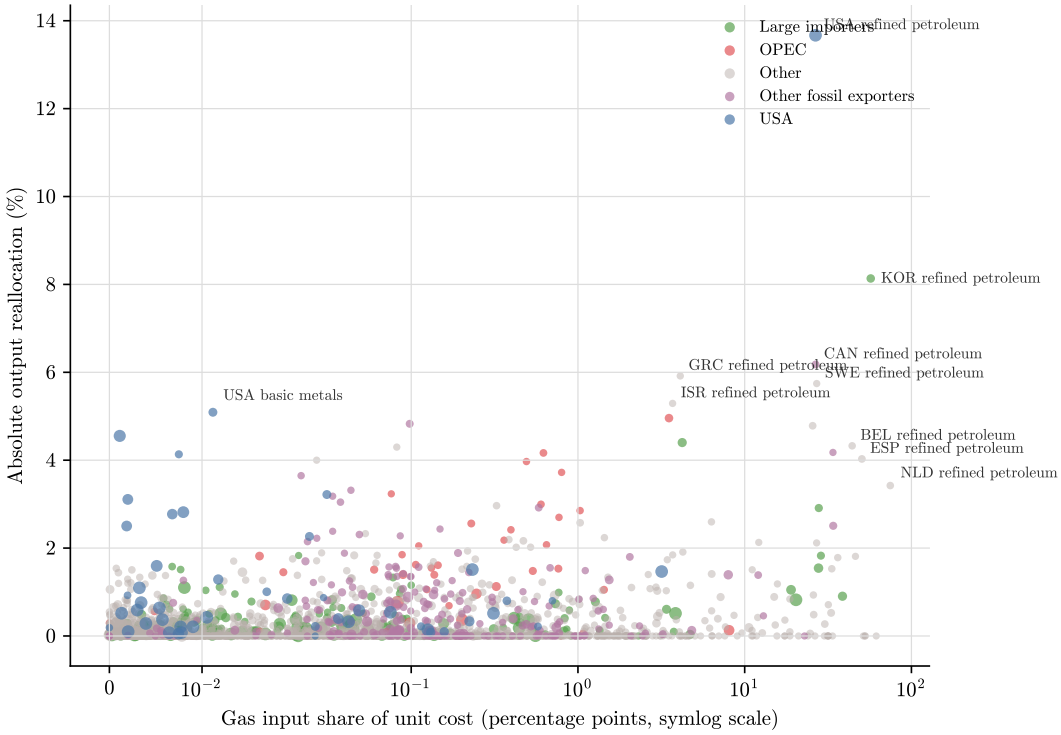



Figure 8: Gas Input Intensity and Production Reallocation

*Notes:* Each point is a country-sector cell with baseline output above 1 billion dollars. The horizontal axis is the gas input share of unit cost, in percentage points; the symlog scale keeps low-intensity sectors visible. The vertical axis is the absolute gross-output effect, observed 2019 minus no-shale, in percent. Marker size is proportional to baseline gross output.

The losses of the gas-heavy exporters are smaller than a single-world-price model implies, because origin differentiation concentrates the gas-price swing in the United States rather than transmitting it to every exporter (Section 5.7 compares the simplified model); the government take works in the opposite direction, tying more of the exporters' income to the fuel revenue that shale erodes.

Table 11: Country Real-Income Effects in the Split Model

| Country/region | No-shale real-income hat | Shale effect (%) |
|---|---|---|
| USA | 0.9935 | +0.65 |
| OPEC | 1.0121 | -1.21 |
| CHN | 0.9991 | +0.09 |
| JPN | 0.9988 | +0.12 |
| IND | 0.9984 | +0.16 |
| RUS | 1.0114 | -1.14 |
| CAN | 1.0017 | -0.17 |
| ROW | 0.9987 | +0.13 |
| CHL | 0.9969 | +0.31 |
| KOR | 0.9969 | +0.31 |
| STP | 0.9976 | +0.24 |
| KAZ | 1.0098 | -0.98 |
| BRN | 1.0067 | -0.67 |

*Notes:* Private real income is the exact-hat welfare index. Positive effects mean observed 2019 real income is higher than in the no-shale counterfactual.

These effects sort into the terms of the exact welfare decomposition in equation (52). The first is the terms-of-trade channel, which combines the fossil-rent income term $\sum_s \theta_n^s \, d\ln \Pi_n^s$ with the fossil cost-of-living term $\sum_s \mu_{n,s} \, d\ln P_s$: countries with positive net fossil exposure lose rent income when shale lowers prices, while net fossil importers gain purchasing power. Table 12 reports net fossil exposure by source, which summarizes the sign of the combined rent and price effect and organizes the importer-exporter split behind the country welfare results.

Figure 9 shows that fossil exposure is an important but incomplete summary of incidence. OPEC and Russia sit on the exporter side and lose real income, while China and other large importers gain purchasing power. The United States is different: it has positive fossil exposure but also benefits from the domestic supply shock and the associated production and price-index changes.

The second channel is oil market power, which the same two no-shale solves used in Section 5.2 let us isolate exactly. Defining the market-power welfare term for country $n$ as the difference $W_n(\text{endogenous } \mu) - W_n(\text{fixed } \mu)$ between the endogenous-markup and fixed-markup no-shale equilibria (Table 8), the implied welfare effect is exactly signed and modest: about a quarter of a log point for OPEC ($-0.28$) and under a tenth for the fringe oil exporters ($+0.08$ for Russia, $+0.06$ for Norway), with importers near zero. OPEC's

Table 12: Fossil net exposure by country

| Country | Oil pp | Gas pp | Coal pp | Total pp |
|---|---|---|---|---|
| CHN | -14.74 | -14.71 | -11.62 | -41.07 |
| OPEC | +30.46 | +6.64 | -0.69 | +36.42 |
| RUS | +10.65 | +16.49 | +4.98 | +32.12 |
| JPN | -4.69 | -4.63 | -2.13 | -11.45 |
| USA | +0.35 | +6.73 | +4.06 | +11.14 |
| KOR | -3.65 | -3.64 | -1.99 | -9.28 |
| IND | -4.69 | -4.79 | +0.92 | -8.55 |
| AUS | -0.50 | +2.58 | +6.13 | +8.21 |
| CAN | +2.93 | +2.77 | +0.37 | +6.07 |
| DEU | -2.56 | -2.47 | -0.66 | -5.70 |
| IDN | -1.57 | -0.74 | +7.31 | +5.01 |
| NOR | +1.53 | +2.68 | -0.02 | +4.19 |

*Notes:* Exposure is the supply share minus model demand share for each fossil source, reported in percentage points. The table summarizes fossil exposure behind the country incidence results.

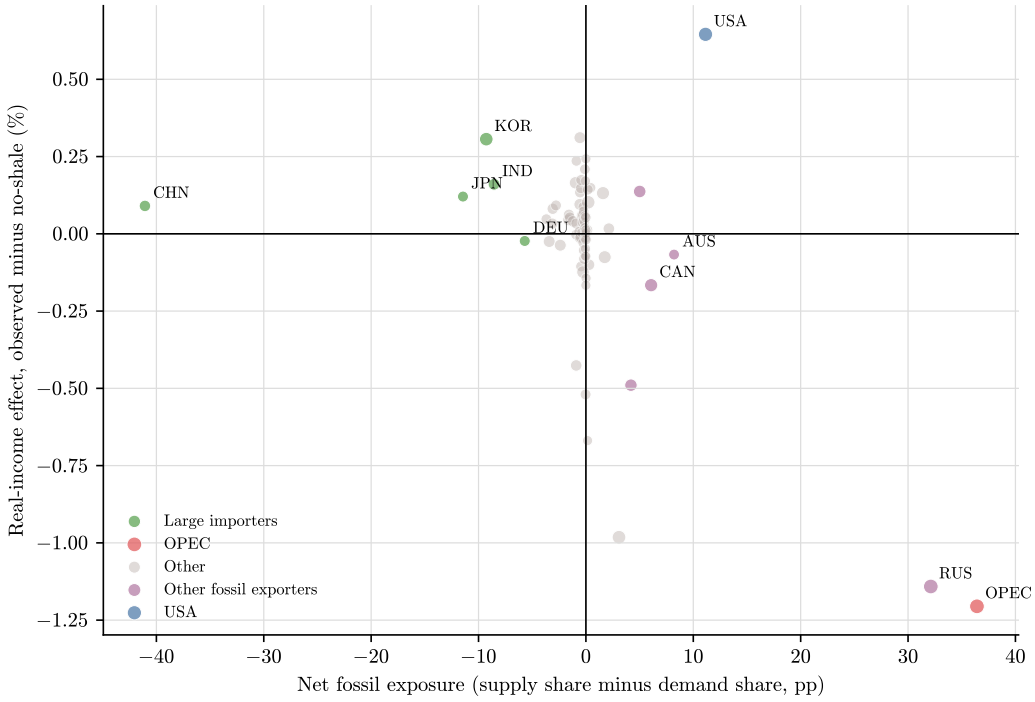



Figure 9: Fossil Exposure and Country Real-Income Incidence

*Notes:* Each point is a model country or aggregate. The horizontal axis is net fossil exposure, defined as fossil supply share minus model fossil demand share, in percentage points. The vertical axis is the private real-income effect, observed 2019 minus no-shale, in percent. Marker size is proportional to gross country-level output reallocation as a share of baseline output.

endogenous restriction of output acts partly as a transfer toward the fringe exporters, whose rents rise with the oil price; it is a distinct welfare margin rather than a movement along a competitive supply curve. The government take amplifies this channel relative to a no-take model, because it ties more of OPEC's income to the oil revenue that the markup defends, though it remains smaller than the terms-of-trade and cost-of-living channels.

The remaining effects operate through the non-energy cost-of-living term $\sum_k \beta_{n,k}\, d\ln P_{k,n}$. Lower-cost shale capacity lowers domestic energy and input costs, the domestic-cost component of that term, while the induced reallocation of production across countries (Section 5.4) enters through its import-price component and shows up directly in country-sector output and trade flows.

Table 13 reports the finite-change counterpart of equation (52), splitting the real-income change into wage income, oil, gas, and coal rents, fixed transfers, and the consumption price index. The components are in log points and sum to the log-point real-income change; at these magnitudes log points and percent differ negligibly. The US gain is mostly a purchasing-power effect from the lower consumption price index, with smaller positive oil- and gas-rent contributions. OPEC's loss reflects lower wage income and lower oil-rent income, partly offset by lower consumer prices.

Table 13: Real-Income Components in the Split Model

| Country | Total | Wage | Oil rents | Gas rents | Coal rents | Prices |
|---|---|---|---|---|---|---|
| | log points, observed minus no-shale | | | | | |
| USA | +0.65 | +0.00 | +0.08 | +0.00 | -0.00 | +0.46 |
| OPEC | -1.20 | -1.80 | -0.48 | +0.01 | -0.00 | +1.77 |
| CHN | +0.09 | -1.02 | -0.02 | +0.00 | -0.02 | +1.15 |
| JPN | +0.12 | -0.91 | -0.00 | -0.00 | -0.00 | +1.03 |
| IND | +0.16 | -0.96 | -0.01 | -0.00 | -0.01 | +1.16 |
| RUS | -1.13 | -2.59 | -0.21 | +0.03 | -0.02 | +1.95 |
| CAN | -0.17 | -1.05 | -0.13 | +0.00 | -0.00 | +1.08 |
| ROW | +0.13 | -1.34 | -0.04 | +0.00 | -0.00 | +1.59 |

*Notes:* Nominal income components use a Shapley decomposition across wage income, fossil rents, and fixed transfers. The price column is the contribution of the consumption price index. Components are reported in log points, so rounded totals need not exactly match percentage real-income effects reported elsewhere.

