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Abstract

We develop a resource extraction model that features imperfect substitution and endogenous market power. We analytically characterize the effect of anticipated future demand shocks on the resource extraction path and show that endogenous market power can dampen the adverse consequences of climate policies due to intertemporal carbon leakages compared to the perfect or monopolistic competition benchmarks. Next, we show that under constant elasticity of substitution between alternative energy resources, resource owner's current market share and reserves-to-extraction ratio are sufficient statistics to calculate the degree of intertemporal leakage. Applying data on OPEC, we find a minor increase in current extraction due to an anticipated increase in the productivity of alternative energy technologies.

JEL code: Q35, Q48, L10, H23
Keywords: Climate policy; variable markups; nonrenewable energy resources; imperfect competition; imperfect substitution

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1 Introduction

Mitigating the greenhouse gas emissions associated with the combustion of fossil fuels is the main challenge in addressing the threat of global warming. According to climate model projections (IPCC, 2014), the 2°C carbon budget will be spent before 2050. This carbon budget specifies the maximum amount of CO_2 that can be emitted to the atmosphere while holding global warming below 2°C (Allen et al., 2009; Meinshausen et al., 2009). The 2015 Paris Agreement sets out a more ambitious target of pursuing further efforts to limit the warming to 1.5°C (Article 2). The 187 participating countries stated their post-2020 goals in their Intended Nationally Determined Contributions (INDCs). For example, the INDC of the US promises a 26-28% reduction in greenhouse gases by 2025 compared to 2005 levels. Meeting such temprature targets requires to limit the use of fossil-fuel resources below their natural reserve levels (Dietz et al., 2017). The other concern is related to the intertemporal allocation of this finite reserve. First best measures to reduce emissions from fossil fuel consumption may not be politically feasible. Nevertheless, there are various alternative policies that might approximate the first best outcome. However, such measures might render climate policy ineffective by inducing earlier extraction of the limited reserves. This is not a desired outcome from a climate perspective.[1]

In this paper, we develop a resource extraction model that features imperfect substitution between alternative energy sources and endogenous market power for the supplier of the scarce resource (which we also refer as oil in the rest of the paper). We analytically characterize the effect of anticipated future demand shocks on the resource extraction path in terms of the fundamental characteristics of demand functions (e.g. convexity and elasticity). We show that endogenous market power can dampen the adverse consequences of climate policies due to intertemporal carbon leakages compared to the perfect or monopolistic com-

[1] For example, a rapidly increasing carbon tax might lead the resource owners to increase near-term extractions (Sinn, 2008). This intertemporal leakage, which is also known as the green paradox, has been anlyzed in different settings. See Eichner and Pethig (2011); Hoel (2011); Gerlagh (2011); and van der Meijden et al. (2015) among others.

petition benchmarks. In this setting, the oil supplier internalizes the effect of the shock on its future market power, and can dampen its consequences via markup adjustments in both periods. The change in the scarcity rent and extraction path can be small depending on the degree of market power and the strength of supply-side substitubilities. Next, by assuming constant elasticity of substitution, we derive sufficient statistics to calculate the degree of intertemporal leakage. Applying current data on OPEC, we analytically quantify the intertemporal leakage rate due to an anticipated increase in the productivity of alternative energy resources. Our results show that the intertemporal leakage is likely to be a minor concern. This result has important implications for the design of climate-related policies.

On the supply side of the oil market, OPEC owns more than 80% of the world's proven oil reserves and exports about 60% of the total petroleum traded internationally (IEA, 2015). According to International Energy Agency (IEA), this substantial market share allows OPEC to influence oil prices.[2] Our model incorporates this feature: the oil supplier exercises some degree of market power. The key to our results is that this market power is endogenous and influenced by demand shocks. On the demand side, the share of imports in the crude oil demand of the OECD countries is around 70% (IEA, 2015). Advances in alternative energy technologies over the last decades have opened the way for industrialized countries to substitute their oil imports with domestic alternatives.[3] The common assumption in the literature is that renewable energy technology is a perfect backstop for nonrenewable fossil-fuel resources. This might not be a realistic assumption given the significant market share of renewables in some countries (Michielsen, 2014; van der Meijden and Withagen, 2016).[4] In our model, different energy resources are imperfect substitutes leading to simultaneous employment along with fossil fuels.

[2]See http://www.eia.gov/finance/markets/supply-opec.cfm.

[3]Due to the oil fracking boom, shale oil production in the United States has increased substantially, displacing the crude oil imports from OPEC countries (Kilian, 2016). Renewable energy investment has risen six fold between 2004 and 2011 which is considered as the key strategy to combat climate change.

[4]Furthermore, it might be unrealistic to assume that the renewables can entirely replace the fossil fuels any soon; for example biofuels and oil (Long, 2014). Even in a scenario in which renewable energy resources dominate the energy market, using existing fossil fuel plants is one of the feasible options to manage the volatility in renewable energy supply (Sinn, 2017).

Our analysis is built on the literature investigating the incomplete pass-through of various shocks in imperfectly competitive markets.[5] We analyze the effect a change in the price of an imperfect substitute as in Auer and Schoenle (2016) and Amiti et al. (2016). We conduct our analysis in terms of demand manifolds, which relates elasticity and convexity of an arbitrary demand function (Mrazova and Neary, 2017), and derive analytical results for the intertemporal leakage as a function of elasticity and convexity of the perceived demand function, and reserves-to-extraction ratio. This expression is valid for a wide range of market competition structures. With constant elasticity of substitution (CES) between alternative resources, the market share of oil is a sufficient statistic for the elasticity and convexity of the demand curve, as in the oligopolistic competition models (e.g. Atkeson and Burstein (2008)). Using this result, we derive analytical expressions leading to straightforward calculations for the intertemporal leakage based on observables or various scenarios for climate targets. For example, we show that current market share and reserves-to-extraction ratio are sufficient statistics to evaluate the intertemporal leakage rate. We contribute to this strand of literature by analyzing the pass-through of a shock in the presence of a dynamic factor, such that the marginal cost item (shadow price of oil) endogenously adjusts to maximize intertemporal profits. We show that pass-through is generally lower compared to the case where markets are analyzed as distinct static entities. Hence, intertemporal allocation of supply contributes to the standard variable markup mechanism and strengthens the limited pass-through.

We are not aware of any other study that analyzes the response of a scarce resource supplier to demand side shocks in a setting with variable markups and imperfect substitutes. The early literature on resource extraction focuses on comparing the equilibrium outcomes under alternative market structures. Salant (1976), Stiglitz (1976), and Sweeney (1977) investigate the resource extraction problem in imperfectly competitive markets. Stiglitz (1976) shows that the extraction paths in competitive and monopoly equilibrium are identical under constant elasticity of demand schedules with zero extraction costs. Stiglitz and Dasgupta

[5]For example, see Atkeson and Burstein (2008); Gopinath et al. (2010); Berman et al. (2012); Weyl and Fabinger (2013); Mrazova and Neary (2017); Amiti et al. (2017).

(1982) analyze the interaction of a nonrenewable resource with a perfect substitute. In the presence of a renewable perfect substitute, they show that if demand elasticity is decreasing in sales, the monopolistic price path is flatter. We characterize such comparisons in terms of the characteristics of an arbitrary demand function, namely the elasticity and convexity. Our qualitative results are quite general in terms of the structure of market competition, while we take the exhaustion date exogenous.

Hoel (1978) and Stiglitz and Dasgupta (1982) investigate the effect of various market structures on the date of innovation of a perfect substitute for a nonrenewable resource. Dasgupta and Stiglitz (1981) and Stiglitz and Dasgupta (1981) analyze the effect of uncertainty in the arrival date of a perfect substitute. The effect of various policies affecting this arrival date is analyzed in the subsequent literature. However, this strand of literature either focuses on competitive markets or on the effect of a perfect substitute development. Related to our analysis, Stiglitz (1976) shows that an exogenous increase in the elasticity of demand leads the monopolist to institute a supply schedule that is more conservationist compared to the competitive equilibrium. As suggested by Stiglitz (1976), "a more interesting case is that where the change in the elasticity of demand is an endogenous variable, say, a function of the price charged in the market". In our model, the elasticity of demand is endogenous, which is functionally related to the monopolist's market power. Hence, the monopolist responds by adjusting its markups endogenously , which can dampen the pass-through of the shock. Furthermore, we characterize the partial effect of the shock in Stiglitz's analysis in terms of its effects on the perceived demand curve: a shift and a tilt. These partial effects generally counteracts each other to determine the strength of supply-side substitubilities or complementarities, which leads to a theoretical ambiguity in the sign of intertemporal leakage.

Our paper contributes to the recent and growing literature investigating the effects of demand-side policies on the intertemporal supply schedule of nonrenewable fossil fuels. The implications of imperfect substitution are analyzed in Long (2014) and Michielsen (2014).

Long (2014) focuses on competitive markets and analyzes the effect of the degree of substitutability. Michielsen (2014) allows for imperfect substitutability in a two-period competitive setting and shows that a lower price of a renewable substitute in the second period always increases the supply of the exhaustible alternative in the first period. While these papers assume perfectly competitive markets, there is a recent literature investigating the effects of climate-related policies on the supply decision of a monopolist owning a scarce resource. Among others, Jaakkola (2013), Andrade de Sá and Daubanes (2015), and van der Meijden et al. (2018) analyze the implications of limit pricing strategy. This strand of literature focuses on the presence of a perfectly substitutable backstop technology. van der Meijden and Withagen (2016) analyze the consequences of a setting with imperfect substitutes and imperfect competition for the demand elasticity of oil. In the current paper, we focus on the market power adjustments due to demand shocks and provide analytical results to characterize the effects of demand shocks on the extraction path.

The rest of the paper is organized as follows: Section 2 describes our model. In Section 3, we investigate the impact of an anticipated demand shock on resource extraction in a general setting with an arbitrary demand function. In Section 4, we impose constant elasticity of substitution (CES) between alternative resources. We derive sufficient statistics to evaluate the impact of climate policies in Section 5. We quantify the implications of our model for intertemporal carbon leakage using data on OPEC in Section 6. Section 7 concludes.

2 Resource Extraction with Endogenous Markups

In this section, we present a resource extraction model with a general demand function and market competition structure. Demand for oil is characterized by $p_t = P(q_t, \boldsymbol{x}_t)$, where q_t denotes the quantity of resource in period t, P is the inverse demand function mapping the quantities to willingness to pay, and $\boldsymbol{x}_t$ is the quantity vector of all competing goods with oil. Here, $\boldsymbol{x}_t$ should be thought of as a vector of the response functions of competing firms producing alternative inputs rather than equilibrium outcomes. Hence, P represents the so-called perceived demand schedule.[6] For brevity, we use P_t and $P(q_t)$ interchangeably and ignore other arguments unless they need to be specified. We assume that the inverse demand function satisfies:

Assumption 1. *(i)* $P_q < 0$ *(ii)* $\lim_{q\to\infty} P_q = 0$ *(iii)* $\lim_{q\to 0} P_q = -\infty$.

Assumption 1(ii) means that the willingness to pay is positive for any $q > 0$, which guarantees that the resource is scarce ($\lambda > 0$) and the intertemporal tradeoff always applies. Assumption 1(iii) rules out a choke price. Therefore, the resource is demanded at any positive price level, which guarantees that $q > 0$ for all periods.

