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ABSTRACT

What is the optimal response of an exhaustible resource producer to sanctions in the form of a price cap? This paper develops a dynamic framework incorporating stochastic prices, financial frictions, and market power to study this novel tool of statecraft. A binding price cap can incentivize increased extraction, stabilizing prices in the global market. But the cap's effectiveness diminishes when the policy is leaky or is weakly enforced, as seen with the G7 price cap on Russian oil. Such imperfections introduce a trade-off between market stability and the welfare of the sanctioned producer. We provide a systematic approach to setting an optimal cap level in these circumstances.

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1 Introduction

We live in an era of heightened geopolitical tensions, where key global commodities are often controlled by states led by adversarial actors. How can pressure be effectively applied to such nations without disrupting access to these essential resources? What strategies and tools of statecraft can be used to sanction a country whose exports are critical to global production?

These questions became especially pressing following Russia's aggression in Ukraine. In late 2022, a coalition of western countries, including the G7, EU, and Australia, implemented a $60 per barrel price cap on seaborne Russian oil. Under this policy, oil exported with the use of Western services, such as insurance or shipping, must legally be sold below this ceiling. The stated goal of the policy was to solve the conundrum: reduce revenue from Russia's energy sales while avoiding a global supply shock.

An effective cap would demonstrate that no country is too large to evade the consequences of sanctions. However, enforcement of the price cap on Russian oil has been lax, jeopardizing the policy's effectiveness. This was in part due to concerns that strict implementation could escalate into an embargo, triggering a supply shock and a surge in oil prices at a time when inflation was already a critical concern for policymakers. Whether these concerns are justified remains an open question and motivates the focus of this paper.

To address these critical issues, we develop a dynamic theory of petrostate behavior under sanctions and propose a framework for optimizing sanctions policy against such actors. There are three key reasons why existing frameworks are inadequate for studying questions related to the price cap.

First, static models commonly used in policy analysis offer only a partial view. Resource extraction is inherently dynamic, requiring a framework that accounts for price fluctuations driven by both endogenous and exogenous factors. A price cap may be binding today but expected to be non-binding in the future, or vice versa, which influences its current effects. In addition, a dynamic model is crucial for addressing policy credibility issues.

Second, models analyzing price caps must align with empirical findings, such as the observed low supply elasticities across countries. The literature has long recognized that the frictionless Hotelling (1931) model predicts perfectly elastic supply, which is inconsistent with reality (Anderson et al. (2018)). Although adjustment costs in dynamic resource extraction models explain short-run supply inelasticity, they are not sufficient in this context for two reasons: first, adjustment costs are likely asymmetric. It is easier to decrease output than to increase it. Since policymakers focus on supply cuts by sanctioned producers, these costs may be less relevant. Second, adjustment cost models predict inaction regions, where small shocks do not elicit response, but large shocks do. Given our interest in the effects of the price cap policy, we are interested in large shifts and the possibly sizable and non-linear responses. Focusing on economic incentives without adjustment costs and solving the problem fully non-linearly provides new insights.

Third, a model for studying national producers under sanctions must include features critical to their context. A first-order issue when it comes to sanctioning large producers is their market power. Furthermore, unlike resource-extracting firms in the private sector, state actors have alternative income sources, such as general taxation (even if they are heavily fiscally dependent on the revenues from exhaustible resource extraction). We show why this matters. Any model used for this task should also be consistent with insights from the resource curse literature, particularly the adverse effects of resource price volatility on commodity-producing economies, due to the imperfect ability to smooth through such shocks. Relatedly, a framework should be able to take into account the complementary effects of other (e.g., financial) sanctions on resource-centered policies.

Our dynamic model responds to these challenges. In our model, exports of an exhaustible resource fund a part of the state's spending, and financial frictions mean that the volatility in the path of its income matters for the time-path of consumption.[1] Furthermore, the price of the commodity varies stochastically over time, reflecting exogenous demand, supply, or sentiment shocks in the global commodity market. The final key element in our framework – which we add after developing the baseline model – is that the producer has market power.[2]

This approach yields several novel findings on producer behavior and the effects of the price cap. To unpack those, we first write down a simple two-period model. This accomplishes two tasks. First, we show that financial frictions endogenously generate hand-to-mouth behavior of the producer, irrespective of the producer's preferences. This result, which underscores the similarities and, most importantly, the differences to the canonical consumption-saving problems, is as far as we know new to the literature on resource extraction, and it motivates the rest of the analysis in which we take the hand-to-mouth behavior as given. Second, the two-period model helps to preview some of the intuition of our dynamic

[1] These frictions are driven, in part, by both the (ex-ante) anticipated possibility of future sanctions and by the imposition of sanctions. Russia has substantial official foreign reserves, but these were frozen by the G7 immediately after the Russian invasion of Ukraine in February 2022. Since that initial freeze, Russia has been allowed to sell oil and some other commodities, accumulating foreign assets in Gazprombank and other "private" entities. Russian authorities may be concerned about future potential freezes of these assets.

[2] This is realistic in the current context, given that Russia is one of the the world's leading oil producers, oil prices spiked immediately after the 2022 invasion began, and a principal rationale for implementing the price cap policy was that a complete EU embargo – refusing to buy Russian oil and effectively blocking sales to third countries – could lead to a contraction in world oil supply and a spike in world prices of oil.

setting with closed-form analytical results.

We then turn to the infinite horizon model. Using continuous-time methods from macroeconomics and finance, we characterize the extraction policy function, where the two state variables are the reserves of the resource and the resource price. We show that the optimal supply curve is inelastic, even without physical adjustment costs.[3]

We develop a decomposition of the inelastic supply schedule that reveals four forces are at play. First, because the price of the resource varies over time, the producer has the incentive to *time-the-market*: extract and sell more when prices are high, and vice versa when prices are low. Second, expected movements in prices drive incentives to *smooth revenues:* extract more when prices are low. Third, price volatility spurs a *precautionary effect*. And finally, a permanently less valuable reosurce is extracted faster: the *non-homotheticity effect*.

The relative strength of these forces is governed by preferences, and in particular the value that the petrostate places on the stability of its consumption (the intertemporal elasticity of substitution). Greater emphasis on stability strengthens the revenue-smoothing motive while diminishing the incentives to time the market.

In our full model, we consider a producer with sufficient size to influence global markets. Market power in this context is determined by the producer's market share (as well as the demand elasticity). Consequently, the degree of market power is endogenous and dynamically evolves based on past extraction decisions. Our findings indicate that market power induces the producer to adopt a more conservationist approach, extracting resources more slowly than they would without such influence. This behavior exerts upward pressure on global prices in normal times.

We use this new setting to study the price cap policy. We start by analyzing a perfect price cap – one that applies to all of the sanctioned producer's sales and is permanent – and then turn to study the effects of an imperfect cap that might be leaky or non-credible.

An important conceptual contribution of our paper is to establish that the price cap policy represents a fundamental change to the stochastic environment in which the sanctioned producer operates. The cap eliminates the upside of high prices, making the stock of reserves less valuable and reducing uncertainty. Consequently, the pre-policy supply curve cannot simply be truncated at the price cap level. Instead, the new environment requires recomputing of the policy rules.

We show that a perfect price cap leads to a *more rapid* depletion of reserves, all else equal:

[3]This finding is consistent with the evidence of a negative correlation between the price of oil and Russian extraction that we present in Section 2, and with the observation that Russian production has changed little in the face of large fluctuations in the oil price over the past few years.

the supply curve shifts outward. This finding, which goes against some of the intuition held by policymakers, is driven by the non-homotheticity effect and by the presence of market power. The former says that because the reserves are less valuable, they are sold faster. If the producer has market power, implementing a perfect price cap significantly diminishes the incentives to exercise market power in equilibrium. The logic behind this is simple: when the price cap is binding, curbing supply leads to lower volumes but unaltered prices, thereby rendering the use of market power ineffective.

This finding has important implications for the impact of the price cap. In particular, a binding price cap can actually *drive down* world oil prices and act as a *stabilizer* of the global oil market. Such effects are stronger the greater the degree of market power of the producer. Price cap can thus be a potent tool and, perhaps surprisingly, its benefits might actually be greater if it is imposed on a country with significant market power.

Our final set of results concerns the effects of an imperfect price cap, i.e., a cap that applies to only a share of a country's sales of a commodity and/or is expected to be temporary. This analysis is important because monitoring and enforcement of any cap is likely to be imperfect, and the sanctioning coalition is likely to be able to impact only a certain part of exporter's sales. Moreover, if the cap is expected to be temporary, the producer might respond very differently to when it is expected to be more permanent.

We find that the effects of a leaky or non-credible price cap are highly state-dependent. If the commodity market is tight and prices are high, the producer finds it optimal to follow the "shut-in" strategy: sharply reduce extraction, further raising global prices, and sell the commodity (at these elevated prices) solely outside the price cap regime. Note that these incentives kick in precisely when the world market is already tight and prices are high. This means that a price cap that is imperfectly enforced and not fully credible can have a destabilizing effect on the world market.

As a result, policymakers designing the price cap policy face a difficult trade-off: exert harm on the sanctioned producer but face heightened chances of a commodity price shock. We show how to use our model to navigate this trade-off. We introduce a new concept of *sanctions possibility frontier* and show how it can be used to set an optimal price cap, for a given set of preferences and depending on the effectiveness of the price cap. Two insights emerge from this analysis. First, the price cap should be less aggressive (e.g. set at a higher level) the greater are the enforcement challenges. Second, policymakers' preferences matter for the optimal price cap level mainly in the intermediate region of price cap effectiveness.

Literature and contribution. A price cap on a non-renewable resource such as oil is a new and live policy and there is little direct literature on this topic, which motivates this project. Our key contribution is to interpret the price cap as a tool that changes the stochastic environment in which the producer operates, and study the impact on the producer's behavior in a fully structural model. Early analysis of the economics of the price cap on Russian oil appears in Wolfram et al. (2022) and Johnson et al. (2023). In a paper that complements ours with the empirical analysis of the cap, Babina et al. (2023) use customs data to provide evidence on the effectiveness of the cap imposed by the G7 on Russia. They find that sanctions have led to a fragmentation of the oil market, with the oil that was destined to Europe trading at steep discounts and below the cap, while the oil sold elsewhere trading at close to global prices. In a complementary theoretical contribution, Salant (2023) studies the effects of pre-announcing the price cap. Sappington and Turner (2023) investigate the impact of a price cap in a static two-producer Cournot model. Wachtmeister et al. (2023) consider what different price cap levels imply for net losses of Russia. Baumeister (2023) provides a broader overview of developments in the oil market since the Covid-19 pandemic.

Price caps have also been examined in other contexts, in the industrial organization or urban economics literatures – see e.g. Bulow and Klemperer (2012) and Leautier (2018) and references within. More broadly, this paper contributes to the rapidly expanding literature on geoeconomics, which studies the interplay between economic relationships, international politics, and power (see Clayton et al. (2023) and references within).

Our paper also contributes to the literature that studies resource extraction. We construct a new, realistic model of resource extraction that combines three key features. First, we embed in our setting a stochastic process for the oil price that we estimate using oil price data.[4] Second, we study the producer that faces financial frictions. And third, the producer is large relative to the market, and thus might have a significant degree of market power. By adding these important components, our model has dramatically different implications as compared to the canonical Hotelling setting, bypassing many of the shortcomings of the canonical model. The Hotelling framework has been studied, extended, and criticized in numerous studies.[5] An important contribution to that literature is Anderson et al. (2018),

[4] Our framework builds on the finance literature (see Cox et al. (1985), Longstaff and Schwartz (1992), Chen and Scott (1993), Duffie and Kan (1996) for models of interest rates, and Schwartz and Smith (2000) and Pindyck (1999) for models of commodity prices).

[5] Classic references include Solow (1974), Stiglitz (1976), Dasgupta and Heal (1974), Pindyck (1980), Arrow and Chang (1982), Salant (1976). For an overview of work in the 50 years after the publication of Hotelling's article, see Devarajan and Fisher (1981). Recent work includes van der Ploeg and Withagen

which embeds the geological features of the oil industry, namely the fact that a well's pressure declines as oil is extracted from it. The authors show that extraction itself is not sensitive to economic conditions and is instead largely determined by the binding geological constraints. In contrast, oil well drilling responds more to the underlying market forces. We complement their findings by documenting that financial constraints and market power, in addition to geological constraints, can drive the inelasticity of supply in response to temporary price fluctuations. We do not introduce separate drilling decision in our model for parsimony, and consequently our model is informative of the economic incentives to extract oil from existing wells and expand capacity by drilling new wells when the producer is under sanctions.

Our paper analyzes the impact of the price cap on the extraction decisions and world oil prices. A complementary paper by Bornstein et al. (2023) develops a quantitative general equilibrium macroeconomic model with oil production sector, and uses it to study the advent of fracking. For a broader overview of the forces that drive oil prices, see Hamilton (2009).

Structure. The rest of the paper is structured as follows. Section 2 describes Russia's oil sector, including its costs, the prices it faces, and typical export volumes and routes, and provides some institutional context on the price cap that is relevant to our model. It also summarizes the results of our empirical exercise, linking extraction decisions and financial frictions. Section 3 uses a two-period model to motivate our modeling of financial frictions and to develop analytically the intuition behind our results. Section 4 presents the baseline model without market power, and Section 5 studies the effects of the price cap in this setting. In Section 6 we construct our equilibrium model with market power, and in Section 7 we study the effects of the price cap on the degree of market power exercised in equilibrium. Section 8 considers the case where the producer can partially bypass the price cap. Section 9 establishes a framework for navigating the trade-off in designing a price cap. Section 10 concludes.

2 Motivating facts and background on price cap policy

This paper's main objective is to develop a dynamic framework for analysis of behavior of a commodity producer under sanctions. While our framework is applicable to any state that exports an exhaustible resource, we are directly motivated by the price cap sanctions imposed

(2012), Newell and Prest (2017), Salant (2012) and Gaudet (2013) and most recently Harstad (2023), who considers the dynamic game between successive governments controlling an exhaustible resource.

on Russia's oil in late 2022. Also, features of the Russian oil context inform our modeling choices. Therefore, in this section we provide the factual background to our analysis. The section ends with a discussion of a simple empirical exercise that motivates our analysis for the oil industry more generally.

2.1 Oil extraction in Russia historically

In the 1970s and 1980s, Russia led global oil production, peaking at over 11 million barrels per day. The collapse of the Soviet Union triggered a dramatic decline in oil production, which fell to as low as 6 million barrels per day (left panel of Figure 1). Major investment beginning in the mid-1990s, along with access to western oil field services, helped to restore production to more than 10 millions barrels per day by 2019, which made Russia the third largest oil producer in the the world (after the US and Saudi Arabia). In recent years, most Russian production has been exported (7.5-8 million barrels per day, out of production of 10-10.5 million barrels per day), making Russia the world's top exporter of crude oil and product combined.[6] The right panel of Figure 1 plots monthly production from January 2018 to March 2023, highlighting the major disruption around the pandemic and the gradual recovery since then. The drop in extraction that coincided with the invasion of Ukraine in February 2022 was relatively small and short-lived.

Of the 7.5 million barrels per day exported by Russia in 2021, crude accounted for 4.7 million barrels and refined products for the remaining 2.8 million barrels.[7,8] Most Russian oil is produced in Western Siberia and transported by pipeline to refineries and shipping facilities in Russia's Western ports. Before the war, Russia's largest oil customer was the European Union, which received 0.7 million barrels of crude oil per day by pipeline and 1.5 million barrels by sea in 2021. The EU also bought 1.2 million barrels of oil product, almost all of which arrived by sea. Overall, the EU imported almost half of Russia's total oil exports. Most of the tankers carrying these fossil fuels to the EU departed from three sets of ports: in the Black Sea, the Baltic Sea, and Murmansk in the far north.

[6] https://www.iea.org/reports/russian-supplies-to-global-energy-markets/oil-market-and-russian-supply-2

[7] https://iea.blob.core.windows.net/assets/9aea25c1-5450-49db-8e1f-a67c0212720c/-16MAR2022_OilMarketReport.pdf

[8] A single barrel of crude oil can be processed to produce multiple refined products such as gasoline, diesel, jet fuel, and other derivatives of oil. Refineries can be designed to produce different mixes of refined products. The scope to change this is limited, especially in the short run. As of 2021, Russia's refining industry had the capacity to serve domestic gasoline demand and the country exported the remaining products. Substituting between exporting crude and exporting refined products is possible to some degree, but the infrastructure differs and there are pipeline and port constraints.