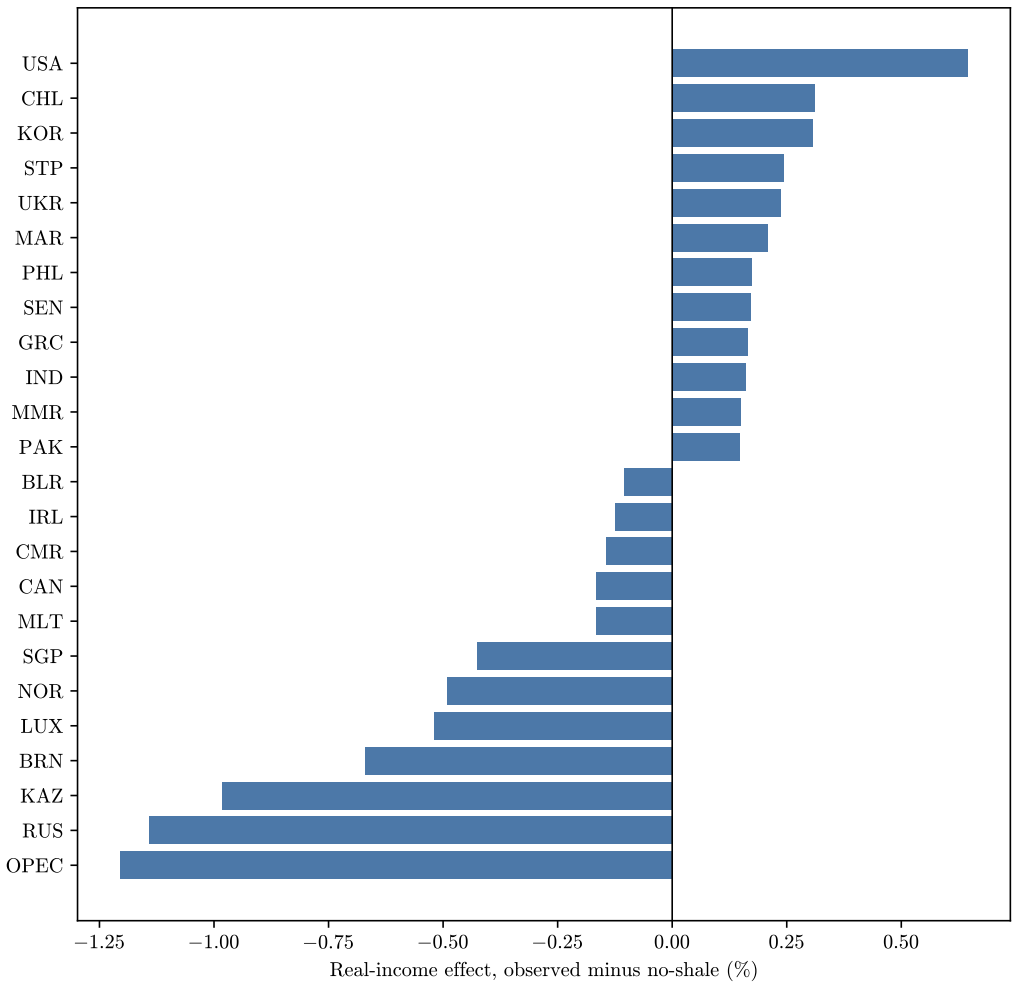



Figure 10: Ranked Country Real-Income Effects

*Notes:* Bars report private real-income effects in the full oil/gas model, observed 2019 minus no-shale, in percent. The figure shows the largest gains and losses among model countries and aggregates.

## 5.6 Emissions

The shale revolution raises total fossil $CO_2$ emissions by 738 $MtCO_2$ per year (Table 14).[3] Oil emissions rise by 356 $MtCO_2$ and gas emissions by 615 $MtCO_2$, while coal emissions fall by 233 $MtCO_2$, so the source accounting shows both a fossil-expansion effect and a coal-substitution effect.

[3]Emissions are obtained by applying combustion $CO_2$ emission factors to the change in fossil quantities: 3.00 tonnes of $CO_2$ per tonne of oil equivalent for oil, 2.00 for gas, and 3.81 for coal. These lie within the range of the fuel-specific default factors in the Intergovernmental Panel on Climate Change (2006) guidelines.

Table 14: Fossil Emissions by Source

| Source | Observed ($MtCO_2$) | No-shale ($MtCO_2$) | Shale effect ($MtCO_2$) |
|---|---|---|---|
| Oil | 13421 | 13065 | +356 |
| Gas | 6846 | 6231 | +615 |
| Coal | 14341 | 14574 | -233 |
| Total | 34608 | 33870 | +738 |

*Notes:* The split model reports oil, gas, and coal emissions separately. The shale effect is observed emissions minus no-shale emissions.

## 5.7 Robustness

Table 15 compares the production-based baseline with the reserve-based robustness run. The reserve-based concept produces similar fossil-price effects and a somewhat larger oil-markup effect. The quantitative conclusions are therefore not driven by using current production rather than cumulative reserves to discipline the supply curvature.

Table 15: Split Elasticity Robustness

| Elasticity concept | Oil price (%) | Gas price (%) | Oil Lerner (pp) |
|---|---|---|---|
| Production-based baseline | -5.38 | -8.48 | -1.55 |
| Reserve-based robustness | -5.61 | -9.34 | -1.87 |

*Notes:* The production-based specification is the baseline. The reserve-based specification uses cumulative 2P reserves along the cost curve as a robustness check.

**Energy and trade elasticities.** Two elasticities are calibrated rather than estimated: the energy-bundle substitution elasticity $\sigma_E$ (baseline 3), which governs the oil demand elasticity, and the Armington trade elasticities $\sigma_k$, which govern the competitive-reallocation channel. They are the natural targets for a sensitivity analysis. We re-solve the full no-shale counterfactual on a grid that varies $\sigma_E \in \{2, 3, 4\}$ and replaces the baseline $\sigma_k$ with an alternative parameterization (Table 16), *recomputing the baseline oil-market moments* (demand elasticity, market shares, and markup) consistently at each node so that the observed equilibrium and the counterfactual remain internally coherent rather than mixing parameters. The headline real-economy outcomes are essentially invariant across the grid: the world oil-price decline stays between 5.2% and 5.6%, the trade-weighted world gas-index decline

between 7.3% and 8.8%, the US real-income gain within two-hundredths of a percentage point of its +0.65% baseline, and world real income within half a basis point. The one object that moves materially is the market-power channel: removing shale raises OPEC's Lerner index by 1.4 percentage points when energy is highly substitutable ($\sigma_E = 4$) and by 1.9 points when it is less so ($\sigma_E = 2$), bracketing the 1.55-point baseline. The effect is larger when oil has fewer substitutes, exactly as the markup formula (35) predicts. The trade elasticities $\sigma_k$ are immaterial here, as they enter only the small competitive-reallocation term in $\varepsilon_o$. The price, welfare, reallocation, and emissions results therefore do not depend on the calibrated elasticities, while the magnitude of the market-power effect scales transparently and monotonically with energy substitutability and remains economically large throughout.

Table 16: Robustness to the Energy-Substitution and Trade Elasticities

| Shale effect | $\sigma_E = 2$ | $\sigma_E = 3$ (baseline) | $\sigma_E = 4$ |
|---|---|---|---|
| Oil price (%) | -5.19 | -5.37 | -5.47 |
| Gas price (%) | -8.79 | -8.47 | -8.28 |
| OPEC Lerner (pp) | -1.84 | -1.55 | -1.36 |
| US real income (%) | +0.68 | +0.66 | +0.65 |
| World real income (%) | +0.155 | +0.147 | +0.140 |

*Notes:* Shale effect (observed minus no-shale) from re-solving the full no-shale counterfactual with the baseline oil-market moments recomputed consistently at each $\sigma_E$. The energy-substitution elasticity $\sigma_E$ has baseline 3. Columns use the baseline Armington elasticities $\sigma_k$; replacing them with the alternative parameterization changes every entry by less than 1.01 (percentage points or percent, as applicable), since $\sigma_k$ enters only the small competitive-reallocation term in $\varepsilon_o$.

**Estimated supply elasticities.** Because the four supply elasticities are estimated, their sampling uncertainty matters for the conclusions. Pending formal standard errors on the cost-curve regressions, we report a ±20% sensitivity band: we scale all four estimated elasticities by a common factor $f \in \{0.8, 1.0, 1.2\}$, regenerate the no-shale capacity shocks (which depend on the elasticities through the fringe supply curve) and the baseline oil-market moments (the fringe elasticity enters the markup) consistently at each $f$, and re-solve (Table 17). The central market-power result is essentially unaffected: shale's effect on OPEC's Lerner index stays within 1.55 to 1.61 percentage points across the band, because the markup depends on the fringe elasticity only through the aggregate $\varepsilon_f s_f$ term, which is disciplined by the observed market shares as much as by the elasticity level. The oil-price response is more sensitive, as one would expect, ranging from 5.3% to 6.0%: a less elastic fringe means removing shale capacity moves the price more. The sign, order of magnitude, and the US real-income gain (+0.65%) are invariant. A ±20% error in the estimated elasticities therefore does not threaten

any qualitative or quantitative conclusion.

Table 17: Robustness to the Estimated Supply Elasticities

| Shale effect | $-20\%$ ($f = 0.8$) | baseline ($f = 1.0$) | $+20\%$ ($f = 1.2$) |
|---|---|---|---|
| Oil price (%) | -5.99 | -5.37 | -5.26 |
| Gas price (%) | -9.52 | -8.47 | -7.09 |
| OPEC Lerner (pp) | -1.61 | -1.55 | -1.59 |
| US real income (%) | +0.71 | +0.66 | +0.62 |
| World real income (%) | +0.166 | +0.147 | +0.121 |

*Notes:* Shale effect (observed minus no-shale) from re-solving the full no-shale counterfactual after scaling all four estimated supply elasticities (oil and gas, conventional and shale-tight) by a common factor $f$, regenerating the no-shale shocks and recomputing the baseline oil-market moments consistently at each $f$. The $\pm 20\%$ band stands in for formal confidence intervals pending standard errors on the cost-curve estimates.

**Equilibrium uniqueness and stability.** The exact-hat counterfactual is the solution of a nested fixed point, so we check that the equilibrium it returns is unique and stable rather than one of several. We re-solve the full no-shale counterfactual from four very different starting points: the trivial all-ones guess, which is the observed world and lies far from the no-shale equilibrium, and three random perturbations whose initial oil-price guesses range from 0.97 to 1.19. All four converge to the same equilibrium. The converged world oil-price change agrees across starts to within $10^{-8}$ (1.0537 in every case), the OPEC Lerner index to within $10^{-9}$, and the entire cross-country wage vector to within $5 \times 10^{-7}$ of the baseline solution. That even the cold observed-world start and a start initialized above the equilibrium both converge to the identical point is numerical evidence that the no-shale equilibrium is unique and globally stable over the relevant region, consistent with the local regularity assumed in Assumption 1.

**Simplified fossil-market model.** The baseline embeds two features that a simpler oil/gas model omits: origin-differentiated (Armington) gas and coal trade, and the government-take fiscal wedge. To show what each adds, we re-solve the no-shale counterfactual in the simplified model that drops both, a single world price for every fuel and no government take, which is the $\sigma_{\text{gas}}, \sigma_{\text{coal}} \to \infty$, $\tau \equiv 0$ limit of the baseline. The market-power core is invariant: OPEC's Lerner index and the oil demand elasticity are unchanged (the markup moves by under a tenth of a percentage point), because origin differentiation sits below the oil–gas–coal nest and the constant take cancels in every quantity response (Section 2.11). The two features instead reshape the *incidence*, and in opposite directions. Government take deepens resource

exporters' losses, because it ties more of their income to the fuel revenue that shale erodes and less to the wage and the markup-leveraged rent. Origin differentiation moves the gas exporters the other way: because imperfect substitution concentrates the no-shale gas scarcity in the United States (US gas +43 percent against roughly +1 percent elsewhere) rather than transmitting it to every supplier, their windfall, and hence their loss from shale, shrinks. On net the gas-heavy exporters see materially smaller losses than the simplified model implies (Russia −1.14 versus −1.91 percent, Norway −0.49 versus −0.97), the oil-dominated OPEC bloc is little changed as the two forces roughly offset (−1.21 versus −1.22), and the United States gains slightly more (+0.65 versus +0.62). Aggregate emissions rise by 738 rather than 636 $MtCO_2$. The sign of every effect, the decoupling of emissions from output, the dominant-firm mechanism, and the production-reallocation pattern are preserved; the two features change the distribution of the welfare effects and where the gas-price decline falls, not the conclusions.