The oil producer excercises a market power and allocates its finite oil reserve, S, over two periods ($t = 1,\, 2$) to maximize its flow of profits by discounting future profits at rate r.[7] The only cost of extracting oil is the opportunity cost of leaving it in the ground. That is, extraction costs are assumed away. Hence, the problem of the firm is:

$$\max_{q_1,q_2} P_1 q_1 + \frac{P_2 q_2}{1+r} \text{ st. } q_1 + q_2 = S. \tag{1}$$

The scarcity constraint always binds by Assumption 1. The Lagrange function is given by $\mathcal{L}(q_1, q_2, \lambda) = P_1 q_1 + P_2 q_2/(1+r) - \lambda(q_1 + q_2 - S)$, where λ is the Lagrange multiplier representing the shadow price of oil, which is the opportunity cost of leaving the oil in the ground. We denote its current value with a time subscript as $\lambda_t = \lambda(1+r)^{t-1}$. Throughout the paper, we work with the implicit representations of first-order conditions, $\mathcal{L}_{q_t} = 0$ and

[6] We ignore the income effects in line with the behavioral assumptions that will be imposed in Section 4.

[7] The infinite horizon counterpart of our model features a two-stage optimal control problem where the shock arrives at the beginning of the second stage and where the length of the stages are given.

$\mathcal{L}_\lambda = 0$, given by:

$$\begin{aligned} F^1(q_1, q_2, \lambda) = P_1 - M_1\lambda &= 0, \\ F^2(q_1, q_2, \lambda) = P_2 - M_2\lambda(1+r) &= 0, \\ F^3(q_1, q_2, \lambda) = q_1 + q_2 - S &= 0. \end{aligned} \tag{2}$$

The firm charges the standard monopoly price, which is a markup (M_t) over the marginal cost given by the shadow price λ. The shadow price grows at the interest rate in accordance with the Hotelling rule. A well-defined solution to the system of equations F is guaranteed by the following assumption:

Assumption 2. *(i) $\kappa_t < 2$, (ii) $0 \leq \eta_t < 1$, where $\eta_t = \varepsilon_q^P = -\frac{q_t}{p_t}\frac{dP_t}{dq_t}$ and $\kappa_t = \varepsilon_{q_t}^{dP_t/dq_t} = -\frac{q_t}{dP_t/dq_t}\frac{d(dP_t/dq_t)}{dq_t}$.*

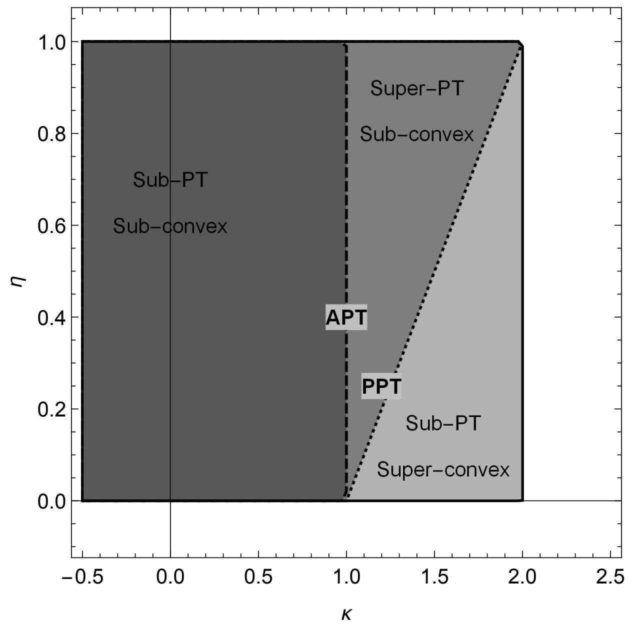
Here, η_t stands for the inverse price elasticity, and κ_t for the convexity of the demand function. For the static profit maximization with constant marginal cost, Assumption 2(i) is a sufficient condition for the second-order condition (SOC) to hold (see Appendix A.1). It is sufficient also for our dynamic problem by leading to a negative definite bordered-Hessian matrix. Throughout the paper, ε_x^y stands for $-(x/y)(\mathrm{d}y/\mathrm{d}x)$, which is the total elasticity of y with respect to x. Assumption 2(ii) follows from the regulatory condition that $M_t > 1$ such that the oil owner makes positive profits. These conditions govern the optimal behavior of the oil supplier for a wide range of market competition structures.[8]

Next, we describe some relations that will be useful throughout the analysis. The markup reflects the market power, and it is a function of the inverse price elasticity:

$$M_t = \frac{1}{1-\eta_t}. \tag{3}$$

[8] This is the case whether the supplier is a single monopolist or it acts in monopolistically or oligopolistically competitive markets, or whether it sets prices or quantities. Note that η_t, and therefore the markup function, depends not only on the partial elasticity of the demand with respect to q_t but also on the conjectured responses of the competing firms. We discuss these points in more detail in Section 4.

Figure 1: Markup Elasticity



Notes: This figure illustrates the demand manifold space. APT and PPT stand for one-to-one absolute and proportional cost pass-through into prices, respectively.

The supply decision alters the market power, which is at the center of our analysis. Representing this relationship, the elasticity of markup function is given by:

$$\varepsilon_{q_t}^{M_t} = -\frac{q_t}{M_t}\frac{\mathrm{d}M_t}{\mathrm{d}q_t} = \frac{\eta_t}{1-\eta_t}\underbrace{(\kappa_t - 1 - \eta_t)}_{\varepsilon_{q_t}^{\eta_t}}. \tag{4}$$

Therefore, the relative size of the elasticity and convexity determines the sign of this relationship (see Appendix A.2 for the details). The condition that the markup is invariant to the supply decision is given by $1 + \eta_t = \kappa_t$. This condition holds "globally" with a constant price elasticity demand function, such as $P(q_t) = \alpha q_t^{-\theta}$. As a result, the markup is constant. To see this point directly, note that the term determining the sign of the derivative is simply the elasticity of the inverse price elasticity, $\varepsilon_{q_t}^{\eta_t} = \kappa_t - 1 - \eta_t$. Here, $\varepsilon_{q_t}^{\eta_t}$ is zero when η_t is constant, hence the invariancy condition.

Figure 1 illustrates the sign of the markup elasticity in terms of the properties of the perceived demand function. Mrazova and Neary (2017) show that, for a given demand function, one can almost always express convexity or elasticity in terms of the other. This curve is called demand manifold which provides a convenient way to conduct comparative statics. The markup is constant on the line labeled as PPT. Therefore, the markup elasticity is zero. Since $M_t = (P_t - \lambda_t)/P_t$ always holds, PPT implies one-to-one proportional cost pass-through into prices which is given by -$(1 - \eta_t)/(2 - \kappa_t)$ (see Appendix A.3 for the details). To the right of PPT, the perceived demand function is superconvex, the markup is decreasing in q, hence the markup elasticity is positive. According to Krugman (1979), the subconvex region on the left is the empirically relevant one, where the markup is increasing in q, the markup elasticity is negative, and, hence, proportional cost pass-through is always incomplete. That is, a 1% increase in marginal cost leads to a less than 1% increase in consumer prices. For the oil producer, the only cost item is the opportunity cost of leaving oil in the ground given by λ_t. Therefore, the current value of marginal cost increases in proportional terms. As a result, when the markup is constant, the resource price will grow at the interest rate, and the monopoly and competitive equilibria coincide (Stiglitz, 1976). Hence, the characterization of this comparison in terms of demand manifold is as follows:

Lemma 1. *If the demand function is globally superconvex (subconvex), then the resource price grows faster (slower) than the interest rate. If $\kappa_t = 1 + \eta_t$, then the resource price grows at the interest rate.*[9]

The convexity of a demand curve is sufficient to characterize absolute cost-pass-through into prices given by $1/(2 - \kappa_t)$ (see Appendix A.3 for the details). As illustrated in Figure 1, the absolute pass-through into prices is one-to-one at unit convexity represented by the line APT. When convexity is lower than unity, the pass-through of a marginal cost shock is incomplete in absolute terms. To the right of the unit convexity line, a unit increase in the marginal cost leads to a more than unity increase in the prices. This covers the superconvex region. The absolute pass-through of a marginal cost shock is always positive by

[9]Demand functions are generally either globally subconvex or globally superconvex. See Mrazova and Neary (2017) for a counter example.

Assumption 2. Therefore, a monopolist supplies less at a higher price when the marginal cost is higher. As the oil supplier faces a higher marginal cost in the future period, the first-period extraction must be higher than the second-period extraction. This outcome is guaranteed by Assumption 1, which rules out corner solutions. We note this point as follows:

Lemma 2. *The first-period extraction is higher than the second-period extraction, such that* $q_1 > q_2$.

The result in Lemma 2 is simple; yet, it is sufficient to prove many of our results in the following sections.

3 Anticipated Demand Shocks

In this section, we analyze how an anticipated future demand shock affects the oil owner's supply decision. Consider an arbitrary demand shock at the second period, which we parametrize with a_2, such that $P_t = f(q_t; a_t)$. We summarize the comparative static results as follows:

$$\frac{\mathrm{d}q_1}{\mathrm{d}a_2} = \frac{M_1 F^2_{a_2}}{|J|}, \; \frac{\mathrm{d}q_2}{\mathrm{d}a_2} = -\frac{M_1 F^2_{a_2}}{|J|}, \; \frac{\mathrm{d}\lambda}{\mathrm{d}a_2} = \frac{F^1_{q_1} F^2_{a_2}}{|J|}. \tag{5}$$

Here, $|J|$ is the determinant of the Jacobian matrix of system F given by $|J| = F^1_{q_1}(1 + r)M_2 + F^2_{q_2} M_1$. The SOC that the bordered-Hessian of the Lagrangian is negative definite is equivalent to $|J| < 0$. The terms $F^t_{q_t}$, namely, the partial effect of q_t on F^t, are given by

$$F^t_{q_t} = -\frac{P_t}{q_t}\eta_t M_t \left(2 - \kappa_t\right) < 0 \text{ for } t = 1, 2. \tag{6}$$

They are negative by the SOC given by Assumption 2(i). Finally, $F^2_{a_2}$ denotes the partial effect of the demand shock on the second period marginal profit given by the implicit relation F^2 (other details are provided in Appendix B.1). As a result, the sign of the effect is determined by $F^2_{a_2}$ as follows:

$$\operatorname{sign}\left(\frac{\mathrm{d}q_1}{\mathrm{d}a_2}\right) = -\operatorname{sign}\left(\frac{\mathrm{d}q_2}{\mathrm{d}a_2}\right) = -\operatorname{sign}\left(\frac{\mathrm{d}\lambda}{\mathrm{d}a_2}\right) = -\operatorname{sign}\left(F^2_{a_2}\right). \tag{7}$$

Next, we focus on the partial adjustment, $F^2_{a_2}$, and the intuition underlying the ambiguity in its sign.