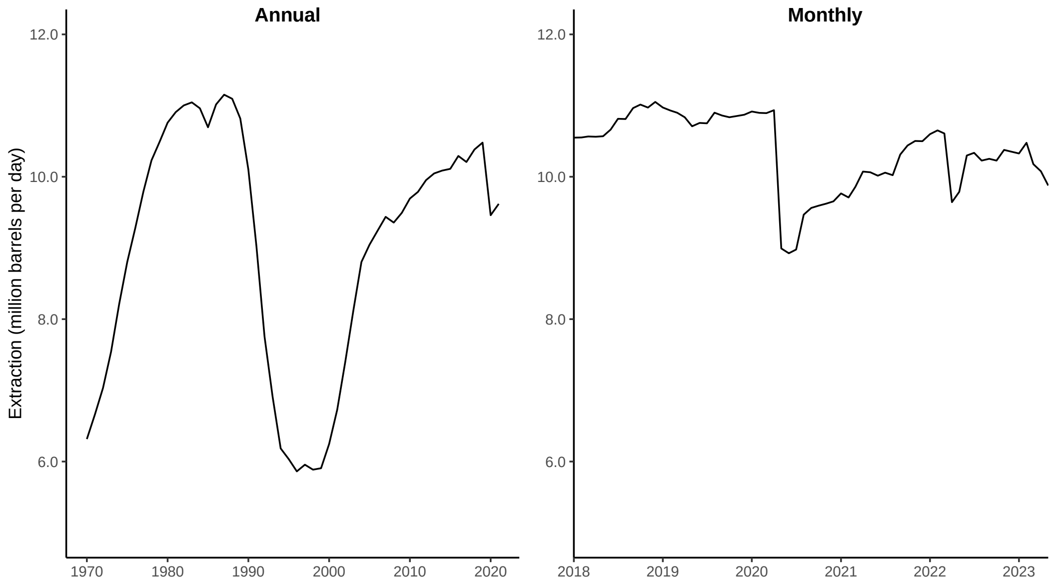

Figure 1: Russia's oil extraction historically: annual, 1970-2020 (left panel) and monthly, January 2018-March 2023 (right panel). Source: CEIC (https://www.ceicdata.com) (left) and U.S Energy Information Administration (right).

China was also an important customer and received 1.6 million barrels of crude per day in 2021, half by pipeline and half by sea. China had previously not purchased a significant quantity of Russia's refined product.

2.2 Russian oil exports since the start of the war

Figure 2 plots Russia's seaborne crude oil exports by destination from January 2022 to September 2023.[9]

Shortly after the invasion of Ukraine in February 2022, Russia's export to the US and the UK quickly collapsed: these countries swiftly implemented embargoes. However, the US and the UK were never the main destination markets for Russian oil. Exports to the EU, Russia's largest customer, diminished much more gradually, and reached practically zero only after the implementation of the embargo on crude oil in December 2022 and on oil product in February 2023. The overall level of exports has remained steady, however, with significant substitution away from the western markets towards buyers from Asia, most notably India, which has previously imported very little oil from Russia.

[9] It does not reflect the approximately 1.5 million barrels of crude oil per day exported via pipeline, roughly half of which used to go to the EU and half to China. Data for oil products paint a similar picture.

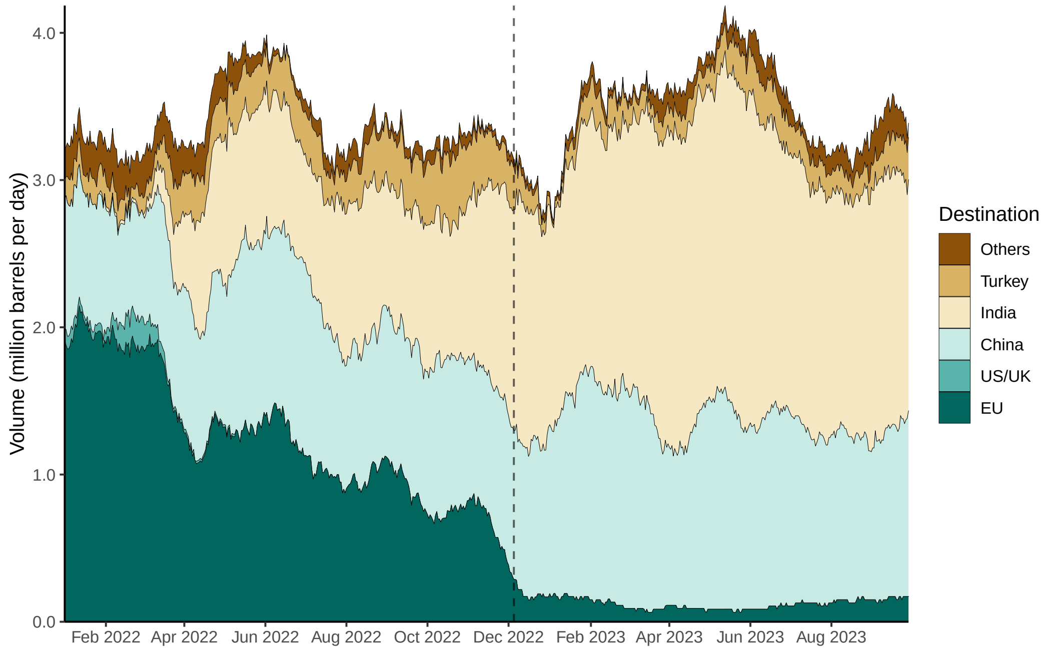

Figure 2: Russia's seaborne crude oil exports by destination, January 2022 - September 2023. Dashed line indicates the start of the price cap policy for crude oil on December 5, 2022. Source: CREA.

We discuss the implementation of the price cap policy in more detail below. However, it should be noted that the steady level of exports from Russia to the global market has been the intended outcome of the policy mix implemented by the G7 and other coalition countries. These countries have aimed to reduce revenues from oil sales without taking Russian supply off the global market, thus avoiding the risk of a damaging global oil supply shock.

2.3 Structural features of Russia's oil extraction

Marginal costs. Naturally, marginal costs are an important element in the producer's decision problem. Most estimates peg marginal costs at most Russian fields at between $5 to $20 per barrel.[10] For example, Osintseva (2021) estimates marginal costs across countries and reports Russia's cost of $19 per barrel. At its lowest point at the beginning of the COVID pandemic, the price of oil was around $20-$25 per barrel, which industry reports

[10] See Wachtmeister et al. (2023) or the S&P Global: `https://www.spglobal.com/commodityinsights/en/ci/research-analysis/global-crude-oil-curve-shows-projects-break-even-through-2040.html`. The latter also report higher costs relating to future exploration of new oil fields.

suggest was above the marginal cost of production.[11] In the main text of the paper, we assume a constant marginal cost of \$19 per barrel, but we explore a richer setting with increasing marginal costs and a capacity constraint in the Appendix.[12]

Storage capacity. Russia has limited onshore storage available, and most of this was already full when the 2022 invasion of Ukraine started.[13] Storage "on the sea" is available but costly: it requires chartering and insuring ships for the duration, and is thus unlikely to be a quantitatively meaningful option, especially beyond the very near term. For these two reasons, we abstract from this margin of adjustment in our model.

State decision-making power, and the federal budget. Like other petrostates, the extraction sector in Russia is effectively a part of the state. To reflect the power of the Russian state over its oil companies and its ability to require payment of ex-post profit taxes in our framework, we find it most natural to analyze the problem of a national-level decision maker.

This modeling choice is supported by the significant dependence of Russia's fiscal budget on oil revenues. In 2021, oil (crude and product) was Russia's largest export by category, followed by natural gas and coal.[14] In total, energy represented more 50% of all export revenues, and oil represented 75% of energy exports. Oil and gas sales are a significant source of federal budget revenues, accounting for between 40 and 50% over the past decade.[15]

Financial constraints. There are at least three reasons why financial constraints probably play an important role in the decision-making of a sanctioned commodity producer. All of these are applicable to the case of Russia.

First, during a time of geopolitical risks and increased uncertainty, risk-averse international investors are almost inevitably reluctant to lend to a state that is being sanctioned.

[11] See CREA (2023) citing Rosneft (2021).

[12] Our results are robust to assuming a non-constant marginal cost and/or a capacity constraint. In particular, in the Appendix we present the results from a model with a cost structure that matches the data published by Rystad Energy as reported in Wachtmeister et al. (2023). These data suggest an L-shaped marginal cost that increases sharply as extraction increases toward a short-run capacity constraint. All our conclusions are robust to this change, although naturally, physical constraints limit any increases in production in the short-run that we predict below to the capacity constraint limit. The results we present in the main text can be thought of as better reflecting the medium-term, helping us clearly expose the incentives to increase production in some scenarios.

[13] https://www.energyintel.com/0000017f-6982-d580-a37f-f99bdebb0000.

[14] https://oec.world/en/profile/country/rus

[15] See e.g. Figure 4 in Chanysheva et al. (2021).

Second, a price cap policy is likely to be employed as a result of major act of aggression, and wars are expensive to run. According to its Ministry of Finance, Russia has dramatically increased military spending. Grozovski (2023) reports that in 2023 Russia has dedicated 40% of its budget to military needs. Guriev (2023) estimates military spending to be in excess of 6% of GDP. Such high spending on war puts significant pressure on the budget, heightening the likelihood of financial constraints being binding. Kennedy (2025) emphasizes that circa half of Russia's war effort is financed off-budget, and documents heightened pressures in the credit markets as a result of the need to finance the war machine.

Third, a price cap policy might be coupled with financial sanctions, which can diminish the financial war chest and effectively cut off the exporter from international financial markets. This is precisely what occurred in the case of Russia in 2022. Western countries froze $300bn of the central bank reserves. In April 2022, the US Treasury Department banned Russia from withdrawing funds held in US banks to pay off its debt obligations. Russian default followed (Itskhoki and Muhkin (2023), Bianchi and Sosa-Padilla (2024), Lorenzoni and Werning (2023)), making borrowing from abroad essentially impossible. And since past saving turned out to be of limited use, the ex post rate of return was negative.

For these reasons, we view the fact that the producer is cash strapped as an integral part of the analysis. In our model, lower revenues translate into lower welfare, as the state is unable to fully isolate consumption from revenue fluctuations. This is motivated by and consistent with the literature that has quantified a strong link between sectoral concentration, sectoral shocks, and macroeconomic volatility (Koren and Tenreyro (2007), van der Ploeg and Poelhekke (2009), Aghion et al. (2009)).

Market power. As the world's largest combined crude and product exporter, Russia has a significant degree of market power. The 2022 invasion of Ukraine, for example, pushed world oil prices up by nearly 40 percent from the end of February to June 2022, presumably at least in part because participants in the oil market were concerned about potential disruptions to Russian supply. In addition, Russia belongs to the OPEC Plus cartel, which periodically sets production quotas and has considerable influence on world prices. Consequently, we make the market power of the producer a central component of our framework.

Price volatility and price-extraction correlation patterns. In recent decades, Russia's oil extraction has been remarkably insensitive to price fluctuations (Figure 3). Our model is consistent with this important observation.

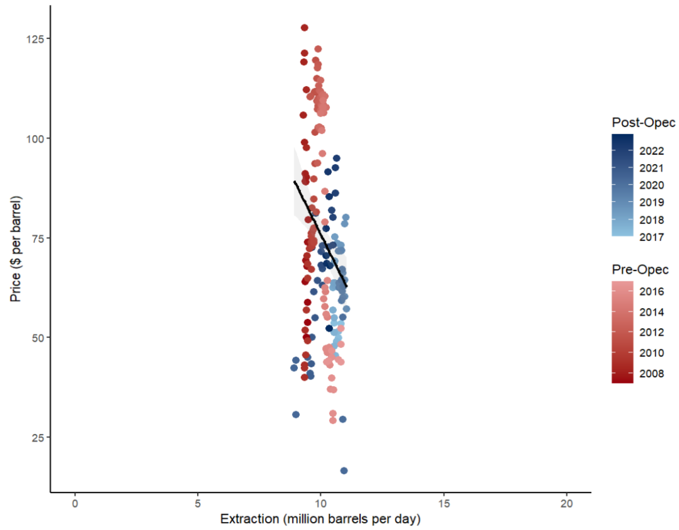

Figure 3: Russia's oil extraction versus Urals price, January 2008 - December 2022. Source: OPEC, Platts, Argus; U.S. Energy Information Administration.

2.4 The G7 price cap on Russian oil: implementation details and enforcement challenges

The G7 price cap on Russian oil operates by setting terms and conditions for the provision of western financial and shipping services. Specifically, services can only be provided for the shipment of Russian oil by companies located in countries in the price cap coalition if the price paid to Russia is at or below the cap.[16] The caps were initially set at $60 per barrel for crude, $100 per barrel for high value refined products (including diesel, gasoline and kerosene) and $45 per barrel for low value refined products (including fuel oil and naphtha).[17] The price cap was implemented in response to the EU's 6th sanctions package, which would have banned the provision of services for the shipment of Russian oil altogether and could have considerably reduced the supply of Russian oil to the world markets (Wolfram (2024)). The price cap effectively allows for an exception to that outright ban.

[16] In addition to the G7, EU and Australia, Albania, Bosnia and Herzegovina, Iceland, Liechtenstein, Montenegro, North Macedonia, Norway, Switzerland and Ukraine have all pledged to follow EU sanctions against Russia.

[17] This design of the policy means that if an entity, e.g., in India, buys crude at or below the cap, it is allowed to sell the refined product at world prices. This arrangement is expected to encourage the flow of Russian oil and helps explain why Russian deliveries to the world market are largely unchanged. But who earns the rents from the difference (world price minus capped price) remains shrouded in some mystery. As an example, an article *Wall Street Journal* in April 2023 cited evidence that Saudi Arabia and the United Arab Emirates were importing Russian oil products at low prices and making high profits (Faucon and Said (2023)), but there is no systematic accounting of where the rents have gone.

Several studies examine some of the impacts of the price cap, including Harris (2023), Hilgenstock et al. (2023), O'Toole et al. (2023), Rosenberg and Van Nostrand (2023), and Kilian et al. (2024). The cap appears to have been largely successful in keeping the supply of Russian oil on the market, as documented above. As we discuss below, in the initial phases the cap policy applied to large volumes of Russian oil trade. Consistent with that, the implementation of the price cap and the EU embargo has coincided with an increase in the discounts on Russian oil (more so for Urals and less so for ESPO).

However, more recently, several important developments appear to have limited the effectiveness of the price cap. First, the price cap has not been strictly enforced. Although CREA data[18] suggest that in April 2023, about 60% of crude oil shipments and 75% of product shipments from Russia's ports were covered by insurers from the EU, G7, or Norway, lack of clear verification procedures has meant that, during the periods when the price cap was binding (i.e., when the market price of oil was above the cap), a significant share of exports have been sold at prices above the cap. Shapoval et al. (2024) report that, in the fourth quarter of 2023, up to 95% of all Russian seaborne crude oil exports took place above the $60 per barrel threshold, indicating that some actors break the rules imposed by the regime.

Furthermore, Russia has increased its capacity to transport its oil. Based on industry data, Shapoval et al. (2024) assess that the share of oil carried by non-coalition tankers has increased from around a fifth in early 2022 to two-thirds and one-third for crude and product, respectively (see also Kennedy (2023)). The same report argues that a significant share of this capacity consists of old tankers that are likely unfit to pass through international waters, e.g. through the territorial waters of Finland, Estonia, and Denmark in the Baltic Sea. Stronger enforcement of environmental and safety standards, such as those imposed by the UN's International Maritime Organization, would therefore indirectly strengthen the degree to which the price cap is binding.

One potential reason for why the enforcement of the price cap policy has appeared to be relatively timid is the concern that a tighter sanctions system might result in Russia strategically responding by limiting its supply. In this light, in the rest of this paper, we provide a framework that helps to tease out the economic incentives of a large, financially constrained producer facing sanctions. This framework is a necessary step to assess the risks and address the concerns that could have limited the degree to which the price cap is enforced.

[18] See https://energyandcleanair.org/russia-sanction-tracker/

2.5 Cross-country empirical analysis: financial frictions and extraction decisions

One of the predictions of our model below is that financially unconstrained state producers tend to be more sensitive, in terms of their extraction decisions, to the price fluctuations. In contrast, the supply schedule of a financially constrained petrostate is predicted to be more inelastic.