# 6 Conclusion

This paper quantifies the effects of the US shale revolution on energy market power, global production reallocation, real income, and emissions. The split oil and gas model sharpens the mechanism. Oil remains the strategic fossil market: shale oil expands the competitive fringe and disciplines OPEC's markup. Gas is modeled as a competitive fossil input: shale gas changes relative downstream energy costs and the location of energy-intensive production.

Four results stand out. First, the shale revolution lowered the oil price by 5.37 percent and the coal price by 1.62 percent. Because gas is origin-differentiated, it lowered the US gas price by about 43 percent while leaving most other origins near 1 percent, and it reduced OPEC's oil Lerner index by 1.55 percentage points. Second, the oil and gas shocks have distinct roles: oil is central for market power and terms of trade, while gas operates through competitive, origin-differentiated fossil supply and downstream energy costs. Third, the production reallocation runs through two margins. The most fuel-intensive sector, refining, expands where shale fuel is cheap, while the larger set of low-fuel-share tradables contracts through a real-exchange-rate channel as the shale windfall raises US income and the US relative wage. This is a Dutch-disease pattern rather than a reshoring of all energy-intensive production. Fourth, real-income effects are asymmetric and emissions rise by 738 $MtCO_2$ per year, with higher oil and gas emissions partly offset by lower coal emissions.

The results point to a trade interpretation of the shale revolution. The shock was not only an energy-market event; it changed the upstream cost structure of a key intermediate input and propagated through global input-output linkages. Separating oil from gas is essential for

this interpretation because the strategic oil channel and the competitive gas channel move welfare, production, and emissions through different margins.

Several modeling choices deserve discussion. First, we treat all non-OPEC oil producers as price takers. A multi-player oligopoly could capture OPEC+ coordination, but the dominant-firm/fringe structure captures the main asymmetry between OPEC and non-OPEC supply. Second, OPEC is aggregated into a single bloc. The calibration maps all 14 OPEC market members into the OPEC income aggregate, but the welfare number for OPEC should be interpreted as a bloc-level object. Third, trade imbalances are held fixed in nominal terms, as in the standard exact-hat literature. Fourth, gas is modeled as a single competitive world market. In practice the shale-gas era decoupled US prices (Henry Hub) from European and Asian benchmarks, so the world-average gas-price decline understates the US-specific decline. We do not exploit a US gas-price wedge; because the production reallocation is driven by the real-exchange-rate channel rather than by local gas costs (Section 5.4), a regionally segmented gas market would refine the cross-section of sectoral effects without overturning the aggregate reallocation result, and we leave it to future work. Finally, the analysis is static; a dynamic extension with investment and learning-by-doing would be a natural next step.

# References


**Abuin, Carlos**, "Power Decarbonization in a Global Energy Market: The Climate Effect of US LNG Exports," 2024. Mimeo, Harvard University.

**Arkolakis, Costas, Arnaud Costinot, and Andrés Rodríguez-Clare**, "New trade models, same old gains?," *American Economic Review*, 2012, *102* (1), 94–130.

**Armington, Paul S**, "A theory of demand for products distinguished by place of production," *Staff Papers*, 1969, *16* (1), 159–178.

**Arora, Vipin**, "Estimates of the Price Elasticities of Natural Gas Supply and Demand in the United States," 2014. MPRA Paper No. 54232, posted 08 Mar 2014.

**Asker, John, Allan Collard-Wexler, and Jan De Loecker**, "(Mis) allocation, market power, and global oil extraction," *American Economic Review*, 2019, *109* (4), 1568–1615.

**_ , _ , Charlotte De Canniere, Jan De Loecker, and Christopher R. Knittel**, "Two Wrongs Can Sometimes Make a Right: The Environmental Benefits of Market Power in Oil," Working Paper 33115, National Bureau of Economic Research 2024.

**Atkeson, Andrew and Ariel Burstein**, "Pricing-to-Market, Trade Costs, and International Relative Prices," *American Economic Review*, 2008, *98* (5), 1998–2031.

**Azar, José and Xavier Vives**, "General Equilibrium Oligopoly and Ownership Structure," *Econometrica*, 2021, *89* (3), 999–1048.

**Balke, Nathan S., Michael D. Plante, and Mine K. Yücel**, "The Shale Revolution and the Dynamics of the Oil Market," *The Economic Journal*, 2024, *134* (662), 2217–2252.

**Boeters, Stefan and Johannes Bollen**, "Fossil Fuel Supply, Leakage and the Effectiveness of Border Measures in Climate Policy," *Energy Economics*, 2012, *34* (Supplement 2), S181–S189.

**Bornstein, Gideon, Per Krusell, and Sergio Rebelo**, "A world equilibrium model of the oil market," *The Review of Economic Studies*, 2023, *90* (1), 132–164.

**_ , _ , and Sergio T. Rebelo**, "Lags, Costs and Shocks: An Equilibrium Model of the Oil Industry," 2017. CEPR Discussion Paper No. DP12047.

**Caliendo, Lorenzo and Fernando Parro**, "Estimates of the trade and welfare effects of NAFTA," *The Review of Economic Studies*, 2015, *82* (1), 1–44.

**Cruz, José-Luis and Esteban Rossi-Hansberg**, "The Economic Geography of Global Warming," *Review of Economic Studies*, 2024, *91* (2), 899–939.

**d'Aspremont, Claude, Rodolphe Dos Santos Ferreira, and Louis-André Gérard-Varet**, "Unemployment in a Cournot Oligopoly Model with Ford Effects," *Recherches Économiques de Louvain*, 1989, *55* (1), 33–60.

**Eaton, Jonathan and Samuel Kortum**, "Technology, geography, and trade," *Econometrica*, 2002, *70* (5), 1741–1779.

**Encaoua, David and Alexis Jacquemin**, "Degree of monopoly, indices of concentration and threat of entry," *International Economic Review*, 1980, pp. 87–105.

**Farrokhi, Farid and Ahmad Lashkaripour**, "Can Trade Policy Mitigate Climate Change?," 2023. Technical report, Purdue University.

**Feyrer, James, Erin T Mansur, and Bruce Sacerdote**, "Geographic dispersion of economic shocks: Evidence from the fracking revolution," *American Economic Review*, 2017, *107* (4), 1313–1334.

**Gabszewicz, Jean Jaskold and Jean-Philippe Vial**, "Oligopoly "à la Cournot" in a General Equilibrium Analysis," *Journal of Economic Theory*, 1972, *4* (3), 381–400.

**Garcia-Lembergman, Ezequiel, Natalia Ramondo, Andrés Rodríguez-Clare, and Joseph S. Shapiro**, "Carbon Emissions in the Global Economy," 2025.

**Ginsburgh, Victor**, "In the Cournot–Walras General Equilibrium Model, There May Be "More to Gain" by Changing the Numeraire than by Eliminating Imperfections: A Two-Good Economy Example," in Jean Mercenier and T. N. Srinivasan, eds., *Applied General Equilibrium and Economic Development*, Ann Arbor: University of Michigan Press, 1994, pp. 217–224.

**Griffin, James M**, "OPEC behavior: A test of alternative hypotheses," *The American Economic Review*, 1985, *75* (5), 954–963.

**Intergovernmental Panel on Climate Change**, "2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy," Technical Report, Institute for Global Environmental Strategies, Japan 2006.

**Kilian, Lutz**, "The impact of the shale oil revolution on US oil and gasoline prices," *Review of Environmental Economics and Policy*, 2016, *10* (2), 185–205.

**Neary, J. Peter**, "Globalization and Market Structure," *Journal of the European Economic Association*, 2003, *1* (2–3), 245–271.

_ , "International Trade in General Oligopolistic Equilibrium," *Review of International Economics*, 2016, *24* (4), 669–698.

**Negishi, Takashi**, "Monopolistic Competition and General Equilibrium," *The Review of Economic Studies*, 1961, *28* (3), 196–201.

**Newell, Richard G. and Brian C. Prest**, "The Unconventional Oil Supply Boom: Aggregate Price Response from Microdata," *The Energy Journal*, 2019, *40* (3), 1–30.

**Nikaido, Hukukane**, *Monopolistic Competition and Effective Demand*, Princeton, NJ: Princeton University Press, 1975.

**Shapiro, Joseph S**, "Trade costs, CO2, and the environment," *American Economic Journal: Economic Policy*, 2016, *8* (4), 220–54.

**Welsby, Dan, James Price, Steve Pye, and Paul Ekins**, "Unextractable fossil fuels in a 1.5°C world," *Nature*, September 2021, *597*, 230–234. Author Correction published on January 25, 2022, available at https://doi.org/10.1038/s41586-021-03700-0.

# A Counterfactual Scenarios and Result Tables

The quantitative tables use the split oil and gas counterfactuals described in the text. The production-based baseline includes the full, quantity-only, elasticity-only, oil-only, and gas-only runs. The reserve-based robustness specification includes the full no-shale run. Table 18 summarizes the scenario definitions and headline fossil-market outcomes underlying the main tables.

The same model outputs produce scenario-level fossil-market outcomes, country real-income effects, country-sector reallocation effects, and real-income component decompositions.

Table 18: Split Oil/Gas Counterfactual Scenarios

| Elasticity concept | Scenario | Oil price (%) | Gas price (%) | Oil Lerner (pp) |
|---|---|---|---|---|
| Production-based | Full no-shale | -5.38 | -8.48 | -1.55 |
| Production-based | Quantity only | -5.16 | -8.05 | -1.37 |
| Production-based | Elasticity only | -0.04 | -0.01 | -0.20 |
| Production-based | Oil only | -3.36 | -1.25 | -1.38 |
| Production-based | Gas only | -1.83 | -7.06 | -0.14 |
| Reserve-based | Full no-shale | -5.61 | -9.34 | -1.87 |

*Notes:* All scenarios are solved in the same global general-equilibrium model.

# B Supplementary Calibration Evidence

## B.1 Calibration Recipe

The calibration starts from a 2019 global input-output economy. The model country set contains 74 individually observed OECD ICIO countries, an aggregate OPEC bloc, and a residual ROW bloc. The model sector set contains the 48 non-energy OECD ICIO sectors. Mining sectors B05 and B06 are removed from the Armington sector set and treated as fossil inputs.

For each non-energy country-sector cell, production cost shares are

$$\gamma_{\ell,nk} = \frac{VA_{nk}}{Y_{nk}}, \qquad \gamma_{E,nk} = \frac{Z_{B05,nk} + Z_{B06,nk}}{Y_{nk}}, \qquad \gamma_{r,nk} = \frac{Z_{r,nk}}{Y_{nk}}, \tag{60}$$

where $r$ runs over the 48 non-energy model sectors. The B06 fossil input is split into oil and gas, producing energy-bundle shares

$$\omega_{o,nk} + \omega_{g,nk} + \omega_{c,nk} = 1 \tag{61}$$

whenever the cell has positive direct fossil purchases. Final-demand shares satisfy

$$\sum_k \beta_{nk} + \mu_{n,o} + \mu_{n,g} + \mu_{n,c} = 1. \tag{62}$$

The income side uses final absorption as the denominator because the exact-hat income equation is written in units of baseline household expenditure. For each country,

$$\theta_n^s = \frac{\Pi_n^s}{X_n^C}, \qquad s \in \{o, g, c\}, \tag{63}$$

and the trade-imbalance wedge is

$$d_n = 1 - \lambda_n^w - \theta_n^o - \theta_n^g - \theta_n^c. \tag{64}$$

Thus $\lambda_n^w + \theta_n^o + \theta_n^g + \theta_n^c + d_n = 1$ by construction.

## B.2 Eora Bridge for the Aggregate OPEC Bloc

The upstream conduct block treats the 2019 OPEC market members as one dominant firm: AGO, ARE, COG, DZA, ECU, GAB, GNQ, IRN, IRQ, KWT, LBY, NGA, SAU, and VEN. The ICIO country detail directly separates AGO, ARE, NGA, and SAU, while the other ten members are included in ROW. The calibration uses Eora as a bridge for splitting the ICIO ROW block; it does not replace ICIO levels with raw Eora levels.