3.1 Supply-side Substitubilities

In the following, we ignore the time index, as we focus on a contemporaneous partial adjustment $F^2_{a_2}$, which is given by $P_a - \lambda(1+r)M_a$. We denote the partial elasticity of y with respect to x by ϵ^y_x, which is defined as $-(x/y)(\partial y/\partial x)$. Substituting the first order condition that $\lambda(1+r) = P/M$, and rearranging F_a in terms of partial elasticities leads to

$$F_a = -\frac{P}{a}\left(\epsilon^P_a - \epsilon^M_a\right), \tag{8}$$
$$\text{where } \epsilon^P_a = -\frac{a}{P}\frac{\partial P}{\partial a} \text{ and } \epsilon^M_a = -\frac{a}{M}\frac{\partial M}{\partial a}.$$

Here, ϵ^P_a is the partial elasticity of the inverse demand function with respect to a, which refers to a shift in the demand curve. The shift is a function describing how the shock changes the willingness to pay at a given point on the demand function. ϵ^M_a is the partial elasticity of the markup with respect to a, which is given by

$$\epsilon^M_a = -\frac{a}{M}\frac{\mathrm{d}M}{\mathrm{d}\eta}\frac{\partial \eta}{\partial a} = -\frac{\eta}{1-\eta}\left(\epsilon^P_a - \epsilon^{\mathrm{d}P/\mathrm{d}q}_a\right), \tag{9}$$
$$\text{where } \epsilon^{\mathrm{d}P/\mathrm{d}q}_a = -\frac{a}{\mathrm{d}P/\mathrm{d}q}\frac{\partial\left(\mathrm{d}P/\mathrm{d}q\right)}{\partial a}.$$

Here, $\epsilon^{\mathrm{d}P/\mathrm{d}q}_a$ is the partial elasticity of the slope of the inverse demand curve with respect to a, which refers to a tilt in the demand curve. The tilt is a function describing how the shock changes the rate of change in willingness to pay at a given point on the demand curve. As a result, ϵ_a^M depends on the proportional shift and the tilt in the demand curve due to a proportional change in the parameter of interest.

Substituting ϵ_a^M in F_a leads to

$$
\begin{aligned}
F_a &= -\frac{P}{a}\left(\left(1+\frac{\eta}{1-\eta}\right)\epsilon_a^P - \frac{\eta}{1-\eta}\epsilon_a^{\mathrm{d}P/\mathrm{d}q}\right) \\
&= -\frac{P}{a}\frac{1}{1-\eta}\left(\epsilon_a^P - \eta\epsilon_a^{\mathrm{d}P/\mathrm{d}q}\right). \qquad (10)
\end{aligned}
$$

This equation expresses the partial change in the marginal profits in terms of the properties of the perceived demand schedule. In the case of perfect competition, this partial adjustment depends only on the shift, such that $F_a = \partial P/\partial a = -(P/a)\epsilon_a^P$. That is, it is completely determined by the change in willingness to pay evaluated at the competitive equilibrium. However, when the supplier has a market power which is endogenous to the demand shock, the relative size of ϵ_a^P and $\epsilon_a^{\mathrm{d}P/\mathrm{d}q}$ is crucial for the comparative static results.

Of particular interest is a demand shock to a substitute good, x. A well-known result is that the partial effect of this change on the marginal profit, F_x, determines the nature of strategic interaction (e.g., see Tirole (1988)). If $F_x < 0$, then there is strategic substitution, which is the usual case if the firms set quantities. If $F_x > 0$, then there is strategic complementarity in quantities. In the case of strategic substitution, a decrease in the marginal cost of the alternative resource decreases the shadow price and second period extraction, and increases the first period extraction. This outcome is referred as the Green Paradox in the literature. In the case of startegic complementarity, the Green Paradox does not arise. Although, strategic complementarity in quantities is a rare situation, equation (9) shows that a sufficiently strong tilt reduces the degree of strategic substitution in quantities. As a result, the effect of the shock on the shadow price and the extraction path can be arbitrarily small. Throughout the paper, we refer to these cases as follows:

Definition 1. (i) substitutability in quantities ($F_x < 0$): Due to an increase in x_2, q_2 and λ decreases, and q_1 increases. (ii) Complementarity in quantities ($F_x > 0$): Due to an increase in x_2, q_2 and λ increases, and q_1 decreases.

In this definition, we avoid labeling the interaction between the competing resources as strategic. The reason is that the ambiguity in the sign of F_a can arise without any strategic interaction (see Amiti et al. (2016)). We illustrate this point in Appendix C by exemplifying the ambiguity with a constant price elasticity demand function as in Stiglitz (1976). This example also clarifies the analytics underlying the ambiguity, the geometric meaning of the tilt, and why the shift and the tilt generally counteracts each other.

To sum, the partial adjustment in the second period can lead to an arbitrarily small effect on the extraction path and the scarcity rent. In the next subsection, we analyze the potential dampening via resource owner's endogenous markup adjustments.

3.2 Intertemporal Pass-through

We have shown that the partial adjustment in the second period can lead to an arbitrarily small effect. In this section, we analyze the pass-through of this partial adjustment to the first-period sales. We start by rearranging this comparative static result in terms of contemporaneous partial adjustments as follows:

$$\frac{\mathrm{d}q_1}{\mathrm{d}a_2} = \underbrace{\frac{h_1 h_2}{h_1 + h_2}}_{H} \left(\frac{F^2_{a_2}}{M_2(1+r)} \right),$$

$$\text{where } h_1 = \frac{M_1}{F^1_{q_1}} \text{ and } h_2 = \frac{(1+r)M_2}{F^2_{q_2}},$$

This decomposition provides a convenient way to analyze how the partial change in marginal profits in the second period, given by $F^2_{a_2}$, is tranmitted to the first-period extraction. In the second term, $F^2_{a_2}$ is normalized by $M_2(1+r)$ which is larger than unity by the regularity condition. In the first term, h_t simply gives how the supply decision of a monopolist responds to a marginal cost shock in a static case, such that as if λ were exogenous. Hence, we refer h_t as the absolute cost pass-through into sales. Since $F^t_{q_t}$ is negative, h_t is negative. That is, the monopolist supply less at a higher price when the marginal cost is higher. The corresponding decomposition in a static case without a shadow price adjustment is given by $[\mathrm{d}q_2/\mathrm{d}a_2]_{\mathrm{d}\lambda=0} = h_2\left(F^2_{a_2}/(M_2(1+r))\right)$.

Proposition 1. *The intertemporal pass-through (H) is lower than the absolute cost pass-through into sales (h_t).*

Proof. The intertemporal pass-through term, H, is simply half of the harmonic mean of its arguments and it is smaller than the minimum of its arguments in absolute terms. □

The underlying reason is the extra degree of freedom that the shadow price path adjusts to maximize intertemporal profits. An important implication of Proposition 1 is that the absolute value of the intertemporal pass-through is bounded above by h_t. By substitution, it can be shown that h_t is given by:

$$h_t = \frac{1}{(\mathrm{d}P_t/\mathrm{d}q_t)(2-\kappa_t)}.$$

We provide the details in Appendix A.3. This upper bound depends on the slope and convexity of the demand curve. In the following, we establish another upper bound which depends only on convexity, and show that H limits to zero as convexity decreases:

Proposition 2. *If the convexity of the demand curve is lower than unity,*[10] *the absolute value of the pass-through term (H) is bounded above. The upper bound decreases with decreasing convexity. As convexity approaches to minus infinity, the upper bound limits to zero, so as the intertemporal pass-through term H.*

Proof. The effect of a marginal cost shock on the sales depends on the slope of the demand curve. As the pass-through into consumer prices can be arbitrarily small, the effect on the sales (h) can be arbitrarily small compared to the competitive case where the effect on the sales is given by $1/(\mathrm{d}P(\bar{q}_t)/\mathrm{d}q_t)$. Here, $P(\bar{q}_t) = \bar{\lambda}$ represents the competitive supply decision.

[10] Note that $\kappa < 1$ is a sufficient condition, and $\kappa > 1$ do not necessarily imply the opposite.

Since a monopolist supply at a steeper portion of the demand curve, there is dampening in the effect on sales compared to the competitive case as long as $\kappa < 1$. This establishes an upper bound for the intertemporal pass-through term, given by $1/(\mathrm{d}P(\bar{q}_t)/\mathrm{d}q_t)(2-\kappa_t)$, and which only depends on convexity as the elasticity is fixed at $p = \bar{\lambda}$. This upper bound approaches to zero as convexity decreases, so as H. □

This result implies that given the size of the partial adjustment F_a, the total effect can be largely dampened in H when the convexity of the perceived demand function is low.

3.3 Total Effect

In this section, we derive our working expressions for the degree of intertemporal leakage. By substitution, we obtain the total elasticity of current extraction with respect to the future demand shock as follows:

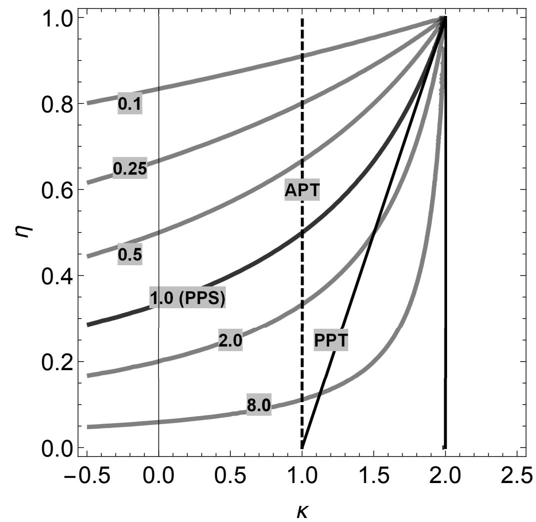
$$\varepsilon_{a_2}^{q_1} = \frac{\left(-\epsilon_{a_2}^{P_2} + \eta_2 \epsilon_{a_2}^{\mathrm{d}P_2/\mathrm{d}q_2}\right) / (1-\eta_2)}{\frac{1}{\tilde{h}_1} + \left(\frac{1}{s-1}\right)\frac{1}{\tilde{h}_2}}, \tag{11}$$

$$\text{where } \tilde{h}_t = \frac{1-\eta_t}{\eta_t(2-\kappa_t)}. \tag{12}$$

where s is reserves to extraction ratio (see Appendix B.2 for the derivation). The term in the numerator comes from $F_{a_2}^2$ given by equation (10). The denominator is a rearrangement of the determinant of the Jacobian. Here, $\tilde{h}_t$ describes static cost pass-through into sales in proportional terms (see Appendix A.3 for the details). The proportional pass-through into sales is simply the elasticity of sales with respect to a constant marginal cost. The intutition underlying the form of the denominator in equation (11) is closely related to that the shift in the shadow price path implies a proportional change in the marginal cost across the two periods.

In Figure 2, $\tilde{h}$ is equal to 1 on the PPS curve. Above (below) the PPS curve, a one percent increase in the marginal cost leads to a less (more) than one percent decrease in

Figure 2: Proportional Cost Pass-through into Sales



Notes: This figure illustrates the proportional cost pass-through rates into sales on the demand-manifold space. APT and PPT stand for one-to-one absolute and proportional cost pass-through into prices, respectively. PPS indicates one-to-one proportional cost pass-through into sales.

sales. Setting h equal to a constant K, and integrating out the demand function defines a class of demand functions with constant proportional pass-through into sales. This class is given by $P(q) = \alpha q^{-1/K} + \beta/q$, where the parameters, α and β, are positive. Figure 2 also illustrates the K percent proportional pass-through curves. When the demand manifold spans low convexity levels, $\tilde{h}$ is more likely to be below 1.