To evaluate this proposition, we analyze the oil production decisions of countries as a function of their financial conditions. The basic hypothesis is that countries facing financial constraints will be less sensitive to market factors and will produce the same amount of oil when global prices are low as when prices are high, or perhaps even less when prices are high. We study responses to oil supply news shocks identified by Känzig (2021), who collects OPEC supply announcements. By analyzing production decisions around these announcements, we can isolate how other, non-OPEC countries respond to unexpected price shocks. We use 53 announcements between 1984 and 2017 and examine countries' production in the month following each OPEC decision compared to the month preceding the decision. Our dependent variable is the change in log production multiplied by negative one if the production increased when prices went down or decreased when prices went up.[19]

We measure a country's financial conditions using a dummy variable for whether its debt to GDP ratio exceeded the median level in a given year. Figure 4 plots country responses to OPEC announcements against the share of years the country had above median debt to GDP levels. There is a negative relationship (coefficient = -.026, std. err. = .010), consistent with the hypothesis that countries facing financial constraints have more inelastic supply responses.[20]

3 A two-period model

The two-period model we develop in this section serves a dual purpose. In Section 3.1 we show that financial frictions can endogenously lead to hand-to-mouth behavior by a producer

[19]Further details about the data used for this analysis are in the appendix. We use observations at the country level since our model focuses on government-level decisions. The results are similar if we exclude countries where the link between oil production decisions and government policy is less strong, such as the United Kingdom and the United States, or if we analyze production decisions six months after the OPEC announcement.

[20]We also examined the relationship between countries' responses to OPEC announcements and the country-level risk premium variable constructed by Damodaran (2022). While slightly noisier, the results also indicate a negative relationship.

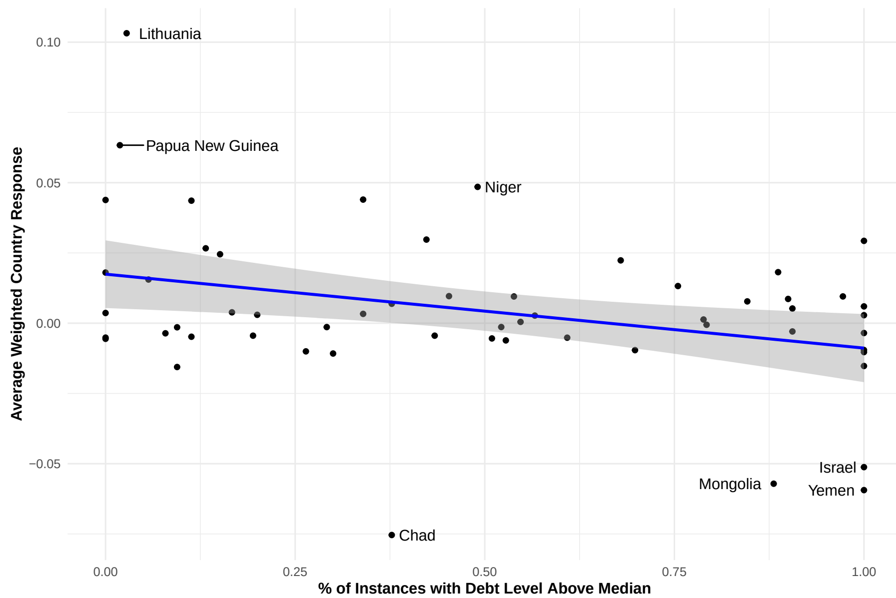

Figure 4: Average oil production response to OPEC announcement as a function of a country's financial conditions. See Appendix for details on data sources.

of a commodity. We then utilize this insight in our full infinite-horizon model where we focus on a hand-to-mouth producer. In Section 3.2, we preview some of the intuition for the mechanisms that drive extraction decisions in our full model.

3.1 Endogenous hand-to-mouth behavior and financial frictions

We start with a model that shows how financial frictions can make the producer endogenously choose to behave in a hand-to-mouth fashion irrespective of preferences, even if the producer maintains market access.

We consider a decision problem of an agent endowed with $x = 1$ of an exhaustible resource. The agent maximizes the utility of consumption for two periods $t \in \{0, 1\}$. Consumption is financed in part by the proceeds from sales of the resource. The price of the commodity can change over time, but any changes are foreseen by the agent (we discuss uncertainty and risk below).

The agent can access financial markets but there are financial frictions: the returns on saving are low and borrowing is expensive; in addition, the agent might have to pay one-off costs to participate in the financial markets. The latter can capture a host of potential costs that the producer might face, including, for example, concessions that the producer needs to make to maintain market access, costs of establishing financial market infrastructure, costs of maintaining appropriate institutions, or costs of revealing information about the state of its finances. We include both the price- and non-price-based frictions to comprehensively capture the set of imperfections that the producer might face.

The agent takes the prices of the resources and the interest rates as given when making its choices. Specifically, the agent solves the following problem:

$$\max_{y_0, y_1, b} u(c_0) + \beta u(c_1) \quad \text{subject to}$$

$$c_0 = p_0 y_0 + b + \tau$$

$$c_1 = \begin{cases} p_1 y_1 - (1 + r_B)b - \Phi + \tau & b > 0 \text{ (borrowing)} \\ p_1 y_1 - (1 + r_S)b - \Phi + \tau & b < 0 \text{ (saving)} \\ p_1 y_1 + \tau & b = 0 \end{cases}$$

$$y_0 + y_1 = 1, \quad y_0, y_1 \geq 0,$$

where u is increasing and concave, $\beta \leq 1$ is the discount factor, b is financial borrowing (when positive) or saving (when negative), $r_B \geq r_S$ are the net interest rates on borrowing and saving, respectively (where we explicitly allow $r_S < 0$ – the case of when some of the savings are confiscated), τ is the income that is unrelated to commodity sales – e.g. it is the income from general taxation, and Φ is the fixed cost of participating in financial markets. The first two constraints are flow budget constraints; the final three together form the resource constraint. p_0 and p_1 are prices of the resource in the current and future period, respectively, which are known with certainty. Henceforth, we normalize $p_0 = 1$.

Solving this problem, we have the following result (all proofs are in the Appendix):

Proposition 1. *Suppose that there are no participation costs: $\Phi = 0$. The producer does not utilize the financial market and lives hand-to-mouth if and only if*

$$1 + r_S \leq p_1 \leq 1 + r_B. \tag{1}$$

Thus, for a given expected price path p_1, there exist thresholds $\bar{r}_S$ and $\bar{r}_B$ such that if $r_S \leq \bar{r}_S$ and $r_B \geq \bar{r}_B$, the producer does not use financial markets and lives hand-to-mouth.

Suppose that market participation costs are non-zero. For a given triple $\{p_1, r_S, r_B\}$ there exists a threshold $\bar{\Phi}$ such that if $\Phi > \bar{\Phi}$, the producer does not participate in the financial market.

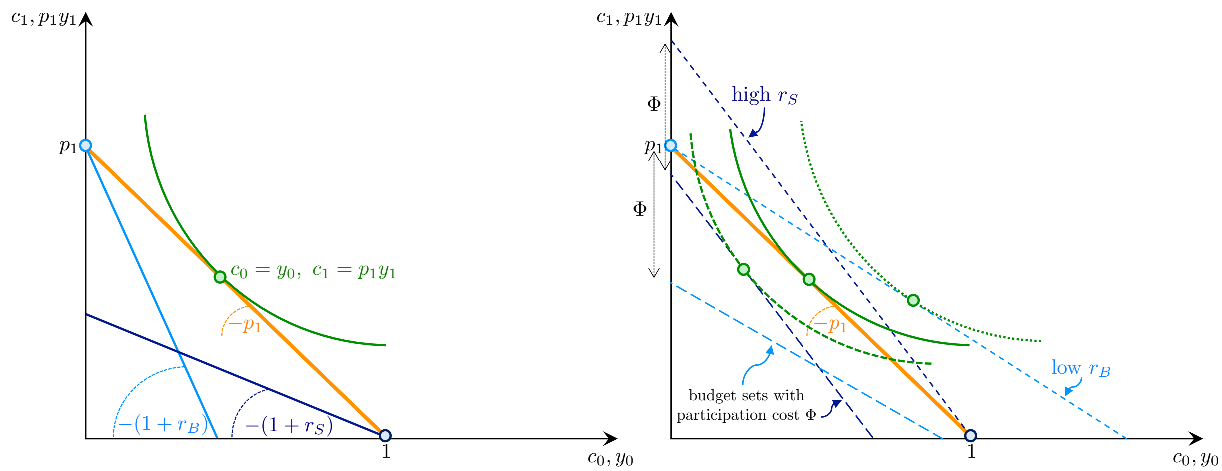

Figure 5: Optimal extraction and consumption in a two-period model

The left panel shows the budget sets and the indifference curves when condition (1) is satisfied. The right panel shows the situation where the condition (1) is not satisfied – r_B is low and/or r_S is high and shows the impact of participation costs $\Phi > 0$. In both panels, the blue dots show the optimal extraction in the two periods conditional on using the financial markets. The green dots show consumption choices (which are also the extraction choices when the producer does not use financial markets).

The intuition behind the proposition can be explained graphically (Figure 5). For simplicity and without loss, we assume that $\tau = 0$. The producer makes a two-stage decision: given the expected price path p_1 and interest rates on borrowing and saving, it first decides whether or not to use financial markets. Then, given this choice, it decides on optimal extraction rate and optimal saving / borrowing.

The left panel of Figure 5 shows the budget sets and the indifference map of the producer when there are no fixed costs to participation in the financial markets, $\Phi = 0$. Note that in this case, conditional on using the financial markets, the producer either extracts nothing in the current period (when borrowing against future extraction) or extracts everything right away (when saving the proceeds from extraction today). Consequently, the budget sets when the producer saves or borrows originate in points $(0, 1)$ and $(p_1, 0)$, respectively, and their slopes are the respective gross interest rates.

An alternative to using the financial markets is to live hand-to-mouth and smooth consumption by extracting positive amount in both periods. The thick yellow line in Figure 5 depicts the budget set in this case. Clearly, the budget set corresponding to the case when financial markets are not used strictly dominates the other two. As a result, the producer finds it optimal not to use the financial markets and instead extract and consume hand-to-mouth, irrespective of preferences. This is the main result of Proposition 1.

The right panel of Figure 5 shows what budget sets look like when the producer faces more favorable prices in the financial market: a higher interest rate on its savings and / or a lower interest rate on its borrowing. When the financial conditions are favorable enough, condition (1) is not satisfied, and it is optimal to go to the corner in terms of extraction, and use financial markets to smooth consumption. However, the figure also shows that, in the presence of sufficiently high fixed costs of participation, the hand-to-mouth behavior remains optimal.

Risky price path. It is straightforward to incorporate uncertainty about prices in our setting. Doing so, we obtain the following result:

Proposition 2. *Suppose that the price of the resource next period, p_1, is stochastic. The producer does not use the financial markets and lives hand to mouth if and only if*

$$1 + r_B \leq \mathbb{E}\left(u'(c_1)p_1\right) \leq 1 + r_B.$$

When uncertainty is present, the relevant measure against which to compare the market interest rates is the marginal utility-adjusted expectation of future price. Concavity of the utility function means that low price realizations receive a relatively higher weight.

Together, Propositions 1 and 2 establish that hand-to-mouth behavior emerges endogenously in the presence of financial market frictions in the context of resource extraction, if these frictions are sufficiently severe. In the remainder of the paper we take it as given that the financial frictions, in terms of low interest rate on saving, high interest rate on borrowing, and high costs of participation, mean that the producer finds it optimal to simply consume the proceeds from oil extraction.

Given the context of our analysis, it is important to note that financial frictions are particularly likely to bite strongly in the case of a national producer under sanctions. Indeed, financial sanctions themselves can severely curtail the ability of the producer to participate in financial markets (e.g. by denying access to financial infrastructure and systems), make borrowing infinitely costly (by sanctioning financial entities and preventing access to debt markets) and make saving an expensive proposition (by freezing or confiscating financial assets of the producer).

3.2 Extraction decisions under uncertainty

We now turn to the problem of choosing the time path for the extraction of the exhaustible resource, taking as given the hand-to-mouth behavior of the producer. This is the core problem that we study in the remainder of the paper. Here we continue with the two period model introduced above in order to establish some intuitive propositions analytically.

The agent solves the following problem:

$$\max_{y_0,y_1} u(p_0 y_0 + \tau) + \beta \mathbb{E}_0 u(p_1 y_1 + \tau) \quad \text{subject to} \quad y_0 + y_1 = 1, \quad y_0, y_1 \geq 0.$$

In general there is no analytical solution. However, much intuition can be gained from two special cases: setting $\tau = 0$ is useful in undertanding the impact of uncertainty; while switching off uncertainty is helpful in understanding the impact of non-oil income τ. Throughout, we assume that u is constant relative risk aversion (CRRA) with the inverse of the intertemporal elasticity of substitution given by γ.

Analytical Case 1: $\tau = 0$.

With no outside income, we have the following result:

Proposition 3. *The optimal period-0 extraction is:*

$$y_0 = \frac{1}{1 + \left(\beta \mathbb{E}_0 \left[\left(\frac{p_1}{p_0}\right)^{1-\gamma}\right]\right)^{\frac{1}{\gamma}}}.$$

This result indicates that the way price uncertainty and price expectations impact extraction decisions depends on the value of γ. Consider first the price expectations, i.e. the $\frac{p_1}{p_0}$ term. An increasing price path reduces extraction today if $\gamma < 1$ and increases it when $\gamma > 1$. To understand the intuition, note that higher expected prices tomorrow induce an income effect (the producer is richer, and so wants to extract more today) and a substitution effect (the producer wants to extract more tomorrow when prices are expected to be higher, relative to today). When $\gamma > 1$, the income effect dominates, and extraction today increases when prices are expected to go up: we refer to this as a *revenue-smoothing effect*.

The effect of risk also depends on the value of γ. A riskier price path spurs a precautionary effect (extract less today to self-insure against such volatility) but also makes the resource a less useful vehicle to achieve self-insurance (since its value fluctuates more). With $\gamma > 1$, the precautionary effect dominates: because of Jensen's inequality, $\mathbb{E}\left[\left(\frac{p_1}{p_0}\right)^{1-\gamma}\right] > \left[\mathbb{E}\left(\frac{p_1}{p_0}\right)\right]^{1-\gamma}$, and more risk reduces extraction today. If the payoff function is logarithmic, i.e. $\gamma = 1$, the two pairs of effects exactly offset, and price volatility and expectations do not affect the extraction path.

Prices Gamma-distributed and $\gamma = 2$. A particularly simple expression obtains when prices in period 1 follow a Gamma distribution and $\gamma = 2$. Gamma distribution is of particular interest, as it emerges naturally in the parametrization of the process for the oil price in our quantitative model. In particular, if resource prices follow a Cox-Ingersoll-Ross process (Cox et al. (1985)) with mean price p_1, volatility parameter σ^2 and mean reversion parameter D,[21] then its limiting distribution is a Gamma distribution. Under these assumptions, extraction today is:

$$y_0 = \frac{1}{1 + \sqrt{\frac{\beta}{\mathbb{E}\left(\frac{p_1}{p_0}\right) - \frac{\sigma^2}{2Dp_0}}}}$$

Higher expected future price $\frac{p_1}{p_0}$ raises extraction today (the dominant income effect); higher volatility decreases extraction today (the dominant precautionary effect). The precautionary effect is stronger if shocks are more persistent and mean reversion is slow (D is low) and it is also state-dependent: stronger when prices today are low (p_0 is low).

Analytical Case 2: $\tau > 0$ and no risk

To obtain an analytical characterization of the producer's decisions when outside income τ is available, assume there is no risk and the price path p_1 is known with certainty.

Proposition 4. *With no uncertainty about p_1, the optimal period-0 extraction is:*

$$y_0 = \frac{1}{1 + \beta^{\frac{1}{\gamma}} \left(\frac{p_1}{p_0}\right)^{\frac{1-\gamma}{\gamma}}} + \frac{\tau}{p_0} \left(\frac{\beta^{-\frac{1}{\gamma}} \left(\frac{p_0}{p_1}\right)^{\frac{1}{\gamma}} - 1}{\beta^{-\frac{1}{\gamma}} \left(\frac{p_0}{p_1}\right)^{\frac{1-\gamma}{\gamma}} + 1} \right). \tag{2}$$

Outside income $\tau > 0$ has two effects on the extraction decisions: first, for constant prices i.e. when $\frac{p_1}{p_0} = 1$, it makes the producer extract faster, as if the producer was more impatient (we refer to this as *non-homotheticity effect*); second, when the prices are expected to change, outside income helps the producer *time the market*: for example, reduce extraction today in anticipation of higher prices tomorrow.

[21] We describe this process in more detail in the context of the dynamic model.