Let $\mathcal{M}$ be the ROW-embedded OPEC part of ICIO ROW and let $\mathcal{R}$ be the residual non-OPEC ROW part. For each model sector $k$, the Eora bridge computes

$$\alpha_k^Y = \frac{GO_{\mathcal{M}k}^{Eora}}{GO_{\mathcal{M}k}^{Eora} + GO_{\mathcal{R}k}^{Eora}}, \qquad \alpha_k^C = \frac{FD_{\mathcal{M}k}^{Eora}}{FD_{\mathcal{M}k}^{Eora} + FD_{\mathcal{R}k}^{Eora}}, \tag{65}$$

with analogous value-added weights for income-side checks. These weights split the ICIO

ROW objects while preserving OPEC-plus-ROW totals inherited from ICIO. The bridge updates production, final demand, intermediate input use, trade shares, income shares, and fossil-demand weights for the aggregate OPEC and residual ROW blocs.

### B.3 Energy Supply, Market Power, and Shock Objects

Oil, gas, and coal prices convert IO revenue into physical quantities. The oil market is strategic: the model-implied baseline OPEC Lerner index is

$$\mu_O = \frac{s_O}{\varepsilon_o + \varepsilon_f s_f}, \tag{66}$$

with $s_O$ and $s_f$ computed from OPEC and fringe physical oil quantities, $\varepsilon_o$ reconstructed from the IO demand system, and $\varepsilon_f$ computed from producer-level oil elasticities. Gas and coal are competitive fossil markets with country-source supply curves.

The no-shale scenarios modify the US oil fringe and US gas supply. The quantity-only run changes the capacity shifters while holding shale/tight elasticities fixed. The elasticity-only run changes extraction curvature while holding the quantity target fixed. The oil-only and gas-only runs apply these shocks source by source.

## C Derivation of Cost Function and Marginal Cost

### C.1 Producer's Problem

Producer $i$ has technology $q_i = A_i m_i^{\nu_i} \ell_i^{1-\nu_i}$ where $m_i$ is a fixed reserve endowment and $\ell_i$ is the choice variable (labor). The cost of producing $q_i$ units is $C_i = w_i \ell_i$ (only labor is paid; reserves are owned).

### C.2 Deriving the Cost Function

From the production function, solve for labor:

$$\ell_i = \left( \frac{q_i}{A_i m_i^{\nu_i}} \right)^{1/(1-\nu_i)}. \tag{67}$$

Substituting into $C_i = w_i \ell_i$:

$$C_i(q_i, w_i) = w_i \left( \frac{q_i}{A_i m_i^{\nu_i}} \right)^{1/(1-\nu_i)}. \tag{68}$$

## C.3 Deriving Marginal Cost

Differentiating with respect to $q_i$:

$$\begin{aligned} MC_i = \frac{\partial C_i}{\partial q_i} &= w_i \cdot \frac{1}{1-\nu_i} \cdot \frac{1}{A_i^{1/(1-\nu_i)} m_i^{\nu_i/(1-\nu_i)}} \cdot q_i^{1/(1-\nu_i)-1} \\ &= \frac{w_i}{(1-\nu_i)A_i^{1/(1-\nu_i)}} \cdot q_i^{\nu_i/(1-\nu_i)} \cdot m_i^{-\nu_i/(1-\nu_i)} \\ &= \frac{w_i}{(1-\nu_i)A_i^{1/(1-\nu_i)}} \left(\frac{q_i}{m_i}\right)^{\nu_i/(1-\nu_i)} \end{aligned} \tag{69}$$

which is equation (18).

## C.4 Deriving Fringe Supply

A price-taking fringe producer earns the net-of-take price $(1-\tau_f)P_o$ and sets $(1-\tau_f)P_o = MC_f$:

$$(1-\tau_f)P_o = \frac{w_f}{(1-\nu_f)A_f^{1/(1-\nu_f)}} \left(\frac{q_f}{m_f}\right)^{\nu_f/(1-\nu_f)}. \tag{70}$$

Solving for $q_f$:

$$\begin{aligned} \left(\frac{q_f}{m_f}\right)^{\nu_f/(1-\nu_f)} &= \frac{(1-\tau_f)P_o(1-\nu_f)A_f^{1/(1-\nu_f)}}{w_f} \\ \frac{q_f}{m_f} &= \left[\frac{(1-\tau_f)P_o(1-\nu_f)A_f^{1/(1-\nu_f)}}{w_f}\right]^{(1-\nu_f)/\nu_f} \\ q_f &= m_f \cdot A_f^{1/\nu_f} \left[\frac{(1-\tau_f)P_o(1-\nu_f)}{w_f}\right]^{(1-\nu_f)/\nu_f} \end{aligned} \tag{71}$$

where the exponent on $A_f$ follows from $\frac{1}{1-\nu_f} \cdot \frac{1-\nu_f}{\nu_f} = \frac{1}{\nu_f}$. Defining $M_f \equiv A_f^{1/\nu_f} m_f$ gives equation (20).

The supply elasticity with respect to price (holding $w_f$ fixed) is immediate, and the constant net-of-take share $(1-\tau_f)$ drops out of it:

$$\epsilon_{s,f} = \frac{d\ln q_f}{d\ln P_o} = \frac{1-\nu_f}{\nu_f}. \tag{72}$$

## C.5 Exact Aggregate Fringe Supply and Local Elasticity

Let $\mathcal{F}$ denote the set of active fringe producers. Using the individual supply curve above, exact aggregate fringe supply is

$$Q_{fringe}(P_o, \{w_i\}_{i\in\mathcal{F}}) = \sum_{i\in\mathcal{F}} A_i^{1/\nu_i} m_i \left[\frac{(1-\tau_i)P_o(1-\nu_i)}{w_i}\right]^{(1-\nu_i)/\nu_i}. \tag{73}$$

Equivalently, define

$$\epsilon_i \equiv \frac{1-\nu_i}{\nu_i}, \qquad B_i \equiv A_i^{1/\nu_i} m_i (1-\nu_i)^{\epsilon_i} w_i^{-\epsilon_i} (1-\tau_i)^{\epsilon_i}. \tag{74}$$

Then

$$Q_{fringe}(P_o) = \sum_{i\in\mathcal{F}} B_i P_o^{\epsilon_i}. \tag{75}$$

Unless all active producers have the same $\epsilon_i$, this sum is not globally equivalent to a single power function of $P_o$.

The local aggregate fringe elasticity is

$$\varepsilon_f(P_o) \equiv \frac{\partial \ln Q_{fringe}(P_o)}{\partial \ln P_o} = \sum_{i\in\mathcal{F}} \frac{q_i(P_o)}{Q_{fringe}(P_o)} \epsilon_i = \sum_{i\in\mathcal{F}} \frac{q_i(P_o)}{Q_{fringe}(P_o)} \frac{1-\nu_i}{\nu_i}. \tag{76}$$

At a baseline price $P_{o,0}$, the exact supply curve can be represented locally by

$$\widetilde{Q}_{fringe}(P_o) = Q_{fringe}(P_{o,0}) \left(\frac{P_o}{P_{o,0}}\right)^{\varepsilon_f(P_{o,0})}. \tag{77}$$

This local representation has the same level and log-derivative as the exact heterogeneous supply curve at $P_{o,0}$.

Define the representative parameter only as an elasticity-equivalent object:

$$\bar{\nu}_f(P_o) \equiv \frac{1}{1+\varepsilon_f(P_o)}. \tag{78}$$

Then

$$\frac{1-\bar{\nu}_f(P_o)}{\bar{\nu}_f(P_o)} = \varepsilon_f(P_o). \tag{79}$$

Thus $\bar{\nu}_f$ is not generally equal to a production-weighted average of the primitive reserve-intensity parameters $\nu_i$.

## C.6 Profits and Mining Labor

Competitive producer profit:

$$\Pi_f = P_o q_f - C_f = P_o q_f - (1-\nu_f) P_o q_f = \nu_f P_o q_f. \tag{80}$$

For OPEC, $P_o = MC_O/(1-\mu_O)$, so cost is $C_O = (1-\nu_O)\cdot MC_O \cdot q_O = (1-\nu_O)(1-\mu_O)P_o q_O$. Profit is:

$$\Pi_O = P_o q_O - C_O = P_o q_O - (1-\nu_O)(1-\mu_O)P_o q_O = [\nu_O + \mu_O(1-\nu_O)]P_o q_O. \tag{81}$$

Mining labor income for a competitive producer: $w_f \ell_f = C_f = (1-\nu_f)P_o q_f$.

For OPEC: total cost is $(1-\nu_O)(1-\mu_O)P_o q_O$, which equals labor income since labor is the only variable input:

$$w_O \ell_O = C_O = (1-\nu_O)\cdot MC_O \cdot q_O = (1-\nu_O)(1-\mu_O)P_o q_O. \tag{82}$$

# D Derivation of Markup Formula

## D.1 Setup

OPEC maximizes profit:

$$\max_{q_O} \pi_O = P_o(Q)\cdot q_O - C_O(q_O, w_O) \tag{83}$$

where total quantity is $Q = q_O + Q_{fringe}(P_o, \{w_i\}_{i\in\mathcal{F}})$. Under the dominant firm model, OPEC internalizes the fringe supply response: when OPEC adjusts $q_O$, total supply $Q$ changes, which moves the market price $P_o$, which in turn shifts fringe supply $Q_{fringe}(P_o)$.

## D.2 First-Order Condition

Differentiating profit with respect to $q_O$:

$$\frac{\partial \pi_O}{\partial q_O} = P_o + q_O \frac{\partial P_o}{\partial q_O} - MC_O(q_O, w_O) = 0. \tag{84}$$

Rearranging:

$$P_o + q_O \frac{\partial P_o}{\partial q_O} = MC_O(q_O, w_O). \tag{85}$$

## D.3 Computing the Price Response

From market clearing $Q^d(P_o) - q_O - Q_{fringe}(P_o) = 0$, totally differentiating with respect to $q_O$:

$$\frac{\partial Q^d}{\partial P_o} \cdot \frac{\partial P_o}{\partial q_O} - 1 - \frac{\partial Q_{fringe}}{\partial P_o} \cdot \frac{\partial P_o}{\partial q_O} = 0. \tag{86}$$

Solving:

$$\frac{\partial P_o}{\partial q_O} = \frac{1}{\frac{\partial Q^d}{\partial P_o} - \frac{\partial Q_{fringe}}{\partial P_o}}. \tag{87}$$

Since $\partial Q^d/\partial P_o < 0$ and $\partial Q_{fringe}/\partial P_o > 0$, the denominator is negative, confirming $\partial P_o/\partial q_O < 0$.

## D.4 Expressing in Elasticity Form

Define the positive demand elasticity:

$$\varepsilon_o \equiv -\frac{\partial Q^d}{\partial P_o} \cdot \frac{P_o}{Q} > 0 \qquad \Rightarrow \qquad \frac{\partial Q^d}{\partial P_o} = -\varepsilon_o \frac{Q}{P_o}. \tag{88}$$

For the fringe, use the exact local aggregate elasticity from equation (76):

$$\varepsilon_f \equiv \frac{\partial Q_{fringe}}{\partial P_o} \frac{P_o}{Q_{fringe}} \qquad \Rightarrow \qquad \frac{\partial Q_{fringe}}{\partial P_o} = \varepsilon_f \frac{Q_{fringe}}{P_o}. \tag{89}$$

Substituting into (87):

$$\frac{\partial P_o}{\partial q_O} = \frac{1}{-\varepsilon_o \frac{Q}{P_o} - \varepsilon_f \frac{Q_{fringe}}{P_o}} = \frac{-P_o}{\varepsilon_o Q + \varepsilon_f Q_{fringe}}. \tag{90}$$

## D.5 Deriving the Markup

Substitute (90) into (85):

$$P_o + q_O \cdot \frac{-P_o}{\varepsilon_o Q + \varepsilon_f Q_{fringe}} = MC_O. \tag{91}$$

Factor out $P_o$:

$$P_o \left(1 - \frac{q_O}{\varepsilon_o Q + \varepsilon_f Q_{fringe}}\right) = MC_O. \tag{92}$$

Divide numerator and denominator by $Q$. Define $s_O \equiv q_O/Q$ and $s_f \equiv Q_{fringe}/Q$:

$$P_o\left(1 - \frac{s_O}{\varepsilon_o + \varepsilon_f s_f}\right) = MC_O. \tag{93}$$

The Lerner index is:

$$\mu_O \equiv \frac{P_o - MC_O}{P_o} = \frac{s_O}{\varepsilon_o + \varepsilon_f s_f} \tag{94}$$

which is equation (35).