The intertemporal leakage rate in the case of perfect competition is given by:

$$\left(\varepsilon_{a_2}^{q_1}\right)^{\text{competitive}} = \frac{-\epsilon_{a_2}^{P_2}/\left(1-\eta_2\right)}{\frac{\eta_1}{1-\eta_1} + \left(\frac{1}{s-1}\right)\frac{\eta_2}{1-\eta_2}}. \tag{13}$$

The derivation is provided in Appendix B.3. The important difference is that the second order terms, namely the convexity and the tilt, do not play a role. In the previous subsections, we have shown that the shock might be ineffective with a strong tilt (subsection 3.1) and a low convexity (subsection 3.2). As a result, in perfect competition, (i) there is no ambiguity in the comparative statics, and (ii) the possibility in imperfect competition that the pass-through can be low with a low convexity does not apply. We will quantify this comparison in the final section. In the following, we note this result:

Lemma 3. *Under perfect competition, a negative demand shock (a decrease in willingness to pay) in the second period always increases first-period extraction.*

4 Productivity Shock to the Substitute

In this section, we employ a CES demand schedule in order to quantify the effect of an increase in the productivity of an alternative energy resource. Final consumption good is produced out of energy (Z) along with a generic production factor (K) by using a Cobb-Douglas technology:

$$Y_t = Z_t^{\theta} K_t^{1-\theta},$$

where $0 < \theta < 1$. The final good market is characterized by perfect competition and each input is paid out its marginal revenue product. Hence, the expenditure share of energy is fixed and given by $E_t^Z = P_t^Z Z_t = \theta E_t$, where P_t^Z is the energy price index and $E_t = P_t Y_t$ is the aggregate income. This assumption is consistent with the empirical evidence that the share of energy spending in GDP is generally stable in the long run (see Hassler et al. (2012)).

There is a generic alternative energy resource (x) which is an imperfect substitute for oil (q) in producing energy. The energy production function takes a CES form as follows:

$$Z_t = \left[\gamma \left(a_t x_t\right)^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\left(q_t\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{14}$$

where σ denotes the elasticity of substitution. The condition that the markup should be above unity requires an elasticity of substitution larger than one.[11] Therefore, the alternative energy resources are gross substitutes. This is a sufficient condition for the SOC to hold.

[11]Recently, Papageorgiou et al. (2017) shows that the elasticity of substitution between clean and dirty energy inputs is significantly higher than 1, and can be as high as 3.

The energy price index, P_t^Z, implied by the CES structure, is

$$P_t^Z = \left(\gamma^\sigma \left(\frac{p_t^X}{a_t} \right)^{1-\sigma} + (1-\gamma)^\sigma (p_t)^{1-\sigma} \right)^{\frac{1}{1-\sigma}},$$

where p^x is the price of the alternative technology and p is the price of oil. The competing alternative energy resource is renewable, or characterized by large reserves compared to oil, and is produced with constant marginal cost. The input demand function for oil is given by

$$q_t = p_t^{-\sigma} (P_t^Z)^{\sigma-1} (1-\gamma)^\sigma E_t^Z,$$

where E^Z stands for the aggregate expenditure on energy.

The treatment in the previous sections was fairly general in terms of the form of market competition. Alternative assumptions on the oil supplier's and the competitors' behavior shape the equilibrium inverse price elasticity, which can differ from the simple partial price elasticity of demand. In the following sections, we derive our main results by assuming that the substitute resource is supplied competitively and the oil owner internalizes the effect of its supply decision on the sales of the alternative resource. For the purpose of comparison with the existing results in the literature, we derive corresponding expressions by imposing some common behavioral assumptions in monopolistic and oligopolistic competition models. Here, we discuss our baseline market structure in comparison to these alternative assumptions.

A monopolistically competitive firm does not internalize the effect of its supply decision on the CES aggregator Z and the price index P^Z (Dixit and Stiglitz, 1977). This is justified if its market share is small. On the other hand, an oligopolistically competitive firm sets quantity given the competitor's supply. That is, it does not internalize the effect of its decision on the competitors' supply. Its market share is large enough to affect the aggregators, Z and P^Z, but not large enough to affect aggregate spending. In the following sections, we provide the corresponding expressions by using these alternative behavioral assumptions. Our baseline behavioral assumption differs by abandoning the myopic conjecture about the supply of imperfect substitute, such that the oil supplier does not ignore the effect of its supply decision on the sales of the alternative resource which is supplied competitively. These points are formally explained in Appendix D.

In the following subsections, we analyze each element characterizing the intertemporal leakage rate given by equation (11).

4.1 Inverse Price Elasticity and Markup Function

If the oil supplier ignores the effect of its supply decision on the energy price index P^Z or the CES aggregator Z, the inverse price elasticity is a constant and equal to $1/\sigma$. Hence, the markup is constant and given by $\sigma/(\sigma-1)$. This is the underlying markup structure in monopolistic competition models (Dixit and Stiglitz, 1977). In our model, we assume that the price index is endogenous to the oil owner's supply decision, such that the oil producer is large enough to influence the energy price index. As a result, the inverse price elasticity is a function of the elasticity of the CES aggregator, as follows:

$$\eta = \frac{1}{\sigma} - \frac{(\sigma-1)}{\sigma}\varepsilon_q^Z. \tag{15}$$

Here, $\varepsilon_q^Z = -\mu + (1-\mu)\varepsilon_q^x$, where ε_q^x denotes the elasticity of oil extraction w.r.t. the alternative resource supply, and where μ_t denotes the oil owner's market share, given by

$$\mu = \frac{pq}{E^Z} = (1-\gamma)\left(\frac{q}{Z}\right)^{\frac{\sigma-1}{\sigma}}.$$

If the oil supplier chooses quantity given the competitor's supply, then $\varepsilon_q^x = 0$. That is, the oil owner does not internalize the effect of its decision on the competitor's supply as in oligopolistic competition models. As a result, the markup can be expressed as $\sigma/((\sigma-1)(1-\mu_t))$, which is increasing in market share. This markup corresponds to that in oligopolistic Cournout competition models as in Atkeson and Burstein (2008). In our model, we assume that the oil supplier internalizes the effect of its supply decision on the sales of the alternative resource.

Because the supply of the alternative resource is characterized by perfect competition, the only margin of adjustment is along the supply curve, and hence ε_q^x is not zero. In this case, the inverse price elasticity and the markup functions are given by:

$$\eta = \frac{1}{\sigma(1-\mu_t)+\mu_t} \text{ and } M_t = 1 + \frac{1}{(\sigma-1)(1-\mu_t)}, \tag{16}$$

where the markup is amplified over the variable Cournot markup since the resource owner internalizes the fact that increasing its supply will further increase its market share by depressing supply of the competing resource.[12] We summarize these points in the following Lemma:

Lemma 4. *(i) Own market share is a sufficient statistic for the inverse price elasticity and markup. (ii) The markup is an increasing function of own market share.*

4.2 Convexity and Markup Elasticity

The relation between convexity and elasticity has important implications for the markup elasticity, as illustrated in Figure 1. At equilibrium, the convexity also depends on the market structure, as discussed previously. In this section, we analyze the markup elasticity and convexity implied by our market structure.

Convexity is given by

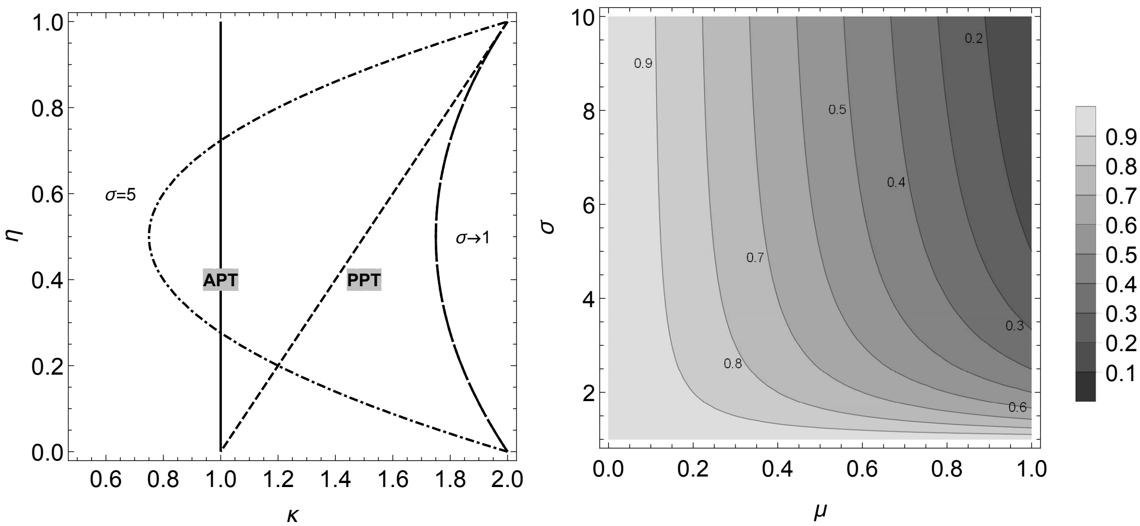
$$\kappa = 2 - \sigma\eta(1-\eta). \tag{17}$$

It can be shown that η is bounded below by $1/\sigma$ by inspecting equation (15). Therefore, $\kappa < 1+\eta$ always holds, which means that the proportional cost pass-through is lower than unity. It is also clear that unless σ is very high, κ is positive.[13] These points are illustrated in the left panel in Figure 3. The right panel illustrates the level sets for the static cost

[12] See Appendix E.1 for the details of the derivations.

[13] The details of the derivations are provided in Appendix E.2. For the purpose of comparison, we derive the same expressions under the monopolistically competitive and oilgopolistically competitive behaviors, and show that there are important differences. These results are provided in Appendix F.

Figure 3: Demand Manifold and Cost Pass-through



Notes: The left panel illustrates the demand manifold. The right panel illustrates the implied cost pass-through rates into prices. APT and PPT stand for one-to-one absolute and proportional cost pass-through into prices, respectively.

pass-through rate into prices ($(1-\eta)/(2-\kappa)$) in the (σ, μ) space. It is seen that, when the market share is small, the pass-through rate is close to one-to-one. As the market share increases, this pass-through can be very low. The important result is that the perceived demand structure is globally subconvex, meaning that:

Proposition 3. *Resource price grows at a lower rate than the competitive rate of price growth which is equal to the interest rate.*

Proof. Follows from Lemma 1. □

The markup elasticity of the oil owner is given by

$$\varepsilon_q^M = \eta(1 - \sigma\eta).$$

See Appendix E.2 for the details. Here, ε_q^M is negative for $\sigma > 1$, implying that the markup is increasing in sales. That is, the proportional cost pass-through is always smaller than unity. By Lemma 4, both the convexity and the markup elasticity can be expressed as a function of market share. We state these results in the following lemma:

Lemma 5. *(i) Own market share is a sufficient statistic for the convexity and markup elasticity. (ii) The markup elasticity is negative.*

4.3 Partial Effect of the Shock on Marginal Profits

We now investigate the comparative statics of system F with respect to a_2, which stands for a shock to the productivity of the alternative energy resource in the second period. Again, we ignore the time index. As in the previous section, the comparative static results depend on the sign of the single partial derivative $F^2_{a_2}$ given by equation (8) or (10). The crucial terms are the shift and the tilt:

$$\epsilon_a^P = -\frac{\sigma - 1}{\sigma}\epsilon_a^Z \text{ and } \epsilon_a^{\mathrm{d}P/\mathrm{d}q} = -\frac{\sigma - 1}{\sigma}\frac{\epsilon_a^Z}{\eta}\left(1 - (1-\eta)(1+\epsilon_\mu^M)\right)$$

Here, ϵ_a^Z is the partial elasticity of Z with respect to a. The CES aggregator is increasing in a, and $\epsilon_a^Z = -(1-\mu)(1-\epsilon_a^x)<0$. For intuition, ϵ_a^x can be considered as the negative of the price elasticity of demand for the alternative resource. That is, ϵ_a^x is always negative. Note that a shock to the productivity parameter and marginal cost are equivalent in absolute terms. We summarize our results for ϵ_a^Z in the following proposition and provide the derivations in Appendix E.3.