To see the first effect most clearly, suppose that prices are expected to remain constant, so that $\frac{p_0}{p_1} = 1$. The expression for y_0 simplifies considerably:

$$y_0 = \frac{1}{1+\beta^{\frac{1}{\gamma}}} + \frac{\tau}{p_0}\left(\frac{\frac{1}{\beta^{\frac{1}{\gamma}}} - 1}{\frac{1}{\beta^{\frac{1}{\gamma}}} + 1}\right).$$

Period-0 extraction is monotonically increasing in τ (since $\frac{1}{\beta^{\frac{1}{\gamma}}} - 1 > 0$). This *non-homotheticity* effect is stronger at low prices, and it is linked to time-discounting (it is greater the further away β is from 1), and disappears when there is no discounting. Intuitively, with outside income, reserve depletion is a less scary prospect, and so the agent moves towards resource depletion more quickly.

To see the second effect, we return to the case when prices are expected to be different in the future relative to today. Consider equation (2). When prices are expected to increase sufficiently, i.e. when $p_1 > \frac{p_0}{\beta}$, the effect of non-oil income changes sign – now, the non-oil income helps the producer *time the market* and reduce output today in anticipation of higher prices in the future. We will see that these forces play out also in our dynamic model which we discuss next.

4 Model of a price-taking producer

Armed with the intuitions from the two-period model, we now turn to our infinite horizon dynamic setup. We begin by studying the decision problem of a state producer of a commodity who takes the price of the commodity as given. This framework offers interesting insights in its own right, and is an important input into our analysis of equilibrium with market power in Section 6.

4.1 Producer's problem

Time is continuous and runs forever. We study a dynamic problem of an agent – e.g. a government of a country – endowed with x_0 amount of natural exhaustible resource, such as oil. We normalize $x_0 = 1$. Profits are $\pi_t := (p_t - \mathcal{M})y_t$, where y_t denotes the amount of oil extracted at time t and $\mathcal{M}$ is the marginal extraction cost (which we assume to be constant).

The producer's problem is:[22]

[22] If $p_t = p \ \forall t$, this becomes a canonical cake-eating problem in continuous time.

$$\max_{y_t} \mathbb{E}_0 \left[\int_0^\infty e^{-\rho t} u(y_t, p_t) dt\right] \text{ subject to } dx_t = -y_t dt,\ x_t \geq 0,\ y_t \geq 0, \tag{3}$$

and the stochastic Markov process for p_t. ρ is a discount rate, and the constraints say that the stock of reserves x_t decreases by the amount extracted y_t, and that the reserves and extraction must be non-negative. We assume that $u(y_t, p_t) := u(\pi_t + \tau)$ is increasing and concave.

Recall from the discussion in Section 3 that our setting implicitly assumes that financial frictions operate in the background, leading the producer to act hand-to-mouth: the producer's consumption is equal to its income. Our model recognizes the importance of financial constraints in the producer's problem and, therefore, can be informative about the interplay between financial and energy sanctions.[23]

4.2 Recursive representation

We denote by $V(x, p)$ the value of owning reserves of x when the current price of the commodity is p. The Hamilton-Jacobi-Bellman equation of the problem in (3) is:

$$\underbrace{\rho V(x,p)}_{\substack{\text{required}\\\text{return}}} = \max_{y_t} \underbrace{u(y,p)}_{\substack{\text{payoff}\\\text{from}\\\text{extraction}}} - \underbrace{V_x(x,p)y}_{\substack{\text{value loss}\\\text{from}\\\text{extraction}}} + \underbrace{V_p(x,p)\mu(p)}_{\substack{\text{value change}\\\text{due to expected}\\\text{price change}}} + \underbrace{\frac{1}{2}V_{pp}(x,p)\sigma(p)}_{\substack{\text{compensation}\\\text{for risk}}}.$$

where $\mu(p)$ and $\sigma(p)$ are the state-dependent drift and variance of the price process, respectively.

To characterize the behavior of the producer, we proceed by solving the functional Hamilton-Jacobi-Bellman (HJB) equation numerically. To do so, we first parametrize the model.

[23] Our setting is thus consistent with a large body of literature in development economics which has found that volatility in the price of exported commodities is largely responsible for the resource curse. This literature has found that an important channel through which country's resource abundance translates into subpar economic performance is through volatility. Our framework assumes that commodity terms of trade volatility exert a negative impact on welfare, e.g. through more volatility and lower economic growth. Furthermore, it implies that better access to financial markets and in particular to attractive saving vehicles dampens this impact. Both implications are consistent with empirical evidence between countries (Mohaddes and Raissi (2017), Cavalcanti et al. (2015)).

4.3 Parametrization

4.3.1 Stochastic process for the price of oil

Our objective is to embed the decision problem of the producer in an empirically-relevant environment. One salient feature of such environment is that commodity prices fluctuate over time. To capture these movements, we parametrize and estimate the stochastic process for the oil price. We assume that the price follows the Cox–Ingersoll–Ross process (also known as a Feller square root process):

$$dp_t = D(\tilde{p} - p)dt + \varsigma\sqrt{p}dW_t \tag{4}$$

where W_t is the standard Wiener process and $\tilde{p}$, D, and ς are (strictly positive) parameters that satisfy $2D\tilde{p} > \varsigma^2$. The process is mean-reverting, and parameter D determines how quickly the gap between the current price and the average price $\tilde{p}$ closes. Parameter ς determines the volatility of the price.[24] The limiting distribution of p_∞ is a Gamma distribution:

$$f(p_\infty; D, \tilde{p}, \varsigma) = \frac{\beta^\alpha}{\Gamma(\alpha)} p_\infty^{\alpha-1} e^{-\beta p_\infty},$$

where $\beta := \frac{2D}{\varsigma^2}$, $\alpha := \frac{2D\tilde{p}}{\varsigma^2}$ and $\Gamma(\alpha)$ is the Gamma function.[25]

We estimate the process in (4) using monthly data on real oil prices from 1973 to 2024.[26] We obtain $\tilde{p} = \$76$ (in 2024 prices), $\varsigma = 2.43$ and $D = 0.21$ (at the annual frequency). With these estimated values, the limiting distribution of the oil price is skewed to the right (Figure 6). The model fits the data very well; the estimated long-run Gamma distribution closely follows the histogram of historical oil prices (the right panel of Figure 6). The estimated parameters imply a significant degree of persistence in the process for the price, with a half-life equal to $\ln 2/D = 3.6$ years.

[24] One advantage of the process in (4) is that it ensures that the price always stays positive: as $p \to 0$, the importance of Brownian noise diminishes, and mean reversion drives the price away from zero. There is no upper bound to the price: we have $p_t \in (0, \infty) \forall t$. Recall that the producer has no market power in this section, an assumption we relax below.

[25] The variance of the limiting distribution is $\frac{2D\tilde{p}}{\varsigma^2}$.

[26] We obtain our data series from the FRED database. We deflate the monthly nominal oil price (code WTISPLC) by the US CPI index (code CPIAUCSL) set to 1 in May 2024. We use maximum likelihood estimation, making use of the numerical implementation of Kladivko (2013).

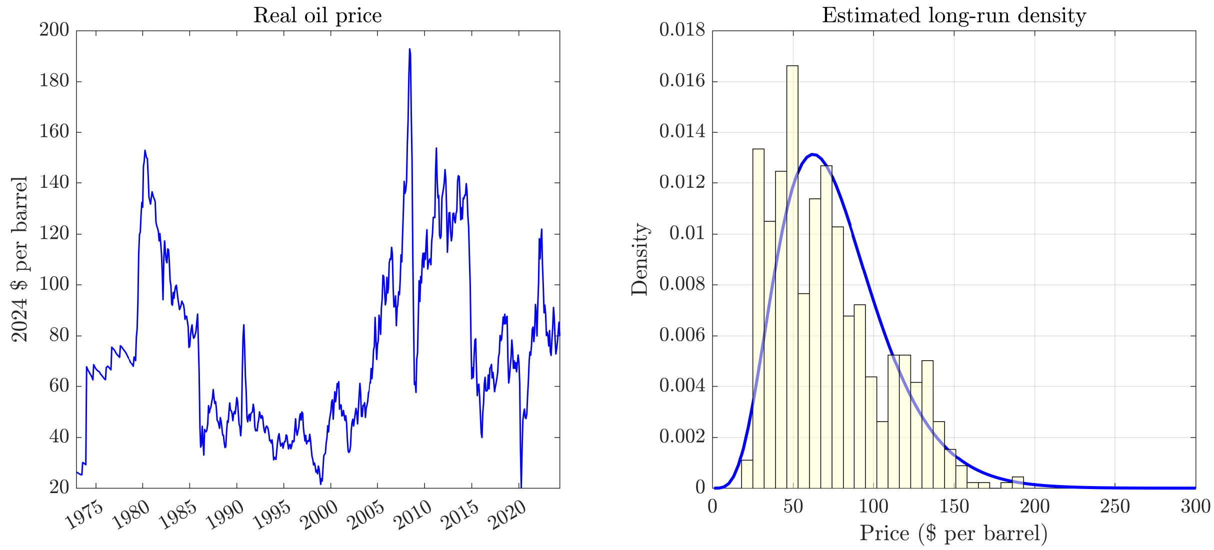

Figure 6: The left panel shows the data on real oil prices used in the estimation of the price process, and the right panel shows that long-run distribution of the estimated process. The bars in the right panel represent the histogram of historical prices since 1973.

4.3.2 Preferences

We assume that the instantaneous utility function is CRRA:[27]

$$u(y) = \frac{(\pi + b)^{1-\gamma}}{1-\gamma}. \tag{5}$$

In our baseline, we set $\gamma = 2$, which corresponds to the calibration of the intertemporal elasticity of substitution that is standard in the literature. We explore the sensitivity of our results to the wide range of values of γ below.

4.3.3 Other parameters

We set the marginal cost of extraction $\mathcal{M} = \$19$ per barrel, reflecting the estimates of Russia's marginal costs in Osintseva (2021).[28]

We set the real interest rate that is used to discount future payoffs to 3%, to match the level of extraction of between 1 and 3% of the resource stock per year (when the producer has market power in the model of the next section). Finally, we set $\tau = 2$, which implies

[27] The results with a broader class of HARA utility functions (which nest both CRRA and CARA) are available upon request. These are in-line with the main results based on CRRA that we focus on.

[28] See the Appendix and footnote 12 for the results based on increasing, L-shaped marginal cost.

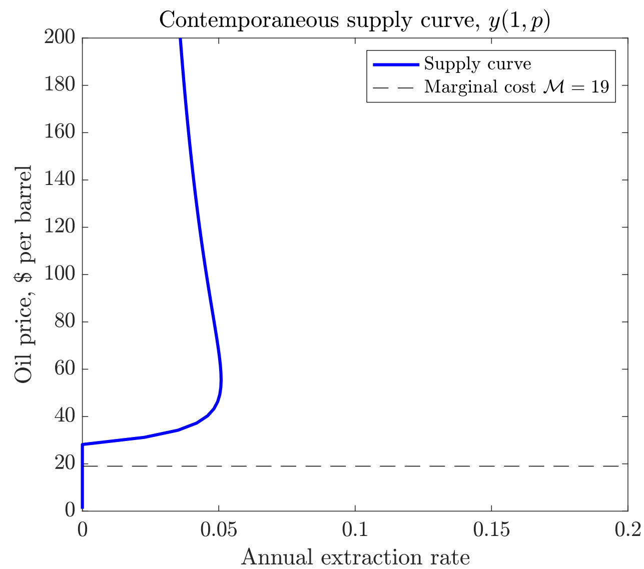

Figure 7: Supply curve when price is stochastic

that income from commodity sales constitutes a substantial fraction – between 1/3 and 1/2 – of the overall income of the state. Throughout, we solve the model fully non-linearly and globally.

4.4 Optimal extraction without the price cap

4.4.1 Contemporaneous supply curve

The solution to problem (3) is a policy function $y(x, p)$ which specifies the optimal level of extraction at each price, for any level of reserves. We focus on a specific part of the policy function – the contemporaneous supply curve, $y(1, p)$.

Figure 7 shows the supply curve implied by the baseline parameterization of our model. The supply curve is highly non-linear: in much of the state space the supply curve is highly inelastic; supply falls sharply as prices fall below $40, and reaches zero at just below $30 per barrel.

This largely inelastic supply curve is consistent with the empirical findings in the literature (Newell and Prest (2017), Caldara et al. (2016), Kilian (2022)) and aligns with the extraction vs. price pattern in the context of Russia (Figure 3).

4.4.2 Forces shaping the supply curve

What explains this shape? We now dissect the forces that drive these results by developing a decomposition of the policy function. We begin with a benchmark case for which an analytical solution is available and then add to it the ingredients of the model one by one.

The analytical benchmark reference point we consider is a supply curve of a producer who faces a constant price of the commodity and does not have outside income $\tau = 0$. In these circumstances, the problem of the producer admits a closed form solution: $y_t = \frac{\rho}{\gamma} x_t \forall t$, i.e. the producer extracts a constant fraction $\frac{\rho}{\gamma}$ of remaining reserves.[29] Since extraction is independent of (the constant) p, the contemporaneous supply curve is a vertical line at $\frac{\rho}{\gamma}$ in the left panel of Figure 8.

Relative to this benchmark, fluctuations in oil prices present in our model induce the *revenue smoothing*, *precautionary* and *time-the-market* effects. Outside income τ induces the *non-homotheticity* effect. We previously described these effects in the context of the two-period model of Section 3.2, and now describe how they work in our more general model.

Consider first adding to the analytical benchmark the possibility that the oil price converges deterministically to its average value.[30] With $\gamma = 2$, the income effect dominates and when prices are low today and expected to rise, the producer increases extraction today. The intuition is that the producer acts to smooth revenues in light of temporary deviations of prices from their average level. With a known price path converging deterministically to the average, the supply curve is thus downward sloping in the current price (a green dashed line in the left panel). In the right panel, we record this effect with the green bars.

If prices instead follow the estimated stochastic process, mean reversion is coupled with volatility and risk. Heightened uncertainty spurs the additional precautionary effect: the producer is more conservationist and the supply curve shifts to the left, although we find this effect to be relatively small quantitatively.

When prices are non-stochastic and fixed forever but the producer has access to non-oil income, the extraction rate rises for any price, but particularly so when prices are low. This is the non-hometheticity effect.[31]

[29] The extraction rate is increasing in the degree of impatience (i.e. in the discount rate ρ) and decreases with γ. In the limit as $\gamma \to \rho$, the extraction rate approaches 1. This is intuitive: with infinite intertemporal elasticity of substitution, the timing of consumption does not matter, and with discounting it is optimal to extract resource instantenously and consume the proceeds.

[30] Technically speaking, we solve the model under the estimated value of mean reversion parameter D but set price volatility $\sigma(p)$ to zero.

[31] With an alternative source of income, the producer extracts all of the commodity in finite time. Thus,

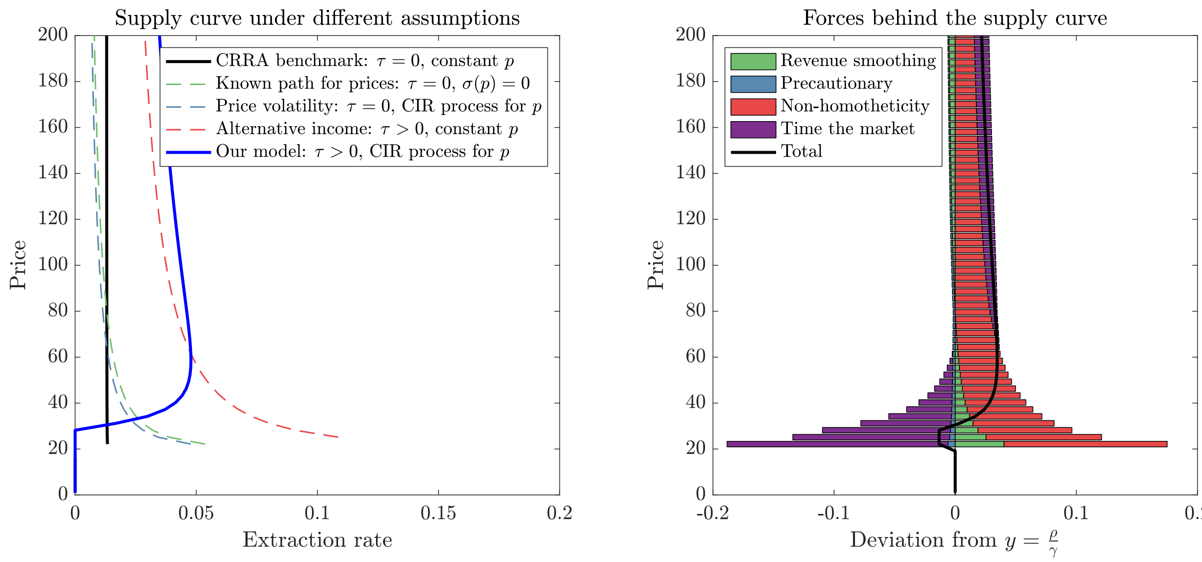

Figure 8: Forces shaping the contemporaneous supply curve

Finally, with both volatile prices and non-oil income, we obtain the contemporaneous supply curve of our main specification. The interesting finding is that the two components together are extremely different from the sum of individual parts. With $\tau > 0$ and with volatile prices, there is a strong motive to time the market. This is because the non-oil income τ provides a cushion against sharp increases in the marginal utility of oil revenues when prices and extraction are low. Consequently, supply responds strongly negatively as prices approach the marginal cost.