Using the local representative definition in equation (78), this can equivalently be written with $(1 - \bar{\nu}_f)/\bar{\nu}_f$ in place of $\varepsilon_f$.

### D.6 Properties of the Markup

The markup $\mu_O$ is: (i) increasing in $s_O$; (ii) decreasing in $\varepsilon_o$; (iii) decreasing in $s_f$; (iv) decreasing in the local fringe supply elasticity $\varepsilon_f$. The oligopolist's own technology $\nu_O$ does not appear directly in $\mu_O$ but affects the equilibrium indirectly through $s_O$ and $MC_O$.

## E Derivation of Oil Demand Elasticity

This appendix provides a step-by-step derivation of the demand elasticity formula (42). Throughout, we hold wages $\{w_n\}$, coal price $P_c$, total expenditure levels $\{X_{i,k}\}$, and sectoral goods price indices $\{P_{r,n}\}$ fixed.

### E.1 Preliminaries

Oil demand from sector $(n, k)$ is:

$$E_{o,n,k} = \alpha_{o,n,k}\left(\frac{P_o}{P_{E,n,k}}\right)^{-\sigma_E} E_{n,k}. \tag{95}$$

Taking logs:

$$\ln E_{o,n,k} = \ln \alpha_{o,n,k} - \sigma_E(\ln P_o - \ln P_{E,n,k}) + \ln E_{n,k}. \tag{96}$$

Total oil demand is

$$Q_o^d = \sum_{n,k} E_{o,n,k} + \sum_n D_{o,n}. \tag{97}$$

We aggregate using shares of total oil demand:

$$\varphi_{o,nk}^{prod} \equiv \frac{E_{o,n,k}}{Q_o^d}, \qquad \varphi_{o,n}^{HH} \equiv \frac{D_{o,n}}{Q_o^d}, \qquad \sum_{n,k} \varphi_{o,nk}^{prod} + \sum_{n} \varphi_{o,n}^{HH} = 1. \tag{98}$$

Let $H = \sum_n \varphi_{o,n}^{HH}$.

## E.2 Step 1: Energy Price Index Response

The CES energy price index is $P_{E,n,k} = [\sum_{s \in \mathcal{S}} \alpha_{s,n,k} P_s^{1-\sigma_E}]^{1/(1-\sigma_E)}$. Taking the log-derivative:

$$\frac{d \ln P_{E,n,k}}{d \ln P_o} = \frac{1}{1-\sigma_E} \cdot \frac{\alpha_{o,n,k}(1-\sigma_E) P_o^{1-\sigma_E}}{\sum_s \alpha_{s,n,k} P_s^{1-\sigma_E}} = \omega_{o,n,k} \tag{99}$$

where $\omega_{o,n,k}$ is the oil expenditure share in the energy bundle.

## E.3 Step 2: Unit Cost Response

From the Cobb-Douglas unit cost $c_{n,k} = A_{n,k}^{-1} w_n^{\gamma_\ell} P_{E,n,k}^{\gamma_E} \prod_r P_{r,n}^{\gamma_r}$, holding $w_n$ and $P_{r,n}$ fixed:

$$\frac{d \ln c_{n,k}}{d \ln P_o} = \gamma_{E,nk} \cdot \frac{d \ln P_{E,n,k}}{d \ln P_o} = \gamma_{E,nk} \omega_{o,n,k}. \tag{100}$$

## E.4 Step 3: Within-Energy Substitution

From (96), differentiating with $E_{n,k}$ fixed:

$$\left. \frac{\partial \ln E_{o,n,k}}{\partial \ln P_o} \right|_{E_{n,k}} = -\sigma_E \left( 1 - \frac{d \ln P_{E,n,k}}{d \ln P_o} \right) = -\sigma_E (1 - \omega_{o,n,k}). \tag{101}$$

This is negative: when $P_o$ rises, firms substitute from oil toward gas and coal within the energy bundle.

## E.5 Step 4: Total Energy Demand Response

From cost minimization, $P_{E,n,k} E_{n,k} = \gamma_{E,nk} c_{n,k} Y_{n,k}$. Taking logs and differentiating at constant $Y_{n,k}$:

$$\begin{aligned} \left. \frac{d \ln E_{n,k}}{d \ln P_o} \right|_{Y_{n,k}} &= \frac{d \ln c_{n,k}}{d \ln P_o} - \frac{d \ln P_{E,n,k}}{d \ln P_o} \\ &= \gamma_{E,nk} \omega_{o,n,k} - \omega_{o,n,k} = -(1 - \gamma_{E,nk}) \omega_{o,n,k}. \end{aligned} \tag{102}$$

This is negative because $\gamma_{E,nk} < 1$.

## E.6 Step 5: Output Response

When $P_o$ rises, all countries' costs rise simultaneously. The output response depends on relative cost changes. The full derivation is in Appendix F; the result is:

$$\frac{d\ln Y_{n,k}}{d\ln P_o} = -\sigma_k \gamma_{E,nk}\omega_{o,n,k} + (\sigma_k - 1)\bar{\Gamma}_{n,k}. \tag{103}$$

## E.7 Step 6: Combining All Production Channels

The total response of oil demand from sector $(n,k)$ is:

$$\frac{d\ln E_{o,n,k}}{d\ln P_o} = \underbrace{-\sigma_E(1-\omega_{o,n,k})}_{\text{within-energy}} \underbrace{-(1-\gamma_{E,nk})\omega_{o,n,k}}_{\text{expenditure}} \underbrace{-\sigma_k\gamma_{E,nk}\omega_{o,n,k} + (\sigma_k-1)\bar{\Gamma}_{n,k}}_{\text{output}}. \tag{104}$$

Collecting the $\omega_{o,n,k}$ terms:

$$\begin{aligned}
&= -\sigma_E + \sigma_E\omega_{o,n,k} - \omega_{o,n,k} + \gamma_{E,nk}\omega_{o,n,k} - \sigma_k\gamma_{E,nk}\omega_{o,n,k} + (\sigma_k-1)\bar{\Gamma}_{n,k} \\
&= -\sigma_E + (\sigma_E-1)\omega_{o,n,k} - (\sigma_k-1)\gamma_{E,nk}\omega_{o,n,k} + (\sigma_k-1)\bar{\Gamma}_{n,k} \\
&= -\left[\sigma_E - (\sigma_E-1)\omega_{o,n,k} + (\sigma_k-1)(\gamma_{E,nk}\omega_{o,n,k} - \bar{\Gamma}_{n,k})\right].
\end{aligned} \tag{105}$$

## E.8 Step 7: Aggregation of Production Demand

With total-demand weights $\varphi^{prod}_{o,nk} = E_{o,n,k}/Q^d_o$:

$$\varepsilon^{prod}_o = \sum_{n,k} \varphi^{prod}_{o,nk}\left[\sigma_E(1-\omega_{o,nk}) + \omega_{o,nk} + (\sigma_k-1)(\gamma_{E,nk}\omega_{o,nk} - \bar{\Gamma}_{n,k})\right]. \tag{106}$$

This is the cell-level counterpart of the matrix expression in equation (41). It is the contribution of production demand to total oil demand elasticity and is already scaled by the production-demand share $1-H$.

## E.9 Step 8: Household Demand

Household demand for oil in country $n$ is $D_{o,n} = \mu_{n,o}X^C_n/P_o$ (Cobb-Douglas). At constant $X^C_n$:

$$\frac{d\ln D_{o,n}}{d\ln P_o} = -1. \tag{107}$$

With weights $\varphi_{o,n}^{HH} = D_{o,n}/Q_o^d$, the household contribution is $H = \sum_n \varphi_{o,n}^{HH} \cdot 1$.

### E.10 Step 9: Total Demand Elasticity

$$\varepsilon_o = \varepsilon_o^{prod} + \sum_n \varphi_{o,n}^{HH}, \tag{108}$$

which is the scalar form of equation (42).

### E.11 Verification of Special Cases

**Case 1: Symmetric oil intensity.** If $\gamma_{E,nk}\omega_{o,n,k} = g_k$ for all $n$ within each sector, then $\Gamma_{k,i} = g_k$ and $\bar{\Gamma}_{n,k} = g_k$. The reallocation term vanishes: $\varepsilon_o = (1-H)[\sigma_E - (\sigma_E - 1)\bar{\omega}_o^{prod}] + H$, where $\bar{\omega}_o^{prod} = (1-H)^{-1}\sum_{n,k}\varphi_{o,nk}^{prod}\omega_{o,n,k}$.

**Case 2: Single energy type, symmetric, no HH demand.** Set $\omega_o = 1$ for all $n, k$, $H = 0$. Within-energy substitution $= \sigma_E(1-1) = 0$, expenditure effect $= 1$, reallocation $= 0$. So $\varepsilon_o = 1$.

To verify directly: with a single energy type and Cobb-Douglas production, total energy expenditure is $P_o Q_o^d = \sum_{n,k}\gamma_{E,nk}c_{n,k}Y_{n,k}$. Under symmetric $\gamma_E$, this equals $\gamma_E \sum c_{n,k}Y_{n,k}$. With $\sigma_k = 1$, $\sum c_{n,k}Y_{n,k}$ is proportional to total income and does not depend on $P_o$ (holding wages fixed). So $P_o Q_o^d$ is constant, giving $d\ln Q_o^d / d\ln P_o = -1$ and $\varepsilon_o = 1$.

**Case 3: $\sigma_k = 1$.** The reallocation term has factor $\sigma_k - 1 = 0$: $\varepsilon_o = (1-H)[\sigma_E - (\sigma_E - 1)\tilde{\omega}_o^{prod}] + H$ where $\tilde{\omega}_o^{prod} = (1-H)^{-1}\sum_{n,k}\varphi_{o,nk}^{prod}\omega_{o,nk}$.

## F Output Response in a World Market

This appendix derives the response of country $n$'s sector $k$ output to a change in $P_o$, accounting for the fact that all countries' costs move simultaneously.

### F.1 Setup

Revenue of country $n$ in sector $k$ from destination $i$ is:

$$R_{n,k,i} = \pi_{n,k,i} X_{i,k} \tag{109}$$

where $X_{i,k}$ is total expenditure on sector $k$ goods in country $i$ (held fixed) and

$$\pi_{n,k,i} = \frac{b_{n,k,i}(c_{n,k}\tau_{n,k,i})^{1-\sigma_k}}{P_{k,i}^{1-\sigma_k}}, \qquad P_{k,i}^{1-\sigma_k} = \sum_l b_{l,k,i}(c_{l,k}\tau_{l,k,i})^{1-\sigma_k}. \tag{110}$$

## F.2 Step 1: Cost Response

$d\ln c_{l,k}/d\ln P_o = \gamma_{E,lk}\omega_{o,l,k}$.

## F.3 Step 2: Price Index Response

$$\frac{d\ln P_{k,i}}{d\ln P_o} = \sum_l \pi_{l,k,i}\gamma_{E,lk}\omega_{o,l,k} \equiv \Gamma_{k,i}. \tag{111}$$

This is the import-share-weighted average oil intensity of all countries supplying market $i$.

## F.4 Step 3: Trade Share Response

$$\frac{d\ln \pi_{n,k,i}}{d\ln P_o} = (1-\sigma_k)(\gamma_{E,nk}\omega_{o,n,k} - \Gamma_{k,i}). \tag{112}$$

If country $n$ is more oil-intensive than the average supplier to market $i$, its cost rises more than the price index, and its trade share falls (since $1-\sigma_k < 0$).

## F.5 Step 4: Revenue Response

Total revenue $R_{n,k} = \sum_i \pi_{n,k,i}X_{i,k}$. Since $X_{i,k}$ is held fixed:

$$\frac{d\ln R_{n,k}}{d\ln P_o} = \sum_i \frac{R_{n,k,i}}{R_{n,k}} \cdot \frac{d\ln \pi_{n,k,i}}{d\ln P_o} = (1-\sigma_k)(\gamma_{E,nk}\omega_{o,n,k} - \bar{\Gamma}_{n,k}). \tag{113}$$

## F.6 Step 5: Output Response

Output equals revenue divided by unit cost: $Y_{n,k} = R_{n,k}/c_{n,k}$. Therefore:

$$\begin{aligned}\frac{d\ln Y_{n,k}}{d\ln P_o} &= \frac{d\ln R_{n,k}}{d\ln P_o} - \frac{d\ln c_{n,k}}{d\ln P_o} \\ &= (1-\sigma_k)(\gamma_{E,nk}\omega_{o,n,k} - \bar{\Gamma}_{n,k}) - \gamma_{E,nk}\omega_{o,n,k} \\ &= -\sigma_k\gamma_{E,nk}\omega_{o,n,k} + (\sigma_k - 1)\bar{\Gamma}_{n,k}. \end{aligned} \tag{114}$$

### F.7 Discussion

If all countries have the same oil intensity within a sector ($\gamma_{E,nk}\omega_{o,n,k} = \bar{\Gamma}_{n,k} \equiv g_k$), the formula reduces to $d\ln Y_{n,k}/d\ln P_o = -g_k$. All countries' output falls by the same proportion, and no competitive reallocation occurs.