Lemma 6. *Market share is a sufficient statistic for* ϵ_a^Z*. It is negative and increasing in market share.*

This result implies that $\epsilon_a^P > 0$. Therefore, the willingness to pay decreases for a given q.

Secondly, ϵ_μ^M is the markup elasticity with respect to market share, which is shaped by assumptions about the oil supplier's behavior. In our baseline market structure, we have:

$$\epsilon_{\mu_2}^{M_2} = -\frac{\mu}{(1-\mu)(\sigma(1-\mu)+\mu)} < 0. \tag{18}$$

which is negative. By using this result, it can be shown that $\epsilon_a^{\mathrm{d}P/\mathrm{d}q} > 0$, which means that the demand curve gets flatter for a given q. Therefore, the shift and the tilt works in opposite directions in determining the shock elasticity of markup (ϵ_a^M) given by equation (9). Substituting the expressions for the shift and the tilt yields $\epsilon_a^M = ((\sigma-1)/\sigma)\epsilon_a^Z\epsilon_\mu^M$ which is positive. Hence, the shock leads to a lower markup for a given q, and the shift and the markup in equation (8) counteracts each other in determining F_a. By substitution, we have:

$$F_a = \frac{\sigma-1}{\sigma}\frac{p}{a}\epsilon_a^Z\left(1+\epsilon_\mu^M\right). \tag{19}$$

In this expression, the second term, $1+\epsilon_\mu^M$, is responsible for the ambiguity in the sign of the effect. Importantly, this term is shaped by assumptions about the oil supplier's behavior, and does not depend on the mechanism through which the shock affects the system. The sign of F_a depends only on the size of ϵ_μ^M. This means that:

Proposition 4. *Market share is a sufficient statistic for the elasticity of markup with respect to market share, and therefore to sign the effect of the demand shock. That is, the direction of the effect depends on the oil supplier's behavior and is independent of the way the shock is realized.*

Solving for μ at the point where $1+\varepsilon_{\mu_2}^{M_2}=0$ leads to a critical value determining the sign of supply side interaction as follows:

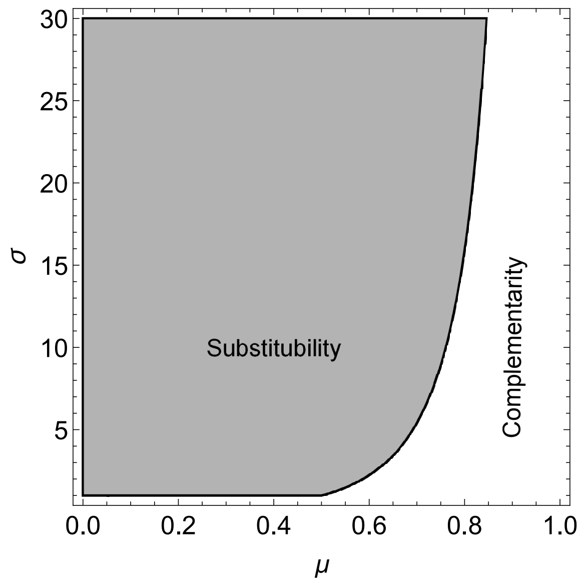
Proposition 5. *For any $\sigma \in (1,\infty)$, there exists a critical market share $\bar{\mu} \in (0,1)$ given by:*

$$\bar{\mu}(\sigma) = \frac{\sigma-\sqrt{\sigma}}{\sigma-1},$$

such that $F_{a_2}^2 = 0$, if $\mu_2 = \bar{\mu}$. If $\mu_2 < \bar{\mu}$, then an increase in the price of the alternative resource decreases the oil price and increases the oil supply in the initial period (subtitubility in second-period quantities). If $\mu_2 > \bar{\mu}$, the opposite holds (complementarity in second-period quantities).

Proof. See Appendix E.4. □

Figure 4: Direction of the Intertemporal Leakage



Notes: This figure illustrates the ciritical market shares determining supply-side substitutabilities and complementarities in quantities.

Figure 4 illustrates this critical level. When $\mu > \bar{\mu}$, there is complementarity between the quantities of alternative resources. It can be shown that $\bar{\mu}(\sigma)$ approaches 1 as σ goes to infinity, meaning that the region where there exist complementarity in quantities vanishes. If the oil owner's second-period market share is smaller than the critical value, then the current oil supply increases in response to an anticipated future increase in the productivity (or decrease in the marginal cost) of alternative energy.

The empirical relevance of this proposition should be assessed by considering OPEC as a single supplier. According to Proposition 5, a reversal of Green paradox (complementarity) occurs, only if the oil owner's extraction path leads to a high market share in the second period. Considering OPEC's current market share, which we discuss in a later section, the implied market share might seem reasonable for the reversal. However, this is a misleading comparison as the current and future market shares are related due to the scarcity constraint, which we analyze in the following subsection. Still, the result in Proposition 5 is important to highlight that the adverse consequences of climate policies can be potentially very small with endogenous market power.[14]

An important implication of Figure 4 is that intertemporal leakage is less of a concern when the elasticity of substitution is low and the market share is high. This is a likely scenario for the global oil market. We will analyze data on the oil market in Section 6.

4.4 Market Shares

Next, we show that the complementarity occurs, only if the extraction path is sufficiently flat. First, we need to describe how market share changes with extraction. The elasticity of market share with respect to extraction is given by $\varepsilon_q^{\mu} = -((\sigma-1)/\sigma)(1+\varepsilon_q^Z)$. In the event of oligopolistically competitive behavior, we have $\varepsilon_q^Z = -\mu$. On the other hand, in our baseline market structure, this term is given by $\varepsilon_q^P - 1$. Therefore, market share elasticity is negative in both cases, and it is increasing in q. This leads to the following result:

Lemma 7. *(i) Market share is globally increasing in q. (ii) $\mu_1 > \mu_2$. (iii) $d\mu_2/dq_1 < 0$.*

Proof. Part (i) has been proved above. Part (ii) follows from Lemma 2 that $q_1 > q_2$. Part (iii) follows from part (i) and from the scarcity constraint. See Lemma 9 in E.2 for the derivation of ϵ_q^{μ}. □

We next show that complementarity occurs in an empirically less interesting space. Consider the implication of the first-order conditions for the market shares:

$$\frac{\mu_2}{\mu_1} = \underbrace{\frac{(s-1)(1+r)}{(1+g)}}_{\bar{s}} \frac{M_2}{M_1}, \tag{20}$$

where g is the GDP growth and s is the reserves-to-extraction ratio (at $t=1$). Note that $s-1$ is simply equal to relative extraction (q_2/q_1). First, from Lemma 2, we know that

[14]If the oil industry is characterized by monopolistic competition, the markup is constant and $\varepsilon_{\mu_2}^{M_2} = 0$. As a result, this term is equal to one, and the impact of the shock does not depend on this term. In the case of oligopolistic Cournot competition, we have $\varepsilon_{\mu_2}^{M_2} = -\mu/1-\mu$. Solving for μ at the point where $1+\varepsilon_{\mu_2}^{M_2} = 0$ leads to a critical value for the reversal condition given by $\bar{\mu} = 1/2$.

$s-1$ is positive and below unity. Second, if we assume that$(1+r)/(1+g)$ is close to unity, unless the first-period extraction is just above $S/2$, leading to an almost flat extraction path, the first term ($\bar{s}$) is below unity.[15] Third, when the demand function is characterized by constant elasticity of substitution, the markup will depend only on the oil supplier's own market share. Since the market shares are sufficient statistics for the markups, the above equation imposes an implicit relation between the first- and the second-period market shares. We can explicitly solve either for μ_2 or μ_1. Only if $\bar{s} > 1$, will the prevailing solution lead to complementarity in quantities. We state these results in the following proposition:

Proposition 6. *If the extraction path is not too flat, such that $\bar{s} < 1$, then first-period extraction cannot decrease due to the shock (no complementarity).*

Proof. The proof is provided in Appendix E.5, where we show that as long as $\bar{s} < 1$, $\mu_2 > \bar{\mu}$ cannot hold. □

5 Intertemporal Leakage

In this section, we start by analyzing the intertemporal leakage for our baseline market structure. Next, we compare it with the intertemporal leakage in perfect or monopolistic competition.

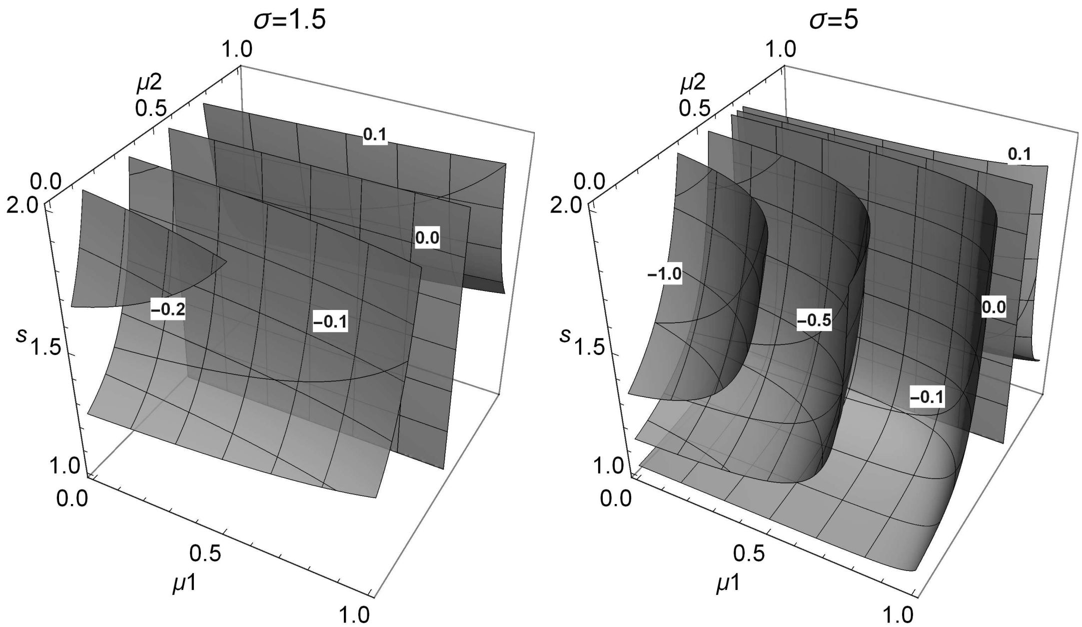
5.1 Intertemporal Leakage Rate with Endogenous Markups

By substitution, we obtain the elasticity of current extraction with respect to a_2 as follows:

$$\varepsilon_{a_2}^{q_1} = \frac{\frac{\sigma-1}{\sigma}\epsilon_{a_2}^{Z_2}\left(1+\epsilon_{\mu_2}^{M_2}\right)}{\frac{\eta_1(2-\kappa_1)}{1-\eta_1}+\frac{1}{s-1}\frac{\eta_2(2-\kappa_2)}{1-\eta_2}} \tag{21}$$

[15] In a two period model, r and g are obtained by compounding annual rates over many years. Therefore, $(1+r)/(1+g)$ might not be close to 1. However, for the same reason, the extraction path cannot be too flat.