In summary, our novel decomposition highlights that the shape of the supply curve is determined by the balance of four forces. The time-the-market effect is most dominant at low prices, driving the upward slope in that region of the state space. For higher prices, the effects broadly offset, resulting in an inelastic supply curve.

4.4.3 How the results depend on preferences for smooth consumption

We now consider how the balance of forces discussed above changes as we vary the curvature of the utility function γ. Figure 9 shows our baseline case in the solid line, as well as three alternative calibrations. We do not view these calibrations as realistic – rather, they are

over time, the extraction rate rises as the reserves are depleted (and reaches 100% when the last unit of the commodity is extracted). This same relationship between extraction rate and the value of the reserves is induced by permanently low price of the resource: low p, if it is permanent, is in a sense equivalent to low x. Following this logic, for low p the producer behaves as if they are more impatient, extracting a higher share of the remaining reserves.

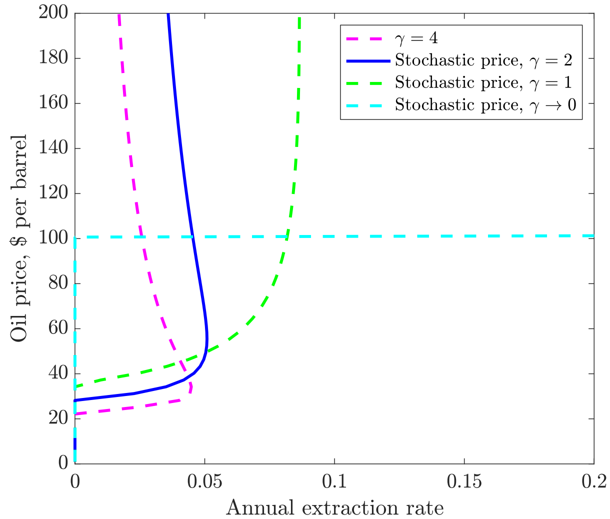

Figure 9: The supply curve under different parametrizations of utility

extreme cases that illustrate how the results depend on γ.

The pink-dashed line shows the supply curve when the producer's utility function has more curvature (i.e. a high γ). Since the timing of the flow of revenues matters more in this case, the revenue smoothing effect is more powerful. It takes an even lower price for the producer to leave the commodity under the ground, and production at high prices is significantly reduced.

The green-dashed line illustrates what happens when the utility function is logarithmic. Lower γ weakens the revenue smoothing motive and strengthens the time-the-market effect.

In the limit $\gamma \to 0$, our model then collapses to the frictionless Hotelling (1931) benchmark: the supply curve becomes infinitely elastic: the producer extracts all or nothing unless the price is expected to increase at the rate of time preference. Note that this is also the supply curve of a producer that faces no financial frictions and maximizes the net present value of profits. Thus, financial frictions act to make the supply less responsive to price fluctuations, in line with the empirical results in Section 2.5.

5 Price cap

We now study how the behavior of the petrostate changes when the price cap policy is imposed. For the time-being we consider a "perfect" price cap, in the sense that it applies to all of the exporter's sales and is perfectly credible and permanent. This is a useful benchmark that helps build understanding of the workings of this new tool; we relax these assumptions below once we introduce the model with market power.

5.1 Price that the producer receives under a price cap

A price cap limits exposure to high oil prices. Denoting with p_r the price actually received by the sanctioned state producer when the price cap of $\bar{p}$ is in force, we have:

$$p_{r,t} = \min\{p_t, \bar{p}\} \tag{6}$$

where $\bar{p}$ is the level of the price cap.

5.2 How does a price cap affect supply?

A naive way of thinking about the price cap would be to use the supply curve we characterized in the previous section, adjusted with a vertical segment at prices above $\bar{p}$. This approach would miss the fact that the price cap represents a change to the fundamental features of the environment in which the producer operates, and thus has a deep impact on the problem and hence on optimal behavior. Our structural model provides insights on the impacts of such a change.

We proceed by solving the model with p_r as given by (6). Figure 10 shows the supply curve for three different levels of $\bar{p}$: \$60, \$45 and \$30 per barrel, along with the supply curve without sanctions in place.

The headline result is surprising: the supply curve shifts out, so that the producer extracts *more* of the commodity with the cap than without! Why?

Since the price cap insulates the producer from periods of upward swings in the price, it brings the environment in which the producer operates closer to one without uncertainty and with a lower average price. Consequently, the optimal behavior resembles more closely the behavior of a producer who faces no uncertainty in the price of the commodity. The black squares in the figure, drawn at respective levels of $\bar{p}$ in each of the three cases, closely follow the supply curve with no volatility in p in Figure 8.[32] Less surprising is the result that the supply curve becomes vertical at prices above $\bar{p}$ as the producer receives $p_{r,t}$ and not p_t, and so becomes unresponsive to the fluctuations in the latter.[33]

[32]Recall the intuition: from the producer's perspective, the price cap makes the resources buried underground less valuable. With $\tau > 0$, the less valuable resource implies a higher extraction rate.

[33]The supply schedule is close to but not exactly vertical above $\bar{p}$ because the expected duration of the

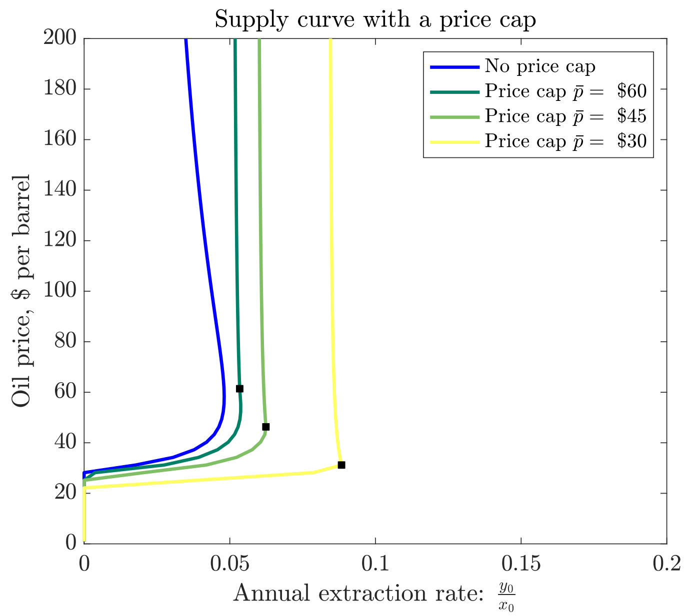

Figure 10: Russia's supply curve under three price cap regimes

The outward shift in the supply curve is an important finding that goes against the often-held intuition that capping prices necessarily lowers the quantity supplied by the sanctioned state. It has a clear and intuitive story behind it that our model elucidates. We now turn to the model with market power, which will further reinforce this conclusion with an additional mechanism.

6 A model with market power

Clearly, the issue of market power is crucial in situations where the sanctioned producer is large. We now enrich our model by considering a state that is large enough to affect global equilibrium prices.

6.1 World demand for oil and producer's market power

We denote the world price of oil with $p_{w,t}$, and assume that the global demand for oil is isoelastic so that

$$p_{w,t} = \delta(r_t + y_t)^{-\epsilon}, \tag{7}$$

price being above the cap is different at different levels of p_t.

where $\delta > 0$, $\epsilon \geq 0$ is the inverse of the elasticity of demand, r_t is the (residual) supply from the rest of the world, which is stochastic, and y_t, as before, is output of the state producer. Fluctuations in r_t reflect demand, supply, or any other shocks that hit the commodity market.

6.2 Producer's problem when the producer has market power

The optimization problem of the producer becomes:

$$\max_{y_t} \mathbb{E}_0 \left[\int_0^\infty e^{-\rho t} u(\pi_t + \tau) dt \right] \text{ subject to } dx_t = -y_t dt,\ x_t \geq 0,\ y_t \geq 0 \tag{8}$$

and the stochastic process for r_t, where now:

$$\pi_t = (p_{w,t} - \mathcal{M}) y_t = \left(\delta \left(r_t + y_t \right)^{-\epsilon} - \mathcal{M} \right) y_t. \tag{9}$$

Note that the effective market power of the producer changes endogenously over time as a result of extraction decisions. The following proposition derives the necessary conditions for a solution of this dynamic monopoly problem.

Proposition 5. *The optimal extraction path satisfies the necessary condition*

$$u_\pi \cdot (p_{w,t} \cdot (1 - \varepsilon_{D,t}) - \mathcal{M}) = v_x, \tag{10}$$

where

$$\varepsilon_{D,t} := -\frac{\partial p_{w,t}}{\partial y_t} \frac{y_t}{p_{w,t}} = \epsilon \cdot \frac{y_t}{r_t + y_t}. \tag{11}$$

is the effective elasticity of demand.

Equation (10) states that at the optimum the marginal utility of extraction is equal to the marginal value of reserves, and thus it agrees with the standard intuition in dynamic optimization. Equation (11) shows that marginal revenue depends on the effective elasticity of demand ε_D, which depends on the parameter ϵ as well as the relative size of the producer in world production. The intuition for why market power depends on the market share is familiar from the Cournot oligopoly model.

We can represent the problem recursively as follows:

$$\rho V(x, r) = \max_y u((p_w(r, y) - \mathcal{M}) \cdot y) - V_x(x, r) y + V_r(x, r) \mu(r) + \frac{1}{2} V_r(x, r) \sigma(r).$$

This HJB equation is different from the price-taker case above in two main respects. First, the stochastic variable is now the residual demand of the rest of the world r_t. Second, the world price is now endogenous – it depends on endogenously chosen output of the producer, as well as on the stochastic r_t. The producer internalizes the impact its decisions have on global prices.

6.3 Equilibrium

An *equilibrium* is a policy function $y(x, r)$ that solves producer's problem and the price function $p_w(r, y(x, r))$ that clears the market for oil.

6.4 Parametrization

The model with market power requires the parameterization of the elasticity of the world demand and of the process for r_t.

Estimating oil demand elasticity is a subject of an extensive empirical literature. Meta-analysis in Uria-martinez et al. (2018) suggests the range for this elasticity in the short-run (around one year) is in the $[0.07, 0.14]$ range.[34] However, these estimates are primarily based on OLS regressions, and so might suffer from the simultaneity bias. Indeed, the recent studies report elasticities that are higher in absolute value (see Baumeister and Hamilton (2019) and references within).[35] To reflect these considerations, we set $1/\epsilon = 0.25$. We discuss below how the results change as we depart from this elasticity in either direction.

In terms of the process for r_t, we estimate the model by simulated method of moments, such that the behavior of the equilibrium price $p_{w,t}$ in the laissez-faire equilibrium follows that of the process for the oil price observed in the data (and estimated in Section 3).

All the remaining parameters are calibrated as before.[36]

6.5 Characterization

The contemporaneous supply curve of a producer with market power is plotted in Figure 11. Relative to the results we have seen before, market power makes the producer more

[34] while the long-run elasticity (after over a decade) is within the $[0.26, 0.82]$ range.

[35] We report the absolute value of the elasticity; of course the demand curve is downward sloping.

[36] To solve the HJB equation with market power and to estimate the model, we develop a new algorithm which we describe in the Online Supplementary material.

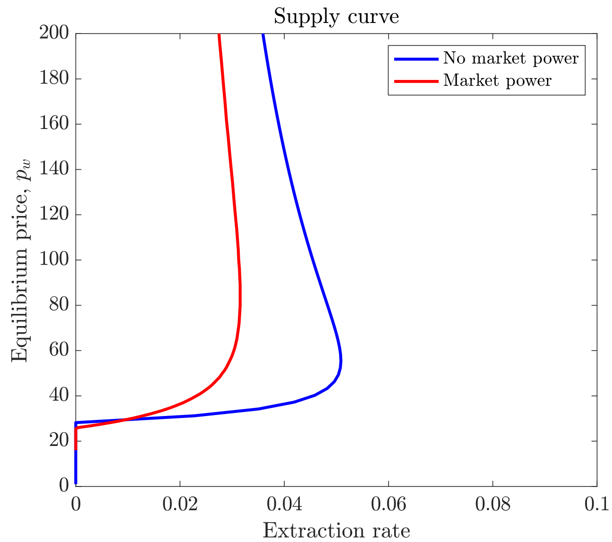

Figure 11: Contemporaneous supply curve with market power

conservationist in our environment, except when prices are marginally above the marginal cost. The supply curve remains inelastic for most of the price range.[37]

7 Price cap when the producer has market power

When the producer has market power and is subject to a price cap, the price that it receives is given by:

$$p_{r,t} = \min \{\bar{p}, p_{w,t}\}, \tag{12}$$

where $\bar{p}$ is the level of the price cap and $p_{w,t}$ is the equilibrium price of oil in the world market. The difference from (6) is that $p_{w,t}$ is now endogenous and determined by the producer's decisions (as well as by the stochastic realization of r_t).

7.1 How does the price cap interact with market power?

An important insight of this section is that the price cap limits the use of market power in equilibrium. Although the economics is straightforward – with a price cap in place, restricting

[37] It is useful to contrast this result with Stiglitz (1976) who studied the role of market power in resource extraction. That paper showed that in a simple benchmark model of resource extraction, market power has no effect on the quantity extracted, highlighting the important difference between exhaustible resources and produced goods. Our framework differs, however, because of the presence of strictly positive marginal costs, financial frictions, and non-oil income.

quantities no longer raises prices, rendering the use of market power ineffective – this insight goes against the popular view that sanctioning a large producer who has substantial market power is necessarily more difficult, or that it risks large adverse market outcomes. In fact, we show below that the opposite is true.

A binding price cap strips the producer of market power. Because of this, one can anticipate the result that the supply curve with a price cap in place is an envelope of two supply curves that we have seen before: (1) when the cap is not binding, optimal extraction follows the pattern described in the previous section; (2) for prices above the price cap, the supply curve instead resembles the schedule in Figure 10, i.e the one without market power and under a binding price cap.

Figure 12 confirms that this conjecture is indeed true. The solid black schedule in the figure is the supply curve with a \$60 price cap in place. The figure shows that when $p_w < \bar{p}$, the cap matters little for the producer's behavior. The producer exercises market power, and the solid black line follows closely the supply curve we described in the previous section (the red line). In contrast, when prices are above \$60 and so the cap binds, the producer ceases to use its market power, the supply curve is shifted to the right. It resembles the supply curve under the cap from a model of a price-taking producer of Section 5.

In between these two regions, the producer gradually reduces the extent to which it uses pricing power in equilibrium, in a way that maintains the equilibrium price at $p_w = \bar{p}$.

7.2 Effect of the price cap on equilibrium prices

Given the optimal behavior of the producer we just described, what happens to equilibrium prices as the cap is introduced?

To answer this question, it is useful to define *reference price* p_t as the hypothetical equilibrium price under the assumption that the producer did not use market power. The reference price is simply a transformation of the state variable r_t, and so provides a measure of tightness of the commodity market that is cleaned of endogenous decisions of the sanctioned patrostate.

A price cap can lower the global equilibrium price of the commodity, especially when the reference price is high (the right panel of Figure 13). This *stabilization effect* comes about precisely because when the cap is binding, the producer ceases to exercise market power and instead has the incentive to supply larger quantity of the commodity to the market.