The naive "small country" calculation gives

$$\frac{d\ln Y_{n,k}}{d\ln c_{n,k}} = -\sigma_k, \qquad \frac{d\ln Y_{n,k}}{d\ln P_o} = -\sigma_k\gamma_{E,nk}\omega_{o,n,k}. \tag{115}$$

This overstates the output decline because it ignores the fact that all competitors' costs also rise. The correction $+(\sigma_k - 1)\bar{\Gamma}_{n,k}$ captures the offsetting effect.

## G Equilibrium Conditions

### G.1 Household Optimization

Given prices, the representative household maximizes $U_n = C_n - \delta_n\mathcal{E}$ subject to

$$\sum_k P_{k,n}C_{n,k} + P_oD_{o,n} + P_gD_{g,n} + P_cD_{c,n} = X_n^C. \tag{116}$$

With Cobb-Douglas upper-tier preferences:

$$P_{k,n}C_{n,k} = \beta_{n,k}X_n^C, \qquad P_oD_{o,n} = \mu_{n,o}X_n^C, \tag{117}$$

$$P_gD_{g,n} = \mu_{n,g}X_n^C, \qquad P_cD_{c,n} = \mu_{n,c}X_n^C. \tag{118}$$

Within each manufacturing sector, CES preferences yield demand for the variety from country $l$:

$$x_{l,k,n} = b_{l,k,n}\left(\frac{p_{l,k,n}}{P_{k,n}}\right)^{-\sigma_k}\frac{\beta_{n,k}X_n^C}{P_{k,n}}. \tag{119}$$

### G.2 Firm Optimization

Manufacturing firms minimize cost subject to (27). Factor demands:

$$w_nL_{n,k} = \gamma_{\ell,nk}c_{n,k}Y_{n,k}, \quad P_{E,n,k}E_{n,k} = \gamma_{E,nk}c_{n,k}Y_{n,k}, \quad P_{r,n}M_{r,n,k} = \gamma_{r,nk}c_{n,k}Y_{n,k}. \tag{120}$$

Within the energy bundle, CES optimization yields demand for each energy type (equation (30)). Competitive energy producers set output where price equals marginal cost. OPEC satisfies the first-order condition (85).

## G.3 Market Clearing

**Labor markets.** For each country $n$:

$$\bar{L}_n = \sum_{i \in n} \ell_i^o + \sum_{s \in \{g,c\}} \sum_{j \in n} \ell_j^s + \sum_k L_{n,k} \tag{121}$$

where $\ell_i^o$ is labor in oil field $i$ and $\ell_j^s$ is labor in competitive fossil source $s \in \{g, c\}$ for producer $j$ located in country $n$.

**Energy markets.**

$$q_O + Q_{fringe}(P_o, \{w_i\}_{i \in \mathcal{F}}) = \sum_{n,k} E_{o,n,k} + \sum_n D_{o,n} \tag{122}$$

$$\sum_j q_{j,s}(P_s, \{w_j\}) = \sum_{n,k} E_{s,n,k} + \sum_n D_{s,n}, \qquad s \in \{g, c\} \tag{123}$$

**Goods markets.** For each sector $k$ and origin $l$:

$$c_{l,k} Y_{l,k} = \sum_n \pi_{l,k,n} X_{n,k} \tag{124}$$

where total expenditure on sector $k$ goods in country $n$ is:

$$X_{n,k} = \beta_{n,k} X_n^C + \sum_r \gamma_{k,nr} c_{n,r} Y_{n,r}. \tag{125}$$

**Trade balance.** For each country $n$:

$$\underbrace{\sum_k \sum_{l \neq n} \pi_{n,k,l} X_{l,k}}_{\text{mfg. exports}} + \underbrace{\sum_s P_s q_{s,n}^{net}}_{\text{energy net exports}} = \underbrace{\sum_k \sum_{l \neq n} \pi_{l,k,n} X_{n,k}}_{\text{mfg. imports}} + \Lambda_n \tag{126}$$

where $q_{s,n}^{net} = Q_{s,n}^{supply} - \sum_k E_{s,n,k} - D_{s,n}$ and $\Lambda_n$ is the exogenous trade imbalance.

# H Full Exact-Hat System

This appendix records the exact-hat equations used in the counterfactual solver. Hats denote counterfactual-to-baseline ratios, $\hat{x} \equiv x'/x$. Baseline cost shares, expenditure shares, trade shares, energy shares, income shares, and fossil-supply shares are observed or calibrated from the baseline economy.

## H.1 Manufacturing And Trade

Unit costs and energy price indices are

$$\hat{c}_{n,k} = \hat{A}_{n,k}^{-1} \hat{w}_n^{\gamma_{\ell,nk}} \hat{P}_{E,n,k}^{\gamma_{E,nk}} \prod_r \hat{P}_{r,n}^{\gamma_{r,nk}}, \tag{127}$$

$$\hat{P}_{E,n,k} = \left( \sum_{s \in \mathcal{S}} \omega_{s,nk} \hat{P}_{s,n}^{1-\sigma_E} \right)^{1/(1-\sigma_E)}, \tag{128}$$

where $\hat{P}_{s,n}$ is the source-$s$ price faced by country $n$: the world price $\hat{P}_o$ for oil, and the origin-differentiated importer index $\hat{P}_{s,n}$ of equation (142) for gas and coal (the two coincide in the homogeneous-good limit). Trade shares and sectoral price indices are

$$\pi'_{l,k,n} = \frac{\pi_{l,k,n} (\hat{c}_{l,k} \hat{\tau}_{l,k,n})^{1-\sigma_k}}{\sum_i \pi_{i,k,n} (\hat{c}_{i,k} \hat{\tau}_{i,k,n})^{1-\sigma_k}}, \tag{129}$$

$$\hat{P}_{r,n} = \left( \sum_l \pi_{l,r,n} (\hat{c}_{l,r} \hat{\tau}_{l,r,n})^{1-\sigma_r} \right)^{1/(1-\sigma_r)}. \tag{130}$$

Sectoral expenditure in country $n$ on sector-$k$ goods is final demand plus intermediate demand:

$$\hat{X}_{n,k} X_{n,k} = \beta_{n,k} X_n^C \hat{X}_n + \sum_r \gamma_{k,nr} c_{n,r} Y_{n,r} \hat{c}_{n,r} \hat{Y}_{n,r}. \tag{131}$$

For each origin country $l$ and sector $k$, goods-market clearing is

$$c_{l,k} Y_{l,k} \hat{c}_{l,k} \hat{Y}_{l,k} = \sum_n \pi'_{l,k,n} X_{n,k} \hat{X}_{n,k}. \tag{132}$$

Energy input hats are

$$\hat{E}_{n,k} = \frac{\hat{c}_{n,k} \hat{Y}_{n,k}}{\hat{P}_{E,n,k}}, \qquad \widehat{E_{s,n,k}} = \hat{E}_{n,k} \left( \frac{\hat{P}_{s,n}}{\hat{P}_{E,n,k}} \right)^{-\sigma_E}. \tag{133}$$

## H.2 Oil Market

OPEC's counterfactual markup is

$$\mu'_O = \frac{s'_O}{\varepsilon'_o + \varepsilon'_f s'_f}, \tag{134}$$

where all shares and elasticities are evaluated at counterfactual values. Each fringe producer $n$ supplies

$$\hat{q}_n = \hat{M}_n \cdot R_n^{\epsilon'_n - \epsilon_n} \cdot \left( \frac{\hat{P}_o}{\hat{w}_n} \right)^{\epsilon'_n}, \tag{135}$$

where $\epsilon_n = (1-\nu_n)/\nu_n$, $\epsilon'_n = (1-\nu'_n)/\nu'_n$, $R_n = P_o/w_n$, and $\hat{M}_n$ includes both capacity shifts and the change in the $(1-\nu)$ term from the supply curve. Aggregate fringe supply is

$$\hat{Q}_f = \sum_{n \in \text{fringe}} \phi_n \hat{q}_n, \tag{136}$$

where $\phi_n = q_n / Q_{fringe}$ are baseline fringe production shares. The counterfactual local fringe elasticity is

$$\varepsilon'_f = \sum_{n \in \text{fringe}} \phi'_n \epsilon'_n, \qquad \phi'_n = \frac{\phi_n \hat{q}_n}{\sum_{m \in \text{fringe}} \phi_m \hat{q}_m}. \tag{137}$$

OPEC's quantity hat from the first-order condition is

$$\hat{q}_O = \left( \frac{\hat{P}_o (1-\mu'_O)/(1-\mu_O)}{\hat{w}_O} \right)^{(1-\nu_O)/\nu_O}. \tag{138}$$

Oil profit hats are

$$\hat{\Pi}^o_n = \frac{\nu'_n}{\nu_n} \hat{P}_o \hat{q}_n \tag{139}$$

for a competitive fringe producer and

$$\hat{\Pi}^o_O = \hat{P}_o \, \hat{q}_O \cdot \frac{\nu_O + \mu'_O(1-\nu_O)}{\nu_O + \mu_O(1-\nu_O)} \tag{140}$$

for OPEC.

## H.3 Competitive Gas And Coal

For $s \in \{g, c\}$, gas and coal are origin-differentiated. Producer $j$ at origin $o$ supplies against its own price hat $\hat{P}_{s,o}$,

$$\hat{q}_{j,s} = \hat{M}_{j,s} \left( \frac{\hat{P}_{s,o}}{\hat{w}_j} \right)^{(1-\nu_{j,s})/\nu_{j,s}}, \tag{141}$$

with aggregate origin supply $\hat{Q}^{supply}_{o,s} = \sum_{j \in o} \phi^s_j \hat{q}_{j,s}$ and competitive profit hat $\hat{\Pi}_{j,s} = (\nu'_{j,s}/\nu_{j,s}) \hat{P}_{s,o} \hat{q}_{j,s}$. The counterfactual bilateral expenditure shares and the importer price index are the exact-hat CES objects, with origin cost hats $\hat{P}_{s,o}$ and trade-cost hats $\hat{\tau}^{\text{tr}}_{s,oi}$ (unity

in the counterfactual),

$$\pi'_{s,oi} = \frac{\pi_{s,oi}\,(\hat{P}_{s,o}\hat{\tau}^{\text{tr}}_{s,oi})^{1-\sigma_s}}{\sum_{o'}\pi_{s,o'i}\,(\hat{P}_{s,o'}\hat{\tau}^{\text{tr}}_{s,o'i})^{1-\sigma_s}}, \qquad \hat{P}_{s,i} = \Big(\sum_{o}\pi_{s,oi}\,(\hat{P}_{s,o}\hat{\tau}^{\text{tr}}_{s,oi})^{1-\sigma_s}\Big)^{\frac{1}{1-\sigma_s}}. \tag{142}$$

The per-importer index $\hat{P}_{s,i}$ replaces the scalar $\hat{P}_s$ wherever source-$s$ demand or the consumption price index appears. Each origin clears in value: writing $S^{\text{base}}_{s,o} = \sum_i \pi_{s,oi} X^{\text{base}}_{s,i}$ for the trade-implied baseline origin revenue and $X^{\text{cf}}_{s,i} = \hat{P}_{s,i}\,\hat{Q}_{s,i}\,X^{\text{base}}_{s,i}$ for counterfactual importer expenditure,

$$\hat{P}_{s,o}\,\hat{Q}^{supply}_{o,s}\,S^{\text{base}}_{s,o} \;=\; \sum_i \pi'_{s,oi}\,X^{\text{cf}}_{s,i}, \qquad s \in \{g,c\},\ \forall o, \tag{143}$$

which at $\hat{P}_{s,o} = 1$ reduces to $S^{\text{base}}_{s,o} = \sum_i \pi_{s,oi} X^{\text{base}}_{s,i}$ (the no-shock identity). The homogeneous-good clearing (151) is the $\sigma_s \to \infty$ limit.