Figure 5: Intertemporal Leakage Rate



Notes: This figure illustrates the leakage rates defined as the elasticity of first-period extraction with respect to the shock. Calculations are based on Proposition 7. Negative values indicate substitutability in quantities where the shock increases current extraction.

We analyzed all the terms in this expression, and showed that market share is a sufficient statistic for each of them. This expression is valid for all the market structures we have considered to this point. This is a powerful expression for evaluating the intertemporal leakage: evaluation of the intertemporal leakage only requires information on the equilibrium outcomes of oil market and does not require any information about the rest of the economy. Once the second- period market share is imposed as a future scenario, the intertemporal leakage can be calculated based on the observables $\{s, \mu_1\}$ for a given σ. That is, it is not necessary to make any assumptions about either the growth rate or the interest rate.

Proposition 7. ***Sufficient Statistics:*** *First- and second-period market shares and reserves-to-extraction ratio are sufficient statistics to evaluate the intertemporal leakage for given σ. More specifically, a set of sufficient statistics is $\{\mu_1, \mu_2, s_1|\sigma\}$.*

Proof. Follows from Lemma E.1, E.2, and E.3. $\square$

Figure 5 illustrates the level sets for the effect of the shock on the (μ_1, μ_2, s) space for a high and low level of σ. In the area behind the zero level set, there is complementarity. Note that there is no solution in the space given by $\mu_1 < \mu_2$. Therefore, a complementarity in quantities is restricted to a small space. When σ is higher, the zero iso-leakage curve locates at a higher μ_2 level. This shrinks the space in which complementarity occurs.

In equation (21), the set of endogenous variables is given by $\{\mu_1, \mu_2, s\}$. We can eliminate one endogenous variable by substituting equation (20). For example, eliminating s leads to:

$$\varepsilon_{a_2}^{q_1} = \frac{\frac{\sigma-1}{\sigma}\epsilon_a^Z\left(1+\epsilon_\mu^M\right)}{\frac{\eta_1(2-\kappa_1)}{1-\eta_1} + \left(\frac{1+r}{1+g}\frac{1-\eta_1}{1-\eta_2}\right)\frac{\eta_2(2-\kappa_2)}{1-\eta_2}}.$$

In this expression the set of exogenous parameters is $\{\sigma, r, g\}$. Given this set, one can calculate the intertemporal leakage based on μ_1 and μ_2. Alternatively, we can base our calculation on the observables, or employ a policy target as additional information in order to calculate the intertemporal leakage. We note these alternative ways as a Corollary to Proposition 7 as follows:

Corollary 1. ***Alternative ways of calculating the intertemporal leakage.***

(i) ***Market shares:*** *Market shares are sufficient statistics to evaluate the intertemporal leakage. More specifically, a set of sufficient statistics is* $\{\mu_1, \mu_2|\sigma, r, g\}$.

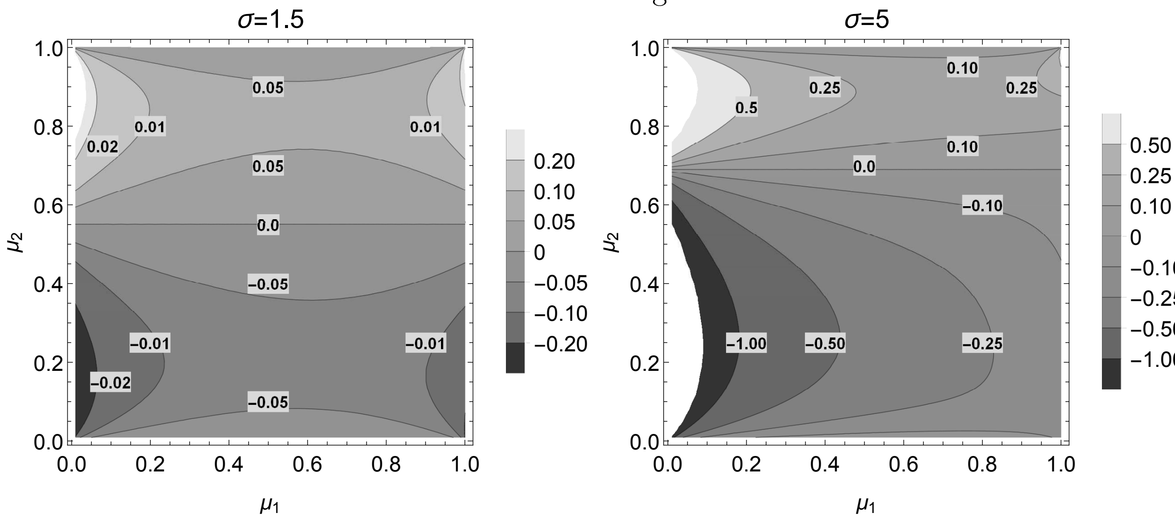
(ii) ***Observables:*** *Current market share* (μ_1) *and the reserves-to-extraction ratio (s) are sufficient statistics to evaluate intertemporal leakage. More specifically, a set of sufficient statistics is* $\{\mu_1, s|\sigma, r, g\}$.

(iii) ***Policy Targets:*** *Current market share* (μ_1) *is a sufficient statistic to evaluate intertemporal leakage due to a given emission target. More specifically, a set of sufficient statistics is* $\{\mu_1, q_2|\sigma, r, g\}$

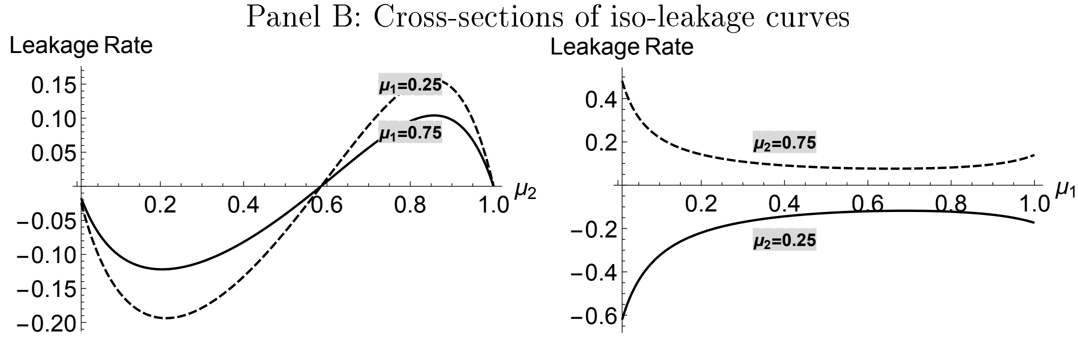
As an example, the upper panel of Figure 6 illustrates the level sets for a high and a low level of σ based on Corollary 1(i). At low levels of σ, the intertemporal leakage rate is smaller. In order to provide the intution underlying the shape of these level sets,

Figure 6: Intertemporal Leakage Rate with Market Shares

Panel A: Iso-leakage curves.



Panel B: Cross-sections of iso-leakage curves



Notes: This figure illustrates the leakage rates defined as the elasticity of first-period extraction with respect to the shock. Calculations are based on Corollary 1(i). Negative values indicate substitutability in quantities where the shock increases current extraction. In all figures, r and g are calculated by compounding an annual interest rate of 0.05 and an annual growth rate of 0.03 over 25 years. In Panel B, elasticity of substitution (σ) is set to 2.

the lower panel presents some cross sections for $\sigma = 2$. The left panel illustrates cross sections at given first-period market shares. The turning point in the complementarity area is not in the admissible space as $\mu_1 > \mu_2$ must always hold. Therefore, the leakage rate is generally U-shaped in second-period market share. Intuitively, the second period market share determines the strength of cross-price effects. When the second period market share is very small, the oil owner does not have much influence on the CES aggregator Z, and cannot dampen the change in the shadow price of oil. On the other hand, when the market share gets closer to $\bar{\mu}$, the strength of supply-side substitutability diminishes. The right panel illustrates cross-sections at given second-period market shares. It is seen that the intertemporal leakage is generally decreasing in the first-period market share in absolute terms. Only when the first period market share is close to one, this relation reverses. The first-period market share determines the market power of the oil owner in dampening the effect of the change in shadow price of oil. When the first period market share is very small, the oil owner does not have much influence on the CES aggregator Z, and cannot dampen the change in the shadow price of oil. On the other hand, when the market share gets closer to one, the oil supplier can pass through the marginal-cost shock fully (Auer and Schoenle, 2016).

5.2 Comparison with the Competitive Leakage Rate

In the case of perfect competition (or monopolistic competition), the effect of the shock on the current period supply is given by:

$$\varepsilon_{a_2}^{q_1} = \frac{(\sigma - 1)\,\epsilon_a^Z}{1 + \left(\frac{1}{s-1}\right)}.$$

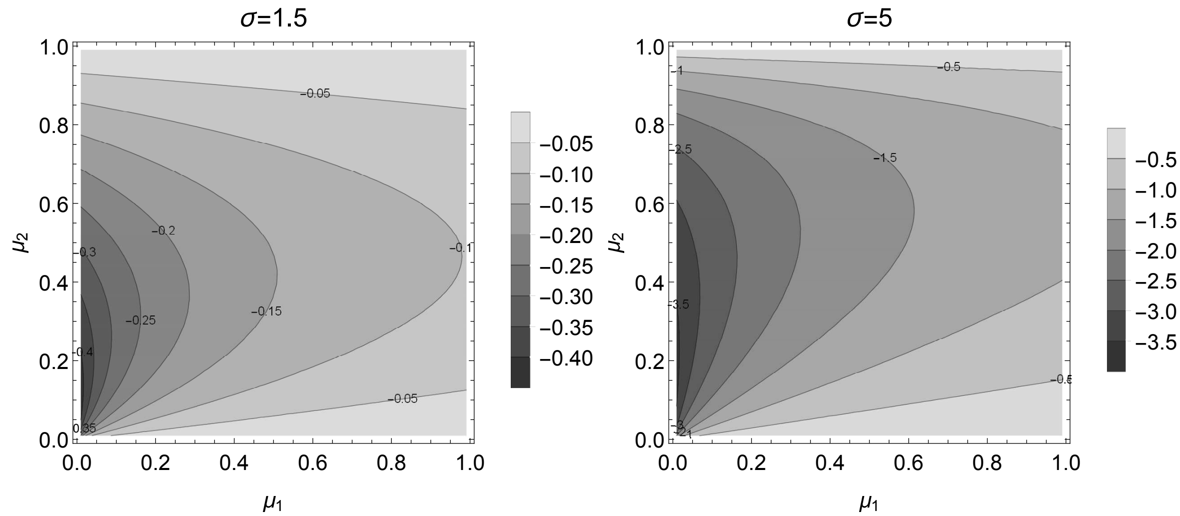
Since $\varepsilon_a^Z < 0$, first-period extraction always increases. We can eliminate one of the endogenous variables by using the implication of the first-order conditions for the market shares given by $\mu_2/\mu_1 = \bar{s}$. For example, substituting for s leads to

$$\varepsilon_{a_2}^{q_1} = \frac{(\sigma - 1)\,\epsilon_a^Z}{1 + \left(\frac{1+r}{1+g}\right)\frac{\mu_1}{\mu_2}}.$$

Figure 7 illustrates the iso-leakage curves in the case of perfect competition on the (μ_1, μ_2) space . In line with Proposition 3, all the iso-leakage curves have negative values. At the high σ level, the intertemporal leakage is higher.