It is important to note that these effects are more pronounced when the producer has substantial degree of market power. This is because the gap between production levels with

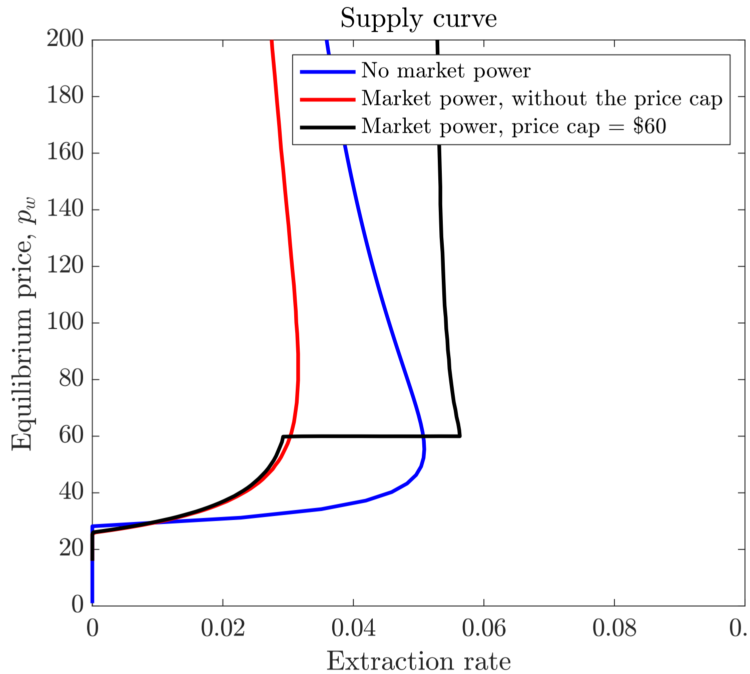

Figure 12: Equilibrium supply in a model with market power with a $60 price cap

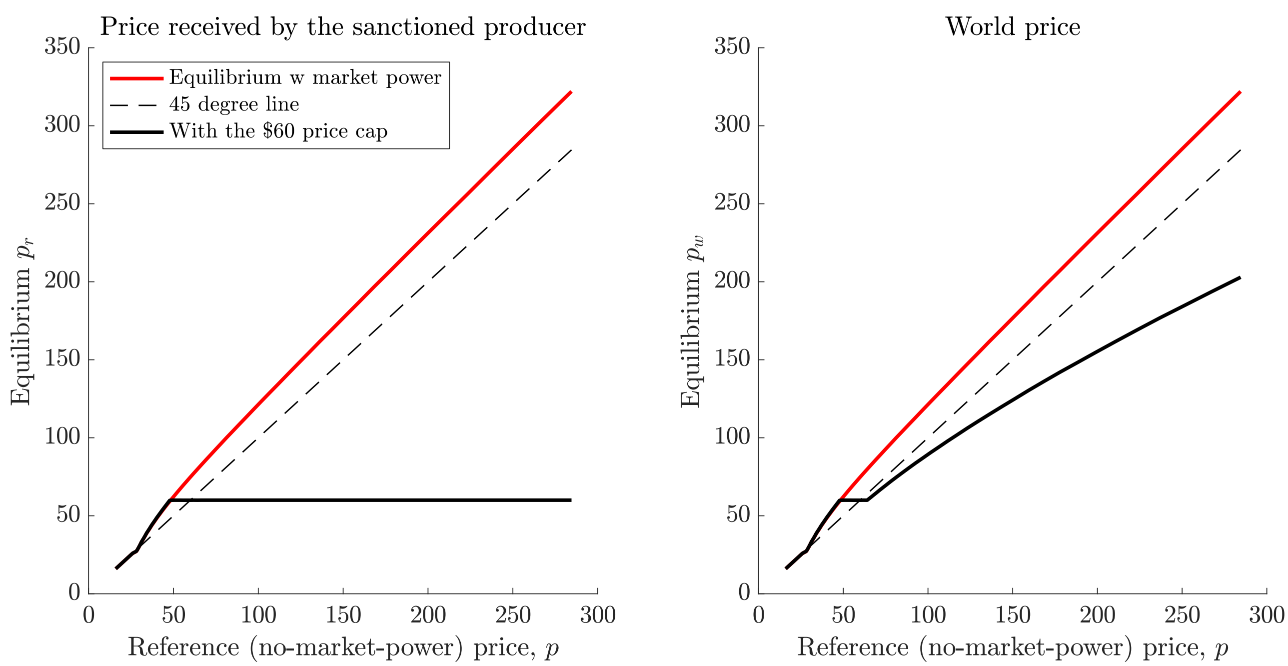

Figure 13: Equilibrium prices in the model with market power, with and without a price cap

and without market power naturally increases with the degree of market power, and this gap is what the price cap eliminates.

We summarize these results in the following proposition.

Proposition 6. *When the sanctioned producer has market power, introducing a price cap that applies to all sales has the following effects:*

(1) the cap limits the extent to which the producer exercises market power in equilibrium;

(2) a binding cap thus tends to reduce *equilibrium world price p_w;*

(3) the decline in p_w upon introduction of cap is larger the higher is reference price p;

(4) the cap thus stabilizes *equilibrium world price p_w;*

(5) for high reference price p, the equilibrium p_w can be below p;

(6) these effects are more powerful when the producer commands significant pricing power.

8 Imperfect price cap

Our analysis has so far assumed that the price cap applies uniformly to all sales by the sanctioned producer and is perceived as fully credible, i.e., expected to remain in place indefinitely. These assumptions are unlikely to hold in practice. In reality, the price cap might cover only a fraction of the exporter's oil sales. For instance, the G7 price cap on Russian oil applies exclusively to seaborne oil and oil products that use Western services, such as transportation and insurance. Moreover, the producer might expect it to be temporary. Practical and political frictions in enforcing the price cap can further allow a significant portion of sales to bypass the sanctions regime. In this section, we relax the assumptions of a perfect price cap and explore how this alters the conclusions of our analysis.[38]

8.1 Leaky price cap

Let us represent the percentage of the producer's current oil reserves that can be exported outside of the cap with parameter $\kappa \in [0, 1]$. For instance, with $\kappa = 0.01$, the producer can

[38] In what follows, the imperfections of the price cap regime are pinned down by exogenous parameters. The capacity to export oil outside the price cap regime is not fixed but rather endogenous. Sanctioned producers can invest in shipping and logistics to bypass the cap. For example, Russia has made significant investments to develop a 'shadow fleet.' The International Working Group on Russian Sanctions (2024) estimate that since the cap's implementation, Russia has spent approximately \$10 billion on expanding its fleet. This effort increased the share of Russian crude oil and oil products exported outside the price cap regime from 20% in April 2022 to 67% in August 2024. For a detailed analysis of endogenous decisions to expand shadow fleet capacity within a static model of oil supply, see Cardoso et al. (2024).

export 1% of its reserves per unit of time without being subject to the price cap. $\kappa = 0$ represents the case of a perfect price cap that applies to all exports (meaning that the producer cannot sell outside the price cap regime), as described in previous sections. In the context of Russia, κ can be thought of as the size of the so-called shadow fleet.

With a shadow fleet of capacity κ, the instantaneous profits from oil sales when the price cap is in place are:

$$\pi_t = \begin{cases} y \cdot (p_w(y) - \mathcal{M}) & \text{if } y \leq \kappa \\ y \cdot (p_w(y) - \mathcal{M}) & \text{if } y > \kappa \text{ and } p_w < \bar{p} \\ \kappa \cdot (p_w(y) - \mathcal{M}) + (y - \kappa) \cdot (\bar{p} - \mathcal{M}) & \text{if } y > \kappa \ \text{ and } p_w > \bar{p} \end{cases} \tag{13}$$

where p_w is the equilibrium oil price. The third line represents profits when extraction is above κ and the cap is binding. In this case the producer receives the world equilibrium price for the quantity κ, and the price cap for the remaining sales.[39]

8.1.1 The effects of a leaky price cap

The combination of market power and the ability to bypass the price cap on some of its sales provides the producer with a potentially appealing strategy to deal with the sanctions: cut the production levels towards κ, thereby squeezing the global market and raising equilibrium prices at which quantity κ is sold. Higher prices in part compensate for the lower quantity. We now show that whether this is indeed an optimal strategy is state dependent, in that it depends on market tightness.

Figure 14 illustrates optimal extraction and equilibrium world prices with a price cap that is imposed on the producer who has access to a shadow fleet capable of carrying 1% of

[39] The first order condition of the producer's problem becomes

$$v_x = \begin{cases} u_\pi \cdot (p_w (1 - \varepsilon_D) - \mathcal{M}) & \text{if } y < \kappa \\ u_\pi \cdot (p_w (1 - \varepsilon_D) - \mathcal{M}) & \text{if } y > \kappa \text{ and } p_w < \bar{p} \\ u_\pi \cdot \left(\bar{p} + \kappa \frac{\partial p_w}{\partial y} - \mathcal{M}\right) & \text{if } y > \kappa \text{ and } p_w > \bar{p} \end{cases} \tag{14}$$

where ε_D is the elasticity of demand. When production is low, so that all oil can be transported outside the cap regime (the first row in (14)), the marginal utility of extracting an additional barrel is given by the marginal utility of oil profits times the world price adjusted downward for the impact that this extraction has on the prevailing oil price. This is also true if the marginal barrel is sold using the coalition services and so under the price cap regime, but if the price cap is not binding (the second row). Finally, when the marginal barrel is sold at a cap, the marginal benefit is just the price cap adjusted for the price impact that the sales of a marginal barrel have on the revenues from the sales of the infra-marginal κ barrels (the final row).

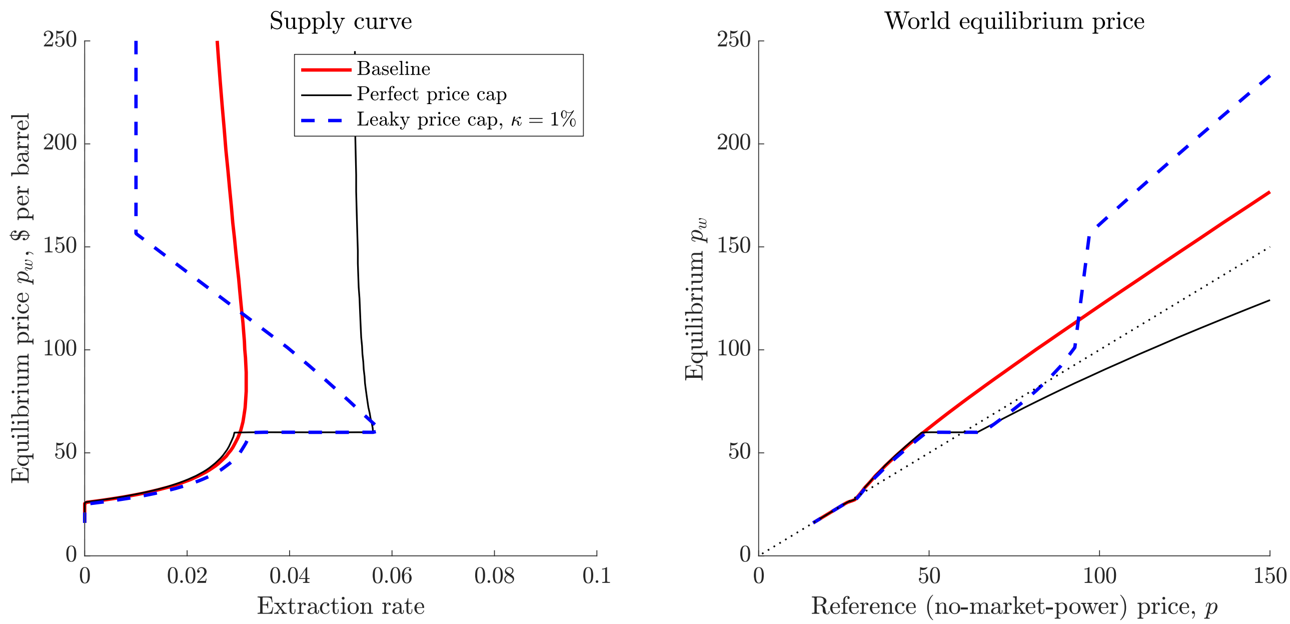

Figure 14: Equilibrium supply and prices under a price cap when Russia has access to a shadow fleet

its total reserves (i.e. about a third of extraction in normal times).

The left panel displays the supply schedule. It is very non-linear, reflecting highly state-dependent behavior of the producer. When the oil market is already tight and prices are high, the producer finds it optimal to restrict supply. In fact, when prices are above \$150 per barrel, the producer reduces production to κ, meaning that it exports only outside the price cap regime. However, when prices are low, the forces described in the previous sections dominate, and the price cap leads to an expansion of the desired supply by the producer. In our parametrization, this happens when the equilibrium price is between \$60 and \$120 per barrel. Thus, the effects of the price cap are strongly state-dependent. As a result, the cap has stabilizing effects when prices are close to its long-term average of \$76, but a destabilizing effect exactly when world prices are already high. This introduces a meaningful trade-off for the sanctioning policymakers, one that we discuss in detail below.

8.2 Expectation that the price cap is temporary

What if the price cap is expected to only last so long? To answer this question, we now assume that the producer believes that the lifting of the cap is a Poisson event with intensity

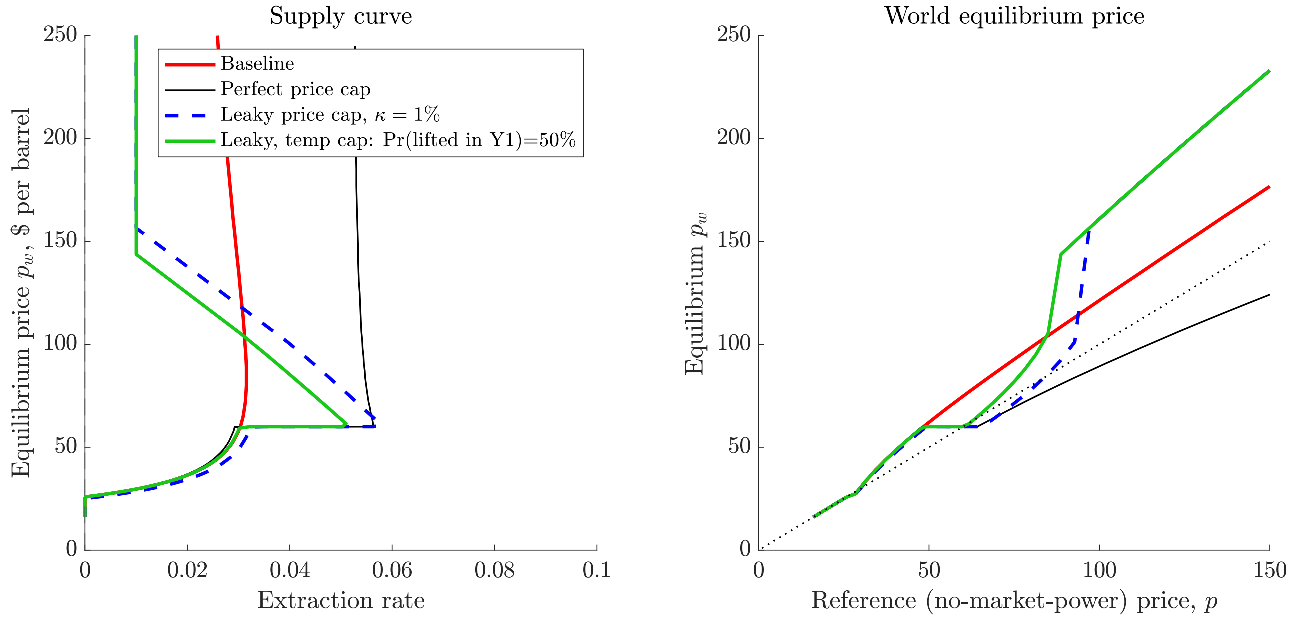

Figure 15: Equilibrium supply and prices when the producer expects the price cap to be temporary

λ, so that the duration of the price cap is an exponentially distributed random variable and

$$Pr(\text{cap lifted before } t) = 1 - \exp(-\lambda t).$$

For concreteness, suppose that the producer perceives that the probability of the cap being lifted in the first year is 50%, implying $\lambda = 0.69$. How does this affect the behavior of the producer?[40]

Figure 15 illustrates how contemporaneous extraction responds to such expectations and what the consequences are for global prices. The expectation that the cap is temporary makes the producer more inclined to shut-in production, hence keeping more barrels of oil under ground and only extracting them when the price cap is lifted. Thus, as illustrated in the right panel of the figure, the lack of credibility reinforces the shadow fleet mechanism in further reducing the stabilization effects of the price cap.

[40] Solving the model becomes technically more challenging in this case. To compute the solution, we introduce another state variable which takes two values, corresponding to the cap being and not being in place. We then impose a Poisson process with the required intensity that governs switching between the cap and the no-cap state.