**Government take.** With a constant per-origin take $\tau_{o,s}$, the producer faces $(1-\tau_{o,s})\hat{P}_{s,o}$; because the take is unchanged across the counterfactual, $((1-\tau')/(1-\tau)) = 1$ cancels and *every* quantity, profit, and mining-labor hat above is unchanged. The take enters only the household budget, through the rebate hat

$$\widehat{\text{reb}}_n = \frac{\sum_s \tau_{n,s} P_{s,n} q_{n,s}\,(\hat{P}_{s,n}\hat{q}_{n,s})}{\sum_s \tau_{n,s} P_{s,n} q_{n,s}}, \tag{144}$$

the take-base-weighted average of the fuel *revenue* hats (for oil this uses $\hat{P}_o\hat{q}_{n,o}$, not the markup-laden rent hat).

## H.4 Income, Labor, And Fossil Market Clearing

Define income shares using $X^C_n$ as denominator. With government take, the rent shares are net of the take, $\theta^s_n = (1-\tau_{n,s})\Pi^s_n / X^C_n$, the rebated-take share is $\theta^{\text{roy}}_n = \sum_s \tau_{n,s} P_{s,n} q_{n,s} / X^C_n$, and the labor share is net of the take, so that

$$\lambda^w_n + \theta^o_n + \theta^g_n + \theta^c_n + \theta^{\text{roy}}_n + d_n = 1, \qquad d_n = \frac{\Lambda_n}{X^C_n}. \tag{145}$$

The income hat adds the rebate term to the budget:

$$\hat{X}_n = \lambda^w_n \hat{w}_n + \theta^o_n \hat{\Pi}^o_n + \theta^g_n \hat{\Pi}^g_n + \theta^c_n \hat{\Pi}^c_n + \theta^{\text{roy}}_n\,\widehat{\text{reb}}_n + d_n, \tag{146}$$

with $\widehat{\text{reb}}_n$ from equation (144); with $\tau \equiv 0$ this collapses to the no-take budget ($\theta^{\text{roy}} = 0$). The $d_n$ term is not multiplied by a hat because trade imbalances are held fixed in levels.

Labor demand includes manufacturing sectors and mining:

$$\hat{w}_n \cdot w_n L_n = \sum_{k=1}^{K} \gamma_{\ell,nk} c_{n,k} Y_{n,k} \hat{c}_{n,k} \hat{Y}_{n,k} + \ell_n^{o,\text{labor}} + \ell_n^{g,\text{labor}} + \ell_n^{c,\text{labor}}. \tag{147}$$

The oil mining labor term is

$$\ell_n^{o,\text{labor}} = \begin{cases} (1-\nu_O)(1-\mu_O) Y_{n,o} \cdot \frac{(1-\mu_O')}{(1-\mu_O)} \hat{P}_o \hat{q}_O & \text{if } n = \text{OPEC}, \\ (1-\nu_n) Y_{n,o} \cdot \frac{(1-\nu_n')}{(1-\nu_n)} \hat{P}_o \hat{q}_n & \text{if } n \in \text{fringe}, \\ 0 & \text{otherwise}, \end{cases} \tag{148}$$

$$\ell_n^{s,\text{labor}} = (1-\nu_{n,s}) Y_{n,s} \cdot \frac{1-\nu_{n,s}'}{1-\nu_{n,s}} \hat{P}_{s,n} \hat{q}_{n,s} \quad \text{for } s \in \{g, c\}. \tag{149}$$

Here $Y_{n,o}$, $Y_{n,g}$, and $Y_{n,c}$ denote baseline fossil gross-output values, not physical quantities. On the supply side (the mining-labor and profit terms) $\hat{P}_{s,n}$ is the origin price country $n$'s producers receive; on the demand side below it is the importer index of equation (142). The two coincide in the homogeneous-good limit, so the equations specialize to the single-price model when $\sigma_s \to \infty$.

Oil market clearing is

$$\underbrace{\sum_{n,k} \varphi_{o,nk}^{prod} \hat{E}_{n,k} \left( \frac{\hat{P}_o}{\hat{P}_{E,n,k}} \right)^{-\sigma_E}}_{\text{production demand}} + \underbrace{\sum_{n} \varphi_{o,n}^{HH} \frac{\hat{X}_n}{\hat{P}_o}}_{\text{household demand}} = s_O \hat{q}_O + s_f \hat{Q}_f. \tag{150}$$

For gas and coal, the active condition is the per-origin value clearing (143); summing it over origins gives the aggregate balance

$$\sum_{n,k} \varphi_{s,nk}^{prod} \hat{E}_{n,k} \left( \frac{\hat{P}_{s,n}}{\hat{P}_{E,n,k}} \right)^{-\sigma_E} + \sum_{n} \varphi_{s,n}^{HH} \frac{\hat{X}_n}{\hat{P}_{s,n}} = \sum_{j} \phi_j^s \hat{q}_{j,s}, \qquad s \in \{g, c\}, \tag{151}$$

which is the single-market quantity clearing of the homogeneous-good model in the $\sigma_s \to \infty$ limit.

## H.5 Counterfactual Oil Demand Elasticity

The counterfactual demand elasticity $\varepsilon'_o$ in equation (134) is recomputed at each iteration. The counterfactual oil share within the energy bundle is

$$\omega'_{o,n,k} = \frac{\omega_{o,n,k}\hat{P}_o^{1-\sigma_E}}{\sum_{s\in\mathcal{S}}\omega_{s,nk}\hat{P}_{s,n}^{1-\sigma_E}}. \tag{152}$$

The competitor-intensity objects are

$$\Gamma'_{k,i} = \sum_l \pi'_{l,k,i}\gamma_{E,lk}\omega'_{o,l,k}, \qquad \bar{\Gamma}'_{n,k} = \sum_i \frac{R'_{n,k,i}}{R'_{n,k}}\Gamma'_{k,i}, \tag{153}$$

where $R'_{n,k,i} = \pi'_{n,k,i}X'_{i,k}$. Define

$$\widehat{E_{o,n,k}} = \hat{E}_{n,k}\left(\frac{\hat{P}_o}{\hat{P}_{E,n,k}}\right)^{-\sigma_E}, \qquad \hat{D}_{o,n} = \frac{\hat{X}_n}{\hat{P}_o}. \tag{154}$$

Then

$$\varphi^{prod\prime}_{o,nk} = \frac{\varphi^{prod}_{o,nk}\widehat{E_{o,n,k}}}{\sum_{a,b}\varphi^{prod}_{o,ab}\widehat{E_{o,a,b}} + \sum_a \varphi^{HH}_{o,a}\hat{D}_{o,a}}, \qquad \varphi^{HH\prime}_{o,n} = \frac{\varphi^{HH}_{o,n}\hat{D}_{o,n}}{\sum_{a,b}\varphi^{prod}_{o,ab}\widehat{E_{o,a,b}} + \sum_a \varphi^{HH}_{o,a}\hat{D}_{o,a}}. \tag{155}$$

The counterfactual demand elasticity used in the markup formula is

$$\varepsilon'_o = \sum_{n,k}\varphi^{prod\prime}_{o,nk}\left[\sigma_E(1-\omega'_{o,n,k}) + \omega'_{o,n,k} + (\sigma_k - 1)(\gamma_{E,nk}\omega'_{o,n,k} - \bar{\Gamma}'_{n,k})\right] + \sum_n \varphi^{HH\prime}_{o,n}. \tag{156}$$

## H.6 Welfare

Private real-income hats are

$$\hat{W}_n = \frac{\hat{X}_n}{\hat{P}_n}, \tag{157}$$

where $\hat{P}_n = \prod_k \hat{P}_{k,n}^{\beta_{n,k}}\hat{P}_o^{\mu_{n,o}}\hat{P}_{g,n}^{\mu_{n,g}}\hat{P}_{c,n}^{\mu_{n,c}}$, with the gas and coal terms evaluated at the importer indices $\hat{P}_{g,n}, \hat{P}_{c,n}$ of equation (142); the government take enters welfare only through $\hat{X}_n$, which carries the rebate term of equation (146). For utility with climate damages, use the level change

$$\Delta V_n = W_n(\hat{W}_n - 1) - \delta_n(\mathcal{E}' - \mathcal{E}). \tag{158}$$

# I Technology Entry and Market Power

This appendix proves Proposition 3 and Corollary 1. The argument updates the heterogeneous fringe through its local supply elasticity, not a production-weighted average of the primitive $\nu_i$'s, and signs the price, markup, and amplification effects by the implicit function theorem under Assumption 1.

## I.1 Exact Fringe Update

Let the incumbent fringe supply at price $P$ be

$$Q_f(P) = \sum_{i \in \mathcal{F}} B_i P^{\epsilon_i}, \qquad \epsilon_i = \frac{1-\nu_i}{\nu_i}. \tag{159}$$

The incumbent local fringe elasticity is

$$\varepsilon_f(P) = \sum_{i \in \mathcal{F}} \frac{q_i(P)}{Q_f(P)} \epsilon_i. \tag{160}$$

Suppose entrants add supply

$$\Delta Q(P) = \sum_{h \in \mathcal{H}} B_h P^{\epsilon_h}, \qquad \epsilon_h = \frac{1-\nu_h}{\nu_h}, \tag{161}$$

where $\mathcal{H}$ is the set of new shale producers. The post-entry exact fringe supply is

$$Q_f^{new}(P) = Q_f(P) + \Delta Q(P). \tag{162}$$

Its local elasticity is

$$\varepsilon_f^{new}(P) = \frac{Q_f(P)}{Q_f^{new}(P)} \varepsilon_f(P) + \frac{\Delta Q(P)}{Q_f^{new}(P)} \varepsilon_h(P), \tag{163}$$

where

$$\varepsilon_h(P) = \sum_{h \in \mathcal{H}} \frac{q_h(P)}{\Delta Q(P)} \epsilon_h. \tag{164}$$

Thus post-entry elasticity rises at price $P$ whenever entrant supply is locally more elastic than incumbent fringe supply:

$$\varepsilon_h(P) > \varepsilon_f(P) \quad \Rightarrow \quad \varepsilon_f^{new}(P) > \varepsilon_f(P). \tag{165}$$

The corresponding representative parameter is then

$$\bar{\nu}_f^{new}(P) = \frac{1}{1 + \varepsilon_f^{new}(P)}. \tag{166}$$

This is the correct update. Averaging the primitive $\nu_i$'s is generally not consistent with the exact aggregate supply curve.

## I.2 Price Effect (Proposition 3, part 2)

Index shale entry by a scalar $t$, with fringe supply $Q_f(P_o, t)$ satisfying $\partial Q_f/\partial t > 0$ (capacity) and $\partial \varepsilon_f/\partial t > 0$ (part 1). The equilibrium pair $(P_o, q_O)$ solves market clearing $q_O + Q_f(P_o, t) = Q^d(P_o)$ together with OPEC's first-order condition $F(q_O, t) \equiv P_R(q_O, t) + q_O\, \partial P_R/\partial q_O - MC_O(q_O) = 0$, where $P_R(q_O, t)$ is the inverse residual demand $D_R(P_o, t) = Q^d(P_o) - Q_f(P_o, t)$. Assumption 1(iv) states $\partial F/\partial q_O < 0$ (residual marginal revenue cuts marginal cost from above). Differentiating market clearing,

$$\frac{dP_o}{dt} = \frac{dq_O/dt + Q_{f,t}}{Q^{d\prime} - Q_{f,P}}, \qquad Q^{d\prime} - Q_{f,P} = D_{R,P} < 0, \tag{167}$$

where the denominator is negative by Assumption 1(i)–(ii). For the numerator, the implicit function theorem applied to OPEC's first-order condition gives $dq_O/dt = -(\partial F/\partial t)/(\partial F/\partial q_O)$. Entry shifts OPEC's residual demand inward and steepens it, so $\partial F/\partial t < 0$, and with $\partial F/\partial q_O < 0$ this yields $dq_O/dt < 0$: OPEC contracts. Moreover the dominant firm accommodates the fringe expansion only partially, $|dq_O/dt| < Q_{f,t}$, so the numerator of (167) is strictly positive. Hence $dP_o/dt < 0$ and

$$P_o' < P_o. \tag{168}$$

Both forces in part 2 act in the same direction: the inward shift ($Q_{f,t} > 0$) and the elasticity increase (which makes $\partial F/\partial t$ more negative) each push the equilibrium price down.