We now conduct scenario comparison between the leakage rates under our baseline market structure and perfect competition. This can be done by comparing the leakage rates for at a given reserves-to-extraction ratio and current market share, and letting the second-period

Figure 7: Intertemporal Leakage in Perfect Competition



Notes: This figure illustrates the leakage rates in the case of perfect competition. Leakage rate is defined as the elasticity of first-period extraction with respect to the shock. r and g are calculated by compounding an annual interest rate of 0.05 and an annual growth rate of 0.03 over 25 years.

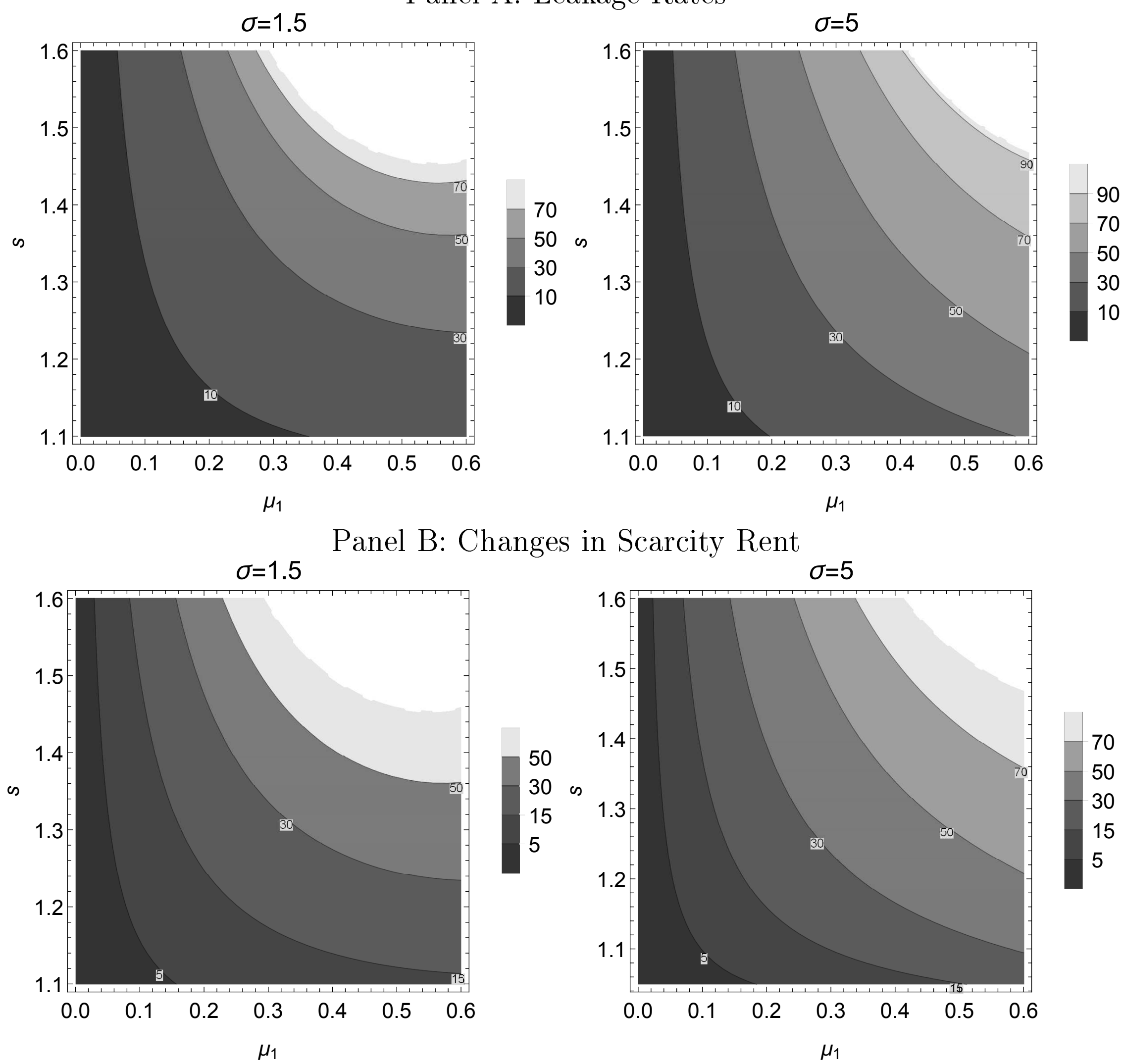
market share be optimally determined by market structure. This can be interpreted as the difference in leakage rates under these two market structure scenarios given the current data on the oil market.

Panel A in Figure 8 illustrates the differences of leakage rates as a percentage of the competitive leakage rate. For example, on the 30% level set, the oligopolistic leakage rate is 30% less than the competitive leakage rate. All the level sets in these figures have positive values, meaning that the oligopolistic leakage rates are smaller than the competitive leakage rates.

The elasticity of the scarcity rent with respect to the future demand shock is given by $\varepsilon^{\lambda}_{a_2} = -\sigma\eta_1^2\varepsilon^{q_1}_{a_2}$ for the CES case. As seen in the lower panel of Figure 8, the change in the scarcity rent with endogenous markups are lower compared to the perfect competition benchmark. The ability to dampen the demand shocks via endogenous markup adjustments leads to lower declines in the scarcity rent given (s, μ_1).

Figure 8: Comparison with Perfect Competition

Panel A: Leakage Rates



Notes: This figure compares the leakage rates to those in perfect competition. Leakage rate is defined as the elasticity of first-period extraction with respect to the shock. Calculations are based on Corollary 1(ii). The differences are expressed as a percentage of the change in the competitive benchmark. A positive value indicates dampening due to variable markups. r and g are calculated by compounding an annual interest rate of 0.05 and an annual growth rate of 0.03 over 25 years.

6 Scenario Analysis

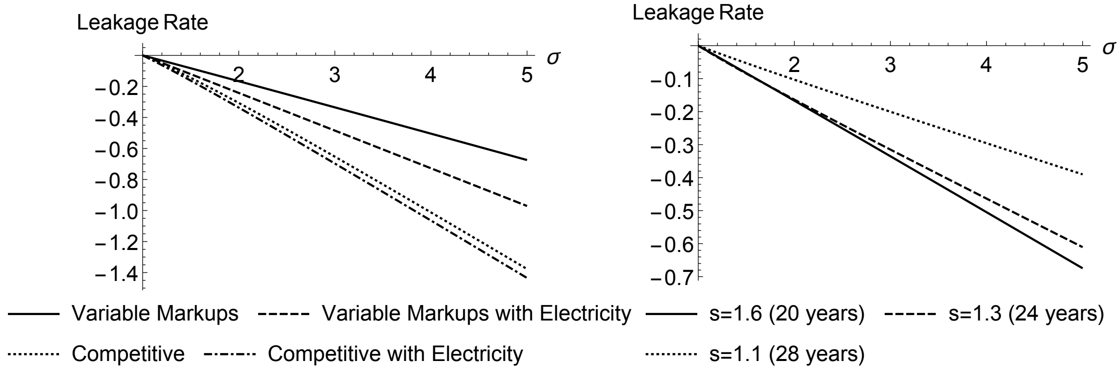
In this section, we calculate leakage rates based on the current market conditions and various projections for future market conditions. We construct our dataset mainly from the reported figures in the World Energy Outlook (WEO) published by the IEA (IEA, 2017) and OPEC Annual Statistical Bulletin (OPEC, 2017). We provide a detailed description of the dataset and its construction in Appendix G. We calculate r and g by compounding an annual interest rate of 0.05 and an annual growth rate of 0.03.

The left panel of Figure 9 compares the leakage rates with variable markups and perfect competition by using data for current market conditions based on Corollary 1(ii). We use OPEC's market share in 2016 as the first period market share and calculate it based on two market definitions by including and excluding the electricity sector. We use OPEC's proven crude oil reserves in 2016 as a proxy for the resource stock and calculate the first period extraction by applying OPEC's crude oil production in 2016 for a window width of 20 years.

Figure 9 illustrates two important results: First, the leakage rates are very close in the case of perfect competition. The difference stems from the change in the price index, and hence, in relative prices. This difference is much larger with variable markups as the market share determines the pass-through rate. Second, the leakage rate with variable markups is much smaller than the competitive leakage rate, espeically when the electricity sector is excluded. The exclusion of the electricity sector results in a substantially higher market share for OPEC, which leads to a higher markup and a higher dampening in the pass-though of the shock. In the rest of the section, we exclude electricity sector in defining the relevant market.

The right panel of Figure 9 presents the leakage rates with variable markups by varying the window width, which effectively determines the reserves-to-extraction ratio (s). The solid lines on the left and right panel of Figure 9 are identical. It is seen that a higher window width (or a lower reserves-to-extraction ratio) leads to a smaller leakage rate. A lower s implies a smoother extraction path and increases the possibility of complementarities.

Figure 9: Market Structure and Leakage Rates

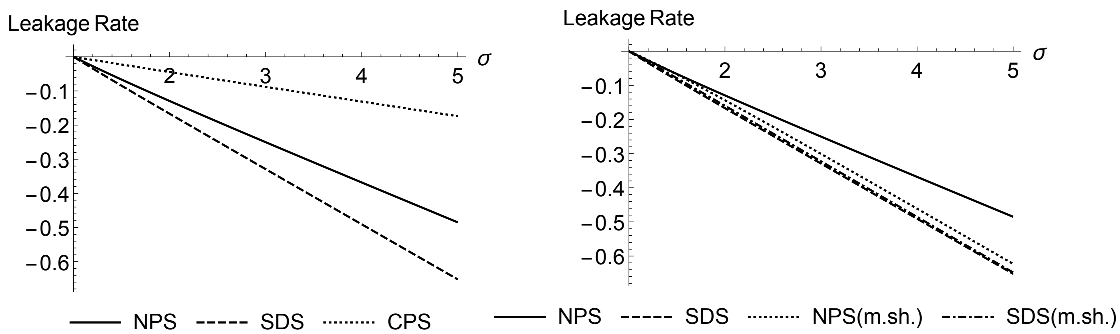


Alternatively, the left panel of Figure 10 presents the results from calculating the first period extraction based on the oil demand projections in the WEO. More specifically, we assume that the first period spans the years between 2016 and 2040, and calculate the first period extraction based on the the Current Policies Scenario (CPS) in the WEO. CPS is a business-as-usual scenario. It takes into account the policies and measures that are in legislaton as of mid-2017. The left panel of Figure 10 shows that the leakage rate under the business-as-usual scenario (CPS) is remarkably small, even for very high values of the elasticity of substitution. In the literature employing computable general equilibrium models, the estimates of elasticity of substitution for an energy-product nest ranges from 0.5 to 2, and it is generally below 1.[16] Recently, Papageorgiou et al. (2017) provide evidence that the elasticity of substitution between clean and dirty energy inputs is significantly higher than 1, and can be as high as 3. Therefore, we consider a value of σ around 2 as a plausible space. For $\sigma = 2$, the intertemporal leakage rate implied by the CPS is -0.04. That is, an anticipated 1% increase in the second-period productivity of the alternative resource, leads the resource owner to increase the first-period extraction only by 0.04%.