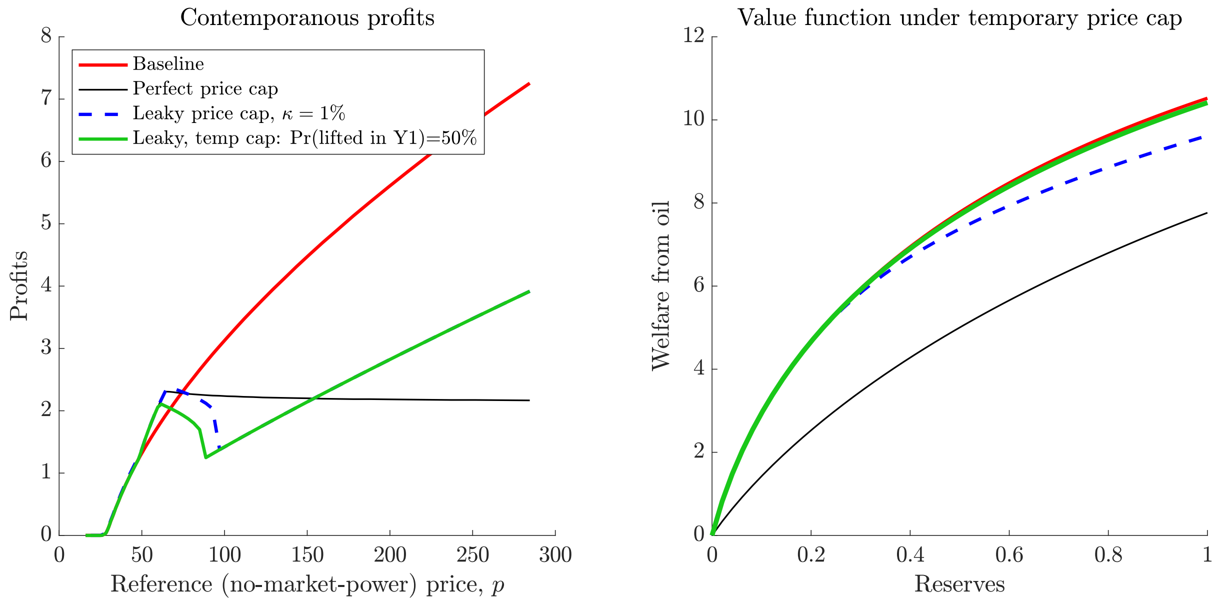

Figure 16: Effects of price caps on producer's contemporaneous revenues and welfare when Russia has access to a shadow fleet or the cap is imperfectly enforced

Note: the right-panel assumes that the (current) reference no-market-power price of oil p is \$80.

8.2.1 The impact of a leaky price cap on profits and welfare

We have now endowed the producer with market power and have made it possible to partially circumvent the price cap regime by exporting oil using a shadow fleet of tankers and services. What impact does a leaky price cap have on producer's profits and welfare in this environment?

Figure 16 offers an answer. Our results suggests that even with a relatively highly inelastic demand embedded in our calibration, the sharp reduction in exports does not generate a price response that is sufficiently strong to make the shut-in a profitable strategy in the short term. The dashed line in the left panel shows that contemporaneous profits plummet by up to 50% (relative to the profits that would have been earned under a perfect price cap) as the producer turns to the shut-in strategy, unless the market prices are already very high, above \$150 per barrel. Shutting in production at κ is optimal not because it increases contemporaneous profits, but because it allows for a more spread-out production profile over time.

Indeed, the static losses are more than compensated for by dynamic gains. The right-hand panel shows that producer welfare increases with κ, which is intuitive, since larger κ gives the producer more options to deal with the sanctions. The interesting result here is quantitative, namely that the ability to circumvent the price cap regime very significantly diminishes the degree to which the cap hurts the producer. Compared to a perfect cap, a leaky cap with $\kappa = 0.01$ reduces the damage in welfare terms by about $\frac{2}{3}$.[41]

These results reveal the key trade-off for sanctioning (western, in case of Russia) policymakers: a lower price cap hurts the producer but might reinforce the destabilizing shocks in the oil market. In the final part of the paper, we contribute a systematic way to navigate this trade-off.

9 Navigating the trade-off

This section introduces a framework to guide policymakers in setting the price cap at the optimal level. The core trade-off in implementing such sanctions lies between two objectives: depriving the sanctioned country of financial resources and mitigating volatility in the market for the targeted commodity. Our contribution is to provide a coherent, structural-model-based tool to navigate this complex decision-making process.

9.1 Objective for the sanctioning coalition

We assume that the objective of the sanctioning policy maker combines two components: the welfare of the sanctioned producer, $v(\bar{p})$, and a measure of unfavorable market outcomes, $\phi(\bar{p})$. The relative weight between these two objectives is given by λ. The policymaker decides on the price cap level to solve:

$$\min_{\bar{p}} \quad \underbrace{v(\bar{p})}_{\substack{\text{a measure of} \\ \text{producer's welfare}}} \quad + \lambda \times \quad \underbrace{\phi(\bar{p})}_{\substack{\text{a measure of} \\ \text{bad outcomes} \\ \text{in the oil market}}} \quad .$$

A higher λ indicates caution: the policymaker with a high λ puts a relatively high weight on minimizing adverse outcomes in the oil market. In contrast, a low λ policymarker is more tolerant of costs and prioritizes the infliction of damage on the sanctioned country. For simplicity, we assume that the preference map (and hence the indifference curves) are linear, but it is straightforward to see how the analysis would change if e.g. strict quasiconcavity were assumed instead. Rather than trying to pin down the preferences of policy makers precisely, we explore how different values of λ affect the optimal choices within our framework.

[41] If a price cap is expected to be lifted with 50% probability within a year, the effects on the intertemporal welfare are significantly diminished.

The next step in our analysis is to use our structural model to quantify the functions $v(\bar{p})$ and $\phi(\bar{p})$.

9.2 Quantifying producer's welfare, $v(\bar{p})$

The measure $v(\bar{p})$ captures the relative reduction in the welfare of the sanctioned producer due to the price cap. Using the structural model, a natural way to quantify this is via the producer's value function, $V(p, 1; \bar{p})$, which solves the HJB equation under a given price cap. The welfare impact of the price cap is then expressed as:

$$v(\bar{p}) := \frac{V(p, 1; \bar{p}) - V(p, 1; \infty)}{V(p, 1; \infty)}$$

where $V(p, 1; \infty)$ represents the value function when there is no price cap (i.e. $\bar{p} = \infty$). This relative measure reflects the proportional welfare loss inflicted by the price cap, normalized by the producer's baseline welfare without sanctions-driven constraints.[42]

9.3 Quantifying market outcomes, $\phi(\bar{p})$

The measure $\phi(\bar{p})$ reflects the probability of undesirable outcomes in the oil market under a price cap. A plausible candidate is the excess probability of an oil price shock, defined as the price of oil exceeding a threshold, such as \$120 per barrel. In this case, we define:

$$\phi(\bar{p}) := \underbrace{Pr(p_w > \$120 \mid \text{price cap of } \bar{p})}_{\text{can compute using the model}} - \underbrace{Pr(p_w > \$120 \mid \text{no price cap})}_{\text{=12\% historically \& in our model}}.$$

The historical probability of such price shocks, approximately 12%, serves as a benchmark in our model. The baseline probability without a price cap aligns with this historical figure, as our structural model is estimated with historical data. The probability under a specific price cap $\bar{p}$ can then be computed through model simulations.[43]

[42]While this measure emphasizes intertemporal welfare, alternative definitions are possible. For instance, policymakers might instead focus on contemporaneous profits rather than full intertemporal welfare. The flexibility of our framework allows for such modifications and facilitates comparisons between different welfare measures to assess the robustness of policy conclusions.

[43]Alternative metrics for $\phi(\bar{p})$ could incorporate additional concerns, such as price volatility or a combination of price levels and volatility. However, the probability-based measure proposed above provides a straightforward and relevant metric for assessing the risks of extreme market disruptions, which are likely central to policymakers' concerns.

9.4 The sanctions possibility frontier

Our framework introduces a novel concept: *the sanctions possibility frontier*. For a given level of price cap leakage (κ), the frontier captures the combinations of (1) damage inflicted on the sanctioned country and (2) the probability of an oil market shock that can be achieved through various price cap levels. It serves as a menu from which policymakers select the optimal price cap, balancing these competing objectives.

9.5 Mapping out the trade-off

The trade-offs can be visualized graphically (Figure 17). The horizontal axis represents the metric v (damage inflicted on the sanctioned producer) and the vertical axis encodes the values of ϕ (probability of an oil market shock).

The thick colored lines represent the limit of sanctions possibilities, showing the combinations of v and ϕ achievable under different levels of price limits. The different curves correspond to varying levels of leakage (κ).

We also plot the indifference curves that represent the preferences of a policymaker with $\lambda = 1$.

If the cap is perfect, there is no trade-off between the two objectives. Lowering the price cap simultaneously inflicts greater harm on the sanctioned producer and stabilizes the global oil market. The sanctions possibility frontier is upward sloping. Under these conditions, the policymaker should always choose the corner solution of the lowest possible price cap above marginal cost, regardless of their preferences. We denote this optimal choice with a star in the figure.

A more realistic case of a leaky price cap introduces the trade-off between market stability and the aims of economic warfare: the sanctions possibility frontier becomes downward sloping, at least for some of the range of $\bar{p}$. The sanctions possibility frontier tends to become steeper as κ increases. With a meaningful trade-off, the choice of the optimal tightness of the price cap becomes dependent on preferences: for example, if κ is such that the sanctioned producer can carry 1/6th of its normal production levels outside of the sanctions regime, a more cautious ($\lambda = 2$) sanctioning policymaker chooses a cap of \$55 a barrel, while a more aggressive policymaker ($\lambda = 1$) would implement the \$20 price cap.

Figure 18 illustrates that preferences play a role in driving the optimal price cap choice for intermediate levels of price cap leakage: as the price cap becomes leaky and ineffective, the optimal choice under two preference settings we consider converges to the same value

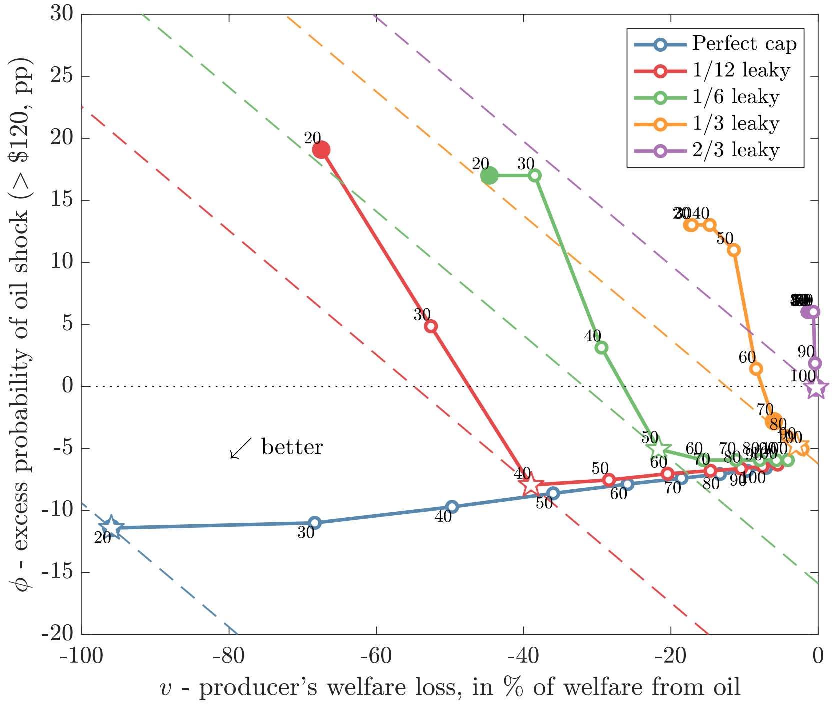

Figure 17: Sanctions possibility trade-off and indifference curves for $\lambda = 1$ policymaker. The thick circled lines show the sanctions possibility frontier for different levels of the cap (in $ per barrel) for various levels of κ. The stars indicate the optimal level of the price cap for any level of leakage.

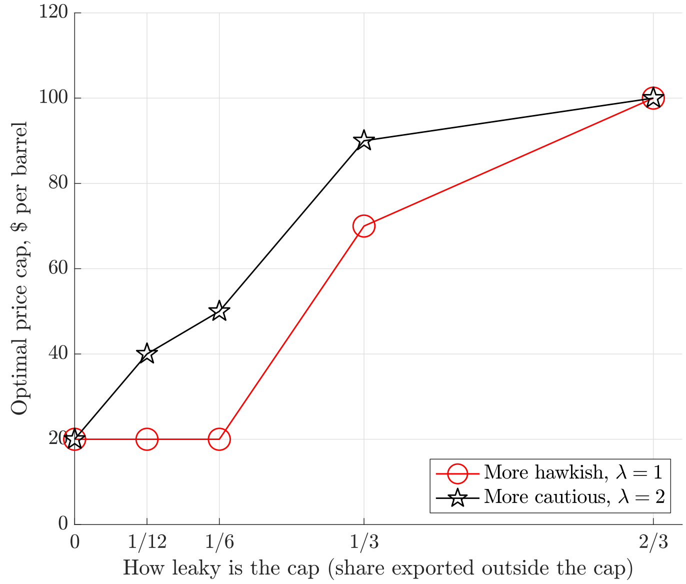

Figure 18: Optimal price cap as a function of leakage

($100).

In summary, the policy framework we put forward can help policymakers navigate the complex trade-off when designing sanctions. The key takeaway is that the optimal price cap level increases with the degree of leakage. The corollary is that efforts to reduce leakage – for example, those targeted at strengthening enforcement, or sanctions that target purchases of oil tankers – can meaningfully improve the trade-off faced by policymakers.

10 Conclusions

The main contribution of this paper is a dynamic model that helps us understand the economic incentives of a financially constrained producer of a non-renewable resource. Our application and focus has been the on the effects of the new instrument of international policy – a price cap.

The analysis uncovered economic forces and intuitions that have been overlooked in the discussions of the price cap. In particular, our model highlights the importance of financial frictions, market power, and the optimal dynamic behavior of the producer in this context. It emphasizes the role of alternative sources of funds or other sources of non-homotheticity in producer's preferences. And it illuminates the fact that the price cap reduces the use of market power in equilibrium, which leads to a stabilizing effect of the price cap on the global commodity market, as long as the price cap is not too leaky.

Finally, we have used the estimated model as a building block of a framework for designing optimal policy. This device is useful because it allows policymakers to think through trade-offs in a consistent manner. The main substantive conclusion from this exercise is that effective enforcement of the cap is a pre-condition for a low level of the cap itself.

Our paper opens up several avenues for future research. Some new research has already built on this analysis by explicitly considering the endogenous decision to expand the capacity of the shadow fleet. Our setting explored the use of the price cap tool in the context of non-renewable resources. But future work might want to consider a setting in which trade of products or exchange of technologies is taking place between the sanctioning and the sanctioned state. Another useful avenue for future research would be to explicitly embed the setting developed here within a general equilibrium model of a world economy, with strategic interactions across participating states. More broadly, the tools developed here could naturally be used in other contexts where a producer faces stochastic market conditions and intertemporal choices.

References

Aghion, Philippe, Philippe Bacchetta, Romain Rancière, and Kenneth Rogoff, "Exchange rate volatility and productivity growth: The role of financial development," *Journal of Monetary Economics*, 2009, *56* (4), 494–513.

Anderson, Soren T., Ryan Kellogg, and Stephen W. Salant, "Hotelling under pressure," *Journal of Political Economy*, 2018, *126* (3), 984–1026.

Arrow, Kenneth J and Sheng-Cheng Chang, "Optimal pricing, use, and exploration of uncertain natural resource stocks," *Journal of Environmental Economics and Management*, 1982, *9* (1), 1–10.

Babina, Tania, Benjamin Hilgenstock, Oleg Itskhoki, Maxim Mironov, and Elina Ribakova, "Assessing the Impact of International Sanctions on Russian Oil Exports," 2023.

Baumeister, Christiane, "Pandemic, War, Inflation: Oil Markets at a Crossroads?," 2023.

_ and James D. Hamilton, "Structural interpretation of vector autoregressions with incomplete identifcation: Revisiting the role of oil supply and demand shocks," *American Economic Review*, 2019, *109* (5), 1873–1910.

Bianchi, Javier and César Sosa-Padilla, "On wars, sanctions, and sovereign default," *Journal of Monetary Economics*, 2024, *141* (October 2023), 62–70.

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.

Bulow, Jeremy and Paul Klemperer, “Regulated prices, rent seeking, and consumer surplus,” *Journal of Political Economy*, 2012, *120* (1), 160–186.

Caldara, Dario, Michele Cavallo, and Matteo Iacoviello, “Oil Price Elasticities and Oil Price Fluctuations,” *International Finance Discussion Papers*, 2016, *2016* (1173), 1–59.

Cardoso, Diego S, Stephen W Salant, and Julien Daubanes, “The Dynamics of Evasion : The Price Cap on Russian Oil Exports and the Amassing of the Shadow Fleet,” 2024.

Cavalcanti, Tiago V., Kamiar Mohaddes, and Mehdi Raissi, “Commodity Price Volatility and the Sources of Growth,” *Journal of Applied Econometrics*, 2015, *30* (6), 857–873.