## I.3 Markup Effect (Proposition 3, part 3)

The exact local markup formula is

$$\mu_O = \frac{s_O}{\varepsilon_o + \varepsilon_f s_f}. \tag{169}$$

After entry,

$$\mu'_O = \frac{s'_O}{\varepsilon'_o + \varepsilon'_f s'_f}. \tag{170}$$

Entry tends to reduce $\mu_O$ through three local forces: it lowers OPEC's share $s_O$, raises the fringe share $s_f$, and raises $\varepsilon_f$ if entrants are more elastic than incumbents. A strict markup decline follows under the sufficient condition

$$\frac{s'_O}{s_O} < \frac{\varepsilon'_o + \varepsilon'_f s'_f}{\varepsilon_o + \varepsilon_f s_f}. \tag{171}$$

This condition makes explicit that the result is local and depends on equilibrium changes in both market shares and demand elasticity. In the baseline shale mechanism, the left side is below one and the right side is above one because fringe entry lowers OPEC's share and raises the effective competitive constraint.

## I.4 Amplification (Corollary 1)

Write OPEC's effective supply $q_O^{\text{eff}}(P_o;\mu)$ as the solution of $MC_O(q_O) = P_o(1-\mu)$, so that

$$\frac{\partial q_O^{\text{eff}}}{\partial P_o} = \frac{1-\mu}{MC'_O} > 0, \qquad \frac{\partial q_O^{\text{eff}}}{\partial \mu} = -\frac{P_o}{MC'_O} < 0, \tag{172}$$

where $MC'_O > 0$ by Assumption 1(iii). Market clearing is $q_O^{\text{eff}}(P_o;\mu) + Q_f(P_o,t) = Q^d(P_o)$. Differentiating in $t$ and $\mu$ and collecting terms,

$$D\, dP_o = -\frac{\partial q_O^{\text{eff}}}{\partial \mu}\, d\mu - Q_{f,t}\, dt, \qquad D \equiv \frac{\partial q_O^{\text{eff}}}{\partial P_o} + Q_{f,P} - Q^{d\prime} > 0. \tag{173}$$

Holding the markup fixed ($d\mu = 0$) gives the fixed-markup price change $dP_o^{\text{fix}} = -Q_{f,t}\, dt/D < 0$. Allowing the markup to respond as in Proposition 3.3 ($d\mu < 0$) adds the term $-(\partial q_O^{\text{eff}}/\partial \mu)\, d\mu = (P_o/MC'_O)\, d\mu < 0$ to the right-hand side of (173), so

$$dP_o^{\text{endog}} = dP_o^{\text{fix}} + \frac{(P_o/MC'_O)}{D}\, d\mu < dP_o^{\text{fix}} < 0, \qquad \Longrightarrow \qquad \left|dP_o^{\text{endog}}\right| > \left|dP_o^{\text{fix}}\right|. \tag{174}$$

The endogenous decline in OPEC's markup shifts its effective supply outward at every price and therefore deepens the price fall, which proves Corollary 1. The amplification gap $(P_o/MC'_O)\, d\mu/D$ is precisely what the fixed-markup no-shale counterfactual in Section 5.2 isolates.

# J Back-of-Envelope Markup Decomposition

This appendix decomposes the shale effect on OPEC's Lerner index into a quantity (market-share) channel and a fringe-elasticity channel, using the markup formula $\mu_O = s_O/(\varepsilon_o + \varepsilon_f s_f)$ at the calibrated demand elasticity $\varepsilon_o = 1.98$. The pre-shale (no-shale) oil-market moments are $s_O = 0.417$, $s_f = 0.583$, and $\varepsilon_f = 1.329$; the post-shale (observed 2019) moments are $s_O = 0.385$, $s_f = 0.615$, and $\varepsilon_f = 1.406$.

Pre-shale: $\mu_O^{pre} = 0.417/(1.98 + 1.329 \times 0.583) = 0.151$.

Post-shale: $\mu_O^{post} = 0.385/(1.98 + 1.406 \times 0.615) = 0.135$.

Counterfactual (post-shale shares, pre-shale fringe elasticity): $\mu_O^{cf} = 0.385/(1.98 + 1.329 \times 0.615) = 0.137$.

The total decline is 1.6 percentage points. The quantity channel, $\mu_O^{pre} - \mu_O^{cf} = 1.4$ points, accounts for about 86 percent, as shale supply lowers OPEC's market share. The fringe-elasticity channel, $\mu_O^{cf} - \mu_O^{post} = 0.2$ points, accounts for the remaining 14 percent, as shale entry raises the local fringe supply elasticity. The elasticity channel is modest in this partial-equilibrium accounting but is amplified in the full general equilibrium through input-output linkages and the endogenous adjustment of the oil demand elasticity, where the full shale effect on the Lerner index is 1.55 percentage points (Table 7).

# K Solution Algorithm

The model is solved by nested iteration. An outer loop clears the energy markets over three scalar price *levels* $(\hat{P}_o, \hat{P}_g, \hat{P}_c)$; an inner manufacturing loop returns wages, costs, income, and energy demand for given energy prices; and, for the origin-differentiated sources, a per-origin price sub-solve (Section K.1) converts each scalar gas or coal level into a vector of origin prices and importer indices. Oil is a single world market throughout.

## K.1 Per-Origin Price Sub-Solve

For each origin-differentiated source $s \in \{g, c\}$, the scalar level $\hat{P}_s$ sets the overall price; the cross-origin dispersion is solved separately, and because the relative prices are level-free they depend only on wages and the supply shocks, not on $\hat{P}_s$. Write $\hat{P}_{s,o} = \hat{P}_s\, r_{s,o}$ for the origin price and $\hat{P}_{s,n} = \hat{P}_s\, \Phi_{s,n}(r)$ for the importer index, where $\Phi_{s,n}(r) = \left(\sum_o \pi_{s,on}\, r_{s,o}^{1-\sigma_s}\right)^{1/(1-\sigma_s)}$. Given wages $\{\hat{w}_n\}$ and shocks $\{\hat{M}_{s,o}\}$, solve the relative prices $\{r_{s,o}\}$ by tatonnement:

1. Form counterfactual bilateral shares $\pi'_{s,on}$ and the index $\Phi_{s,n}$ from equation (142) evaluated at $\hat{P}_{s,o} = r_{s,o}$.

2. Origin demand (expenditure) $D_{s,o} = \sum_n \pi'_{s,on} X^{\text{base}}_{s,n} \Phi_{s,n}$; origin supply (revenue) $S_{s,o} = S^{\text{base}}_{s,o} r_{s,o} \hat{q}_{s,o}$, with $\hat{q}_{s,o} = \hat{M}_{s,o}(r_{s,o}/\hat{w}_o)^{(1-\nu)/\nu}$ from equation (141).
3. Update $r_{s,o} \leftarrow r_{s,o} (D_{s,o}/S_{s,o})^{\kappa}$ and renormalize so the $S^{\text{base}}_{s,o}$-weighted geometric mean of $\{r_{s,o}\}$ is one; iterate until the per-origin ratios $D_{s,o}/S_{s,o}$ are equalized (relative clearing).

At $r_{s,o} = 1$ this reduces to $S^{\text{base}}_{s,o} = \sum_n \pi_{s,on} X^{\text{base}}_{s,n}$, the no-shock identity, so the sub-solve returns $r_{s,o} \equiv 1$ and $\Phi_{s,n} \equiv 1$ under no shock. The common level of the cleared ratios is left to the outer loop.

## K.2 Outer Loop: Energy Market Equilibrium

1. Guess the three scalar energy levels $(\hat{P}_o, \hat{P}_g, \hat{P}_c)$.
2. Run the per-origin sub-solve for gas and coal to obtain $\{\hat{P}_{s,o}\}$ (supply) and $\{\hat{P}_{s,n}\}$ (demand).
3. Run the inner loop (manufacturing equilibrium) to obtain all hats, with household and firm fuel demand facing the importer indices $\hat{P}_{s,n}$.
4. Form the residuals. Oil clears in quantity, equation (150). Each origin-differentiated source clears in *value*: the scalar level $\hat{P}_s$ is moved to zero the aggregate value residual $\sum_n \left(\text{source-}s \text{ expenditure}_n\right) - \sum_o S^{\text{base}}_{s,o} \hat{P}_{s,o} \hat{q}_{s,o} / \sum_o S^{\text{base}}_{s,o}$, the aggregate counterpart of equation (143); the relative dispersion is already cleared inside the sub-solve.
5. Update the three levels (a Newton/Krylov step on the log-prices) and iterate until the residuals vanish.

## K.3 Inner Loop: Manufacturing Equilibrium

Given energy prices (levels and the per-origin objects from the sub-solve):

1. Compute energy price indices $\hat{P}_{E,n,k}$ from equation (128) using baseline $\omega_{s,nk}$ and the importer indices $\hat{P}_{s,n}$.
2. Guess wages $\{\hat{w}_n\}$ (one country as numeraire).
3. Iterate unit costs $\hat{c}_{n,k}$ from equation (127) with sectoral price indices $\hat{P}_{r,n}$ from equation (130) until convergence (IO fixed-point iteration).
4. Compute counterfactual trade shares $\pi'_{l,k,n}$ from equation (129).
5. Update total sectoral absorption $X'_{i,k}$ from equation (131) using current $\hat{X}_n$ and $\hat{Y}_{n,k}$.

6. Compute revenue weights $R'_{n,k,i}/R'_{n,k}$ using $\pi'$ and $X'_{i,k}$, then update $\Gamma'_{k,i}$, $\bar{\Gamma}'_{n,k}$, and recompute $\varepsilon'_o$.

7. Solve OPEC FOC for $\hat{q}_O$ using $\hat{w}_O$ from labor market clearing.

8. Compute profit hats: $\hat{\Pi}^o_O$ from equation (140), $\hat{\Pi}^o_n$ for the fringe from equation (139), and $\hat{\Pi}_{j,s} = (\nu'_{j,s}/\nu_{j,s})\hat{P}_{s,o}\hat{q}_{j,s}$ for $s \in \{g, c\}$ at the origin prices.

9. Compute the rebate hats $\widehat{\text{reb}}_n$ from equation (144) (the take-base-weighted average of the fuel *revenue* hats), then income hats $\hat{X}_n$ from equation (146), including the rebate term $\theta^{\text{roy}}_n \widehat{\text{reb}}_n$ and the constant $d_n$.

10. Update $\hat{Y}_{n,k}$ from goods market clearing (132).

11. Compute labor demand: model sectors plus mining labor (equations (148)–(149)), the gas and coal terms at the origin prices $\hat{P}_{s,n}$.

12. Update wages and iterate until convergence.

Because the resource rents and the rebate both feed $\hat{X}_n$, which in turn feeds energy demand, steps 8–9 are iterated to a fixed point: the rebate $\widehat{\text{reb}}_n$ co-converges as a fourth iterate alongside $(\hat{\Pi}^o_n, \hat{\Pi}^g_n, \hat{\Pi}^c_n)$ under common damping. With $\tau \equiv 0$ the rebate is identically one and this collapses to the no-take fixed point.

## K.4 Convergence

The algorithm converges when oil quantity clearing, the gas and coal aggregate value residuals, the per-origin relative-clearing dispersion, and labor market clearing are all within tolerance $\epsilon = 10^{-6}$:

$$\max\left\{|\hat{Q}^d_o - \hat{Q}^s_o|,\ |Z^{\text{val}}_g|,\ |Z^{\text{val}}_c|,\ \max_{s,o}\left|\ln(D_{s,o}/S_{s,o}) - \overline{\ln(D_s/S_s)}\right|,\ \max_n |\hat{L}^d_n - 1|\right\} < \epsilon, \quad (175)$$

where $Z^{\text{val}}_s$ is the aggregate value residual of source $s$ and the fourth term is the per-origin dispersion about its $S^{\text{base}}$-weighted mean.