Chanysheva, Amina, Pierre Kopp, Natalia Romasheva, and Anni Nikulina, “Migration attractiveness as a factor in the development of the russian arctic mineral resource potential,” *Resources*, 2021, *10* (6), 1–25.

Chen, Ren-Raw and Louis Scott, “Maximum likelihood estimation for a multifactor equilibrium model of the term structure of interest rates,” *The Journal of Fixed Income*, 1993, *3* (3), 14–31.

Clayton, Christopher, Matteo Maggiori, and Jesse Schreger, “A Framework for Geoeconomics,” *SSRN Electronic Journal*, 2023, (August).

Cox, John C., Jonathan E. Ingersoll, and Stephen A. Ross, “A Theory of the Term Structure of Interest Rates,” *Econometrica*, mar 1985, *53* (2), 385.

CREA, “EU oil ban and price cap are costing Russia EUR 160 mnday, but further measures can multiply the impact,” Technical Report 2023.

Damodaran, Aswath, “Country Risk: Determinants, Measures and Implications - The 2022 Edition,” *SSRN Electronic Journal*, 2022, pp. 1–127.

Dasgupta, Partha S and Geoffrey M Heal, “The optimal depletion of exhaustible resources,” *The Review of Economic Studies*, 1974, *41* (Supplement), 3–28.

Devarajan, S. and A. C. Fisher, “Hotelling’s "Economics of Exhaustible Resources" Fifty Years Later,” 1981.

Duffie, Darrell and Rui Kan, “A Yield-Factor Model of Interest Rates,” *Mathematical Finance*, 1996, *6* (4), 379–406.

Faucon, Benoit and Summer Said, “Saudi Arabia, U.A.E. Scoop Up Russian Oil Products at Steep Discounts,” *The Wall Street Journal*, 2023, *April.*

Gaudet, Gérard, “The Economics of Exhaustible Resources,” in Geoffrey M Heal and Theodore Panayotou, eds., *Handbook of Environmental Economics*, Vol. 4, Elsevier, 2013, pp. 121–176.

Grozovski, Boris, "Russia's Unprecedented War Budget Explained," Technical Report 2023.

Guriev, Sergei, "Russia's Economy, War in Ukraine, and Hopes for Post-Putin Liberalization - Sergei Guriev at Harvard," 2023.

Hamilton, James D., "Understanding Crude Oil Prices," *The Energy Journal*, 2009, *30* (2), 179–206.

Harris, Benjamin H, "The Origins and Efficacy of the Price Cap on Russian Oil," Technical Report 2023.

Harstad, Bård, "The Conservation Multiplier," *Journal of Political Economy*, 2023, *131* (7), 1731–1771.

Hilgenstock, Benjamin, Elina Ribakova, Nataliia Shapoval, Tania Babina, Oleg Itskhoki, and Maxim Mironov, "Russian Oil Exports Under International Sanctions," 2023, (April), 1–27.

Hotelling, Harold, "The Economics of Exhaustible Resources," *Journal of Political Economy*, 1931, *39* (2), 137–175.

Itskhoki, Oleg and Dmitry Muhkin, "Sanctions and the exchange rate," 2023.

Johnson, Simon, Lukasz Rachel, and Catherine Wolfram, "Design and Implementation of the Price Cap on Russian Oil Exports," *Journal of Comparative Economics*, 2023.

Känzig, Diego R., "The macroeconomic effects of oil supply news: Evidence from opec announcements," *American Economic Review*, 2021, *11* (4), 1092–1125.

Kennedy, Craig, "Measuring the shadows," Technical Report 2023.

_ , "Russia's Hidden War Debt," 2025.

Kilian, Lutz, "Understanding the estimation of oil demand and oil supply elasticities," *Energy Economics*, 2022, *107.*

_ , David Rapson, and Burkhard Schipper, "The Impact of the 2022 Oil Embargo and Price Cap on Russian Oil Prices," 2024.

Kladivko, Kamil, "CIR Maximum Likelihood Implementation in MATLAB," *Department of Statistics and Probability Calculus, University of Economics*, 2013, *1* (3).

Koren, M. and S. Tenreyro, "Volatility and Development," *The Quarterly Journal of Economics*, feb 2007, *122* (1), 243–287.

Leautier, Thomas Olivier, "On the long-term impact price caps: investment, uncertainty, imperfect competition, and rationing," *International Journal of Industrial Organization*, 2018, *61* (January 2016), 53–95.

Longstaff, Francis A and Eduardo S Schwartz, "Interest rate volatility and the term structure:

A two-factor general equilibrium model," *The Journal of Finance*, 1992, *47* (4), 1259–1282.

Lorenzoni, Guido and Iván Werning, "A Minimalist Model for the Ruble during the Russian Invasion of Ukraine," *American Economic Review: Insights*, 2023, *5* (3), 347–356.

Mohaddes, Kamiar and Mehdi Raissi, "Do sovereign wealth funds dampen the negative effects of commodity price volatility?," *Journal of Commodity Markets*, dec 2017, *8* (304), 18–27.

Newell, Richard G and Brian C Prest, "The Unconventional Oil Supply Boom: Aggregate Price Response from Microdata," *The Energy Journal*, 2017, *38* (2).

Osintseva, Marina A., "Differentiation of oil production break-even level among world oil companies," *International Journal of Energy Economics and Policy*, 2021, *11* (4), 249–256.

O'Toole, Brian, Olga Khakova, Tomasz Wlostowski, and Charles Lichfield, "Rebooting the Russian oil price cap," Technical Report 2023.

Pindyck, Robert S, "Uncertainty and Exhaustible Resource Markets," *Journal of Political Economy*, 1980, *88* (6), 1203–1225.

_ , "The long-run evolution of energy prices," *The Energy Journal*, 1999, pp. 1–27.

Rosenberg, Elizabeth and Eric Van Nostrand, "The Price Cap on Russian Oil: A Progress Report," Technical Report 2023.

Rosneft, "Annual Report: Spearheading the Energy Transition," Technical Report 2021.

Salant, Stephen W., "Exhaustible Resources and Industrial Structure: A Nash-Cournot Approach to the World Oil Market," *Journal of Political Economy*, 1976, *84* (5), 1079–1093.

Salant, Stephen W, "The Hotelling Principle, Backwardation of Futures Prices and the Values of Developed and Undeveloped Oil Fields," *The Energy Journal*, 2012, *33* (3), 1–28.

_ , "Targeted Price Ceilings in Competitive Models," 2023.

Sappington, David and Douglas Turner, "On the Design of Price Caps as Sanctions," 2023.

Schwartz, Eduardo S and James E Smith, "Short-term variations and long-term dynamics in commodity prices," *Management Science*, 2000, *46* (7), 893–911.

Shapoval, Nataliia, Jacob Nell, Craig Kennedy, and Benjamin Hilgenstock, "Working Group Paper # 18 Energy Sanctions: Four Key Steps to Constrain Russia in 2024 and Beyond," Technical Report 2024.

Solow, Robert M, "The Economics of Resources or the Resources of Economics," *The American Economic Review*, 1974, *64* (2), 1–14.

Stiglitz, Joseph E, "Monopoly and the Rate of Extraction of Exhaustible Resources," *The*

American Economic Review, 1976, *66* (4), 655–661.

The International Working Group on Russian Sanctions, "Working Group Paper 21: The Path Forward on Energy Sanctions. A Toolkit to Step Up Pressure on Russia in 2025," Technical Report 2024.

Uria-martinez, Rocio, Paul Leiby, Gbadebo A Oladosu, David C Bowman, and Megan M. Johnson, *Using Meta-Analysis to Estimate World Oil Demand Elasticity* number February 2018.

van der Ploeg, Frederick and Cees Withagen, "Too Much Coal, Too Little Oil," *Journal of Public Economics*, 2012, *96* (1-2), 62–77.

_ and Steven Poelhekke, "Volatility and the natural resource curse," *Oxford Economic Papers*, 2009, *61* (4), 727–760.

Wachtmeister, Henrik, Johan Gars, and Daniel Spiro, "The price cap on Russian oil: a quantitative analysis," 2023.

Wolfram, Catherine, "Understanding the Price Cap on Russian Oil and Its Role in Depressing Russian Oil Revenues," Technical Report August 2024.

_ , Simon Johnson, and Lukasz Rachel, "The Price Cap on Russian Oil Exports , Explained," *Belfer Center Policy Brief*, 2022, (December).

Appendix

A Data appendix

Figure 4 relies on country-level data on oil production and financial constraints plus data on OPEC pricing decisions.

A.1 Oil production and oil pricing decision data

The analysis uses a country-level data set comprising 70 non-OPEC countries and 53 OPEC announcements that span 1984 to 2017. The OPEC announcements come from Känzig (2021), who sources post-2002 dates from publicly available announcements and derives pre-2002 dates from OPEC resolutions and Bloomberg news reports. The monthly oil production data from the US Energy Information Administration (EIA) enables the calculation of production changes between the month following each OPEC pricing decision and the preceding month. The oil production data set includes 106 countries. Of these, 26 countriesâAlgeria, Angola, Azerbaijan, Bahrain, Brunei, Congo-Brazzaville, Ecuador, Equatorial Guinea, Gabon, Indonesia, Iran, Iraq, Kazakhstan, Kuwait, Libya, Malaysia, Mexico, Nigeria, Oman, Qatar, Russia, Saudi Arabia, South Sudan, Sudan, the United Arab Emirates, and Venezuelaâwere OPEC or OPEC+ members for at least part of the analysis period and were excluded. Additionally, countries with minimal production levelsâBelize, Taiwan, Barbados, Morocco, Slovakia, Senegal, Tajikistan, Jordan, Sweden, and Sloveniaâ were removed. The analysis focuses on the remaining 70 countries with substantial production levels outside OPEC. Guyana is excluded because it began oil production after December 2019, and the latest OPEC announcement is in 2017. For each country-OPEC decision pair, we calculated the change in log production multiplied by negative one if the production increased when prices went down or decreased when prices went up. Figure 4 plots the average for each country.

A.2 Financial conditions data

We use two measures of a country's financial conditions: the debt-to-GDP ratio and the country risk premium developed by Damodaran (2022). The debt-to-GDP ratio data are sourced from the IMF's Global Debt Database[44] and represents the total stock of debt liabilities issued by the central government as a share of GDP. We construct a dummy indicating whether the value is above or below the median and then average these over the relevant time period. Twelve countries (Burma, China, Congo-Kinshasa, Cuba, Egypt, Former Serbia and Montenegro, Former USSR, Former Yugoslavia, Georgia, Netherlands, Philippines, and Uzbekistan) are excluded due to missing debt data, leaving 57 countries represented in Figure 4. The country risk premium, sourced from Damodaran (2022) and available starting in 2001 reflects the default spread on a government bond.

[44] https://www.imf.org/external/datamapper/CGDEBTGDP@GDD/CHN/FRA/DEU/ITA/JPN/GBR/USA

B Proofs of Propositions in Section 3

Proof of Propositions 1 and 2

Consider the problem int the text. The FOC with with respect to y when there is borrowing is:

$$(y_0+b+\tau)^{-\gamma} \leq \beta\pi_H p_H(p_H(1-y_0)-(1+r_B)b-\Phi+\tau)^{-\gamma}+\beta\pi_L p_L(p_L(1-y_0)-(1+r_B)b-\Phi+\tau)^{-\gamma}.$$

The FOC with respect to b is:

$$(y_0+b+\tau)^{-\gamma} = \beta(1+r_B)\left(\pi_H(p_H(1-y_0)-(1+r_B)b-\Phi+\tau)^{-\gamma}+\pi_L(p_L(1-y_0)-(1+r_B)b-\Phi+\tau)^{-\gamma}\right).$$

With $\Phi = 0$, combinig these conditions we obtain the condition required for agent to borrow:

$$1 \geq \frac{1}{1+r_B}\frac{p_H\pi_H u'(c_H)+p_L\pi_L u'(c_L)}{\pi_H u'(c_H)+\pi_L u'(c_L)} = \frac{1}{1+r_B}\mathbb{E}\left(u'(c_1)p_1\right).$$

Analogous condition for saving completes the proof.

Proof of Propositions 3 and 4

Here, p_0 and p_1 are the prices of the resource today and tomorrow, y_0 and y_1 are the respective extraction rates. Furthermore, suppose that $p_1 = p_H > p_0$ with prob π_H and $p_1 = p_L < 0$ with prob $\pi_L = 1-\pi_H$. The necessary first order condition is

$$p_0\left(p_0y_0+\tau\right)^{-\gamma} = \beta\left(\pi_H p_H(p_H(1-y_0)+\tau)^{-\gamma}+\pi_L p_L(p_L(1-y_0)+\tau)^{-\gamma}\right).$$

Consider first the case with no outside income, $\tau = 0$. The optimal period-0 extraction is given by:

$$p_0\left(p_0y_0\right)^{-\gamma} = \beta\left(\pi_H p_H(p_H(1-y_0))^{-\gamma}+\pi_L p_L(p_L(1-y_0))^{-\gamma}\right).$$

Re-arranging yields the result in Proposition 3. In the case of outside income and no risk in the price path, the FOC is:

$$p_0(p_0y_0+\tau)^{-\gamma} = \beta p_1(p_1(1-y_0)+\tau)^{-\gamma}.$$

Solving for y_0 we obtain the expression in Proposition 4.

C Increasing marginal costs and capacity constraints

In the model of this paper we made a simple assumption about the marginal cost of the producer under sanctions: we assumed it is constant and equal to $19 per barrel. In this Appendix we explore how an alternative formulation, with increasing marginal cost and a short-term capacity constraint, affects our results. This exercise shows that our framework is flexible and can accommodate a range of assumptions about the production technology of the producer.

We assume that the marginal cost increases in the extraction rate. Specifically, we target the marginal cost curve estimated by Rystad Energy and reported in Wachtmeister et al. (2023). We assume that, measured in dollars per barrel, the marginal cost is

$$\mathcal{M}(y) = 1.5 + \frac{0.25}{\sqrt{0.03 - y}}.$$

The blue curve in the left-most panel of Figure 19 illustrates this cost curve: marginal cost is low and quite flat, but increases sharply as production approaches the capacity constraint of a 3% extraction rate.

The remaining three panels illustrate how the baseline results using the model with market power (in red) change when this more complex cost structure is assumed (in blue). The bottom line is that all our results are robust to such a change in the cost structure. One natural change is that whenever our framework predicts extraction above the capacity constraint of 0.03, the model now predicts the producer to be at the corner, producing virtually at capacity (see e.g. the third panel, which shows the effect of a perfect price cap).

We opted for the variant with the model with constant marginal cost in the main text since that model better illustrates the true incentives to increase extraction as a result of the cap. But if the producer is bound by short-term capacity constraints, there will be a limit on how much the actual extraction rate can increase.

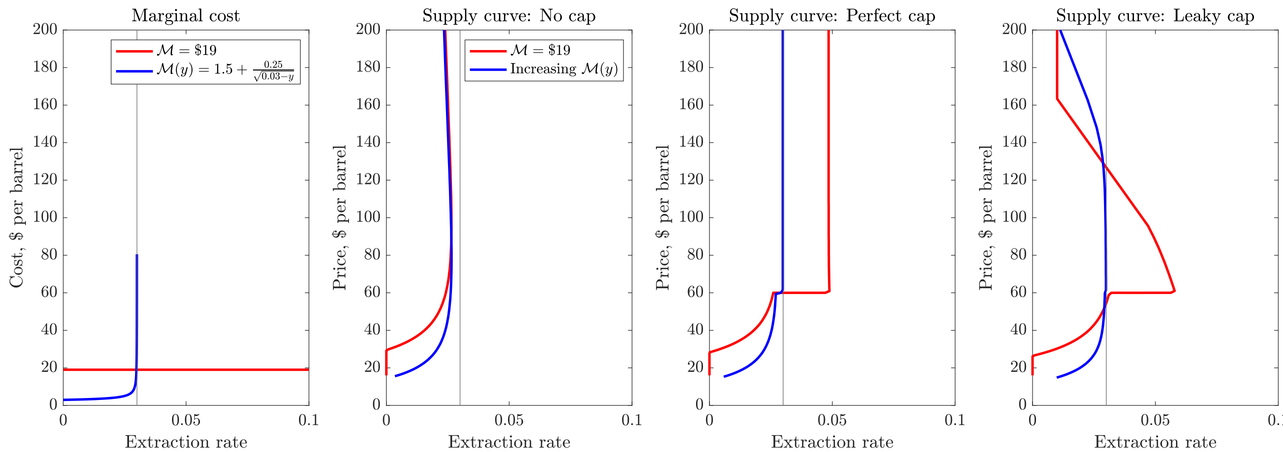

Figure 19: The results with increasing marginal cost and a capacity constraint