Figure 10 also presents the leakage rates given the extraction paths implied by various future policy scenarios in WEO. The New Policies Scenario (NPS) incorporates policies and measures in the CPS and the official targets and plans of announced policies, such as those in the Nationally Determined Contributons of the Paris Agreement. The Sustainable

[16] See, for example, Table H3 in Michielsen (2014) for a survey of these results.

Figure 10: Leakage Rates by the WEO Scenarios



Notes: CPS, NPS, and NDS indicate the Current Policies Scenario, the New Policies Scenario, and the Sustainable Development Scenario in the World Energy Outlook 2017 (IEA, 2017).

Development Scenario (SDS) achieves three policy goals: universal access to energy services by 2030, substantial mitigation in the air polluton, and effective action against climate change. The underlying assumption in calculating a leakage rate under these scenarios is that these policies are credible from the view point of the resource owner. A calculated leakage rate under NPS and SDS informs about the effect of an additional anticipated change in the productivity of the alternative resource. In Figure 10, the leakage rate is higher for the scenarios that are more ambitious in their climate targets, which is in line with the previous result presented on the right panel of 9 as the extraction paths implied by the SDS and NPS are much steeper compared to that of CPS. In the most ambitious scenario (SDS), the intertemporal leakage at $\sigma = 2$ is still low (-0.17).

Next, we conduct a robustness analysis where we base our calculations only on the current market share and projected market shares in the WEO using Corollary 1(i). That is, we do not use any information on the extraction rate and reserve level. The right panel of Figure 10 presents these calculations labeled as NPS(m.sh.) and SDS(m.sh.), along with the corresponding calculations from the left panel indicated as NPS and SDS. There are no drastic differences for a given scenario, in particluar for SDS. It is also seen that NPS(m.sh.) and SDS(m.sh.) lead to similar leakage rates. The differences in the leakage rates are less than that calculated based on the extraction projections. The reason is that, although these two scenarios imply very different extraction paths, the decrease in the market share over time is close and small across these two scenarios.[17]

7 Conclusion

In this paper, we construct a two-period resource extraction model to investigate the effects of a demand-side shock on the intertemporal allocation of a scarce resource. The main pillars of the model are imperfect substitution and endogenous markups. We show that the unintended adverse consequences of subsidizing alternative energy R&D can be small with variable markups.

Our scenario shows that, given the current policies in effect and the market conditions in the oil market, (i) intertemporal leakage is much smaller compared to those documented in the literature under perfectly competitive oil market assumption, and (ii) it is likely to be a minor concern. Using the business-as-usual scenario in the WEO, our model implies that a 1% anticipated increase in the productivity of alternative energy resources by 2040 increases the extraction between 2016 and 2040 by only 0.04%.

Our results mitigate the concerns about the unintended consequences of demand side policies due to intertemporal leakages. Furthermore, these results underline the importance of subsidizing the development of clean energy technologies that will replace fossil-fuel use in the presence of commitments to a carbon budget via international climate agreements. According to our results, intertemporal leakage is less of a concern when the elasticity of substitution is low and the market share of oil is high. This is a realistic scenario given the current conditions in the global oil market. On the other hand, it is also likely that future entails more substitution possibilities and a lower market share for oil, in which case intertemporal leakage can become important for welfare.

A further implication of the mechanisms we have docuemented might be that price-based policy instruments aiming to substitute away fossil-fuel use in the medium term, such as carbon taxation, might have to be more aggressive to reach the desired targets, as the oil

[17] We could not obtain data on projected market shares under the CPS in IEA (2017).

suppliers might be able to dampen the shocks in their markups. Substantiating this point requires further research.

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Appendix

A Derivations and Proofs in Section 2

A.1 Convexity and Second Order Condition

In order to obtain the expression in Assumption 2(i), we simply rearrange the SOC as follows:

$$\begin{aligned}\frac{\mathrm{d}^2\mathcal{L}_t}{\mathrm{d}q_t^2} = \frac{q_t^2}{p_t}\frac{\mathrm{d}^2 p_t}{\mathrm{d}q_t^2} + 2\frac{q_t}{p_t}\frac{\mathrm{d}p_t}{\mathrm{d}q_t} &< 0, \\ \eta_t\kappa_t - 2\eta_t &< 0, \\ \kappa_t &< 2.\end{aligned}$$

where the last line is the SOC as stated in Assumption 2.

A.2 Markup elasticity

We start with stating a useful relationship that we use throughout the paper:

Lemma 8. *Elasticity of elasticity is given by*

$$\varepsilon_x^{\varepsilon_x^y} = \varepsilon_x^{dy/dx} - \varepsilon_x^y - 1.$$

Proof. The derivation is as follows:

$$\begin{aligned}\varepsilon_x^{\varepsilon_x^y} &= -\frac{\mathrm{d}\ln\varepsilon_x^y}{\mathrm{d}\ln x} = -\frac{\mathrm{d}}{\mathrm{d}\ln x}\ln\left(-\frac{x}{y}\frac{\mathrm{d}y}{\mathrm{d}x}\right), \\ &= -\left(\frac{\mathrm{d}\ln x}{\mathrm{d}\ln x} - \frac{\mathrm{d}\ln y}{\mathrm{d}\ln x} + \frac{\mathrm{d}\ln(-\mathrm{d}y/\mathrm{d}x)}{\mathrm{d}\ln x}\right), \\ &= -\left(1 + \varepsilon_x^y - \varepsilon_x^{\mathrm{d}y/\mathrm{d}x}\right).\end{aligned}$$

□

Taking the derivative of equation (3) with respect to q_t gives:

$$\frac{\mathrm{d}M_t}{\mathrm{d}q_t} = -M_t^2 \frac{\mathrm{d}\eta_t}{\mathrm{d}q_t}.$$

Derivative of η_t with respect to q_t can be calculated by using the result in Lemma 8 as:

$$\frac{\mathrm{d}\eta_t}{\mathrm{d}q_t} = \frac{\eta_t}{q_t} \left[1 + \eta_t - \kappa_t\right].$$

By substituting the final expression in the markup and using the definition of elasticity, we obtain the expression given by equation (4).

A.3 Static Cost Pass-through

Consider the static problem of a monopolist with constant marginal cost denoted with c. The first order condition would be represented by the implicit relation given by $F(q) = P(q) - M(q)c = 0$. Applying the implicit function theorem gives:

$$\frac{\mathrm{d}p}{\mathrm{d}c} = \frac{\mathrm{d}P}{\mathrm{d}q}\frac{M}{F_q} = \frac{1}{2-\kappa} > 0. \tag{22}$$

Therefore, the absolute change in sales due to a unit increase in marginal cost is given by $1/\left(2-\kappa_t\right)$. By using the implication of the FOCs that $P_1/P_2 = M_1/(1+r)M_2$, it can be shown that the porportional pass-through into prices is given by:

$$-\frac{c}{p}\frac{\mathrm{d}p}{\mathrm{d}c} = -\frac{1-\eta}{2-\kappa}$$

The effect on the sales is given by

$$\frac{\mathrm{d}q}{\mathrm{d}c} = \frac{M}{F_q} = \frac{1}{\left(\mathrm{d}P/\mathrm{d}q\right)\left(2-\kappa\right)} < 0, \tag{23}$$

which is always negative by the SOC. That is, due to an exogenous increse in the marginal cost, the monopolist supply less at a higher price, which is the standard reaction of a monopolist. By using the implication of FOCs that $P_1/P_2 = M_1/(1+r)M_2$, it can be shown that the porportional pass-through into prices is given by:

$$-\frac{c}{p}\frac{\mathrm{d}q}{\mathrm{d}c} = \frac{1-\eta}{\eta(2-\kappa)}$$

B Derivations and Proofs in Section 3

B.1 Comparative statics

The determinant of the Jacobien of the system of equations F is given by:

$$|J| = \begin{vmatrix} F^1_{q_1} & F^1_{q_2} & F^1_{\lambda} \\ F^2_{q_1} & F^2_{q_2} & F^2_{\lambda} \\ F^3_{q_1} & F^3_{q_2} & F^3_{\lambda} \end{vmatrix} = \begin{vmatrix} F^1_{q_1} & 0 & -M_1 \\ 0 & F^2_{p_{jt}q_2} & -(1+r)M_2 \\ 1 & 1 & 0 \end{vmatrix}$$
$$= F^1_{q_1}(1+r)M_2 + F^2_{q_2}M_1 < 0$$

$F^t_{q_t}$ has been derived in the main text. The inequality above follows the result that $F^t_{q_t} < 0$. Other partial derivatives are easy to verify. The partial derivatives of system F with respect to a_2 is given by:

$$F_{a_2} = \begin{bmatrix} F^1_{a_2} \\ F^2_{a_2} \\ F^3_{a_2} \end{bmatrix} = \begin{bmatrix} 0 \\ F^2_{a_2} \\ 0 \end{bmatrix}.$$

We obtain the comparative statics results given by equation (5) by applying the Cramer's rule.

B.2 The intertemporal leakage rate

Substituting ε_a^M in F_a, we have:

$$F_{a_2}^2 = M_2 \frac{P}{a} \left(-\epsilon_a^P + \eta_t \epsilon_a^{\mathrm{d}P/\mathrm{d}q} \right).$$

Substituting this expression and $|J|$ in the comparative static result and rearranging the resulting expression lead to :

$$\begin{aligned}\frac{\mathrm{d}q_1}{\mathrm{d}a_2} &= \frac{M_1 F_{a_2}^2}{|J|} = \frac{M_1 M_2}{F_{q_1}^1 (1+r) M_2 + F_{q_2}^2 M_1} \frac{P_2}{a_2} \left(-\epsilon_{a_2}^{P_2} + \eta_2 \epsilon_{a_2}^{\mathrm{d}P_2/\mathrm{d}q_2} \right) \\ &= \frac{\frac{P}{a}\left(-\epsilon_{a_2}^{P_2} + \eta_2 \epsilon_{a_2}^{\mathrm{d}P_2/\mathrm{d}q_2} \right)}{\frac{F_{q_1}^1}{M_1}(1+r) + \frac{F_{q_2}^2}{M_2}}\end{aligned}$$

Substituting $F_{q_t}^t$ given by equation (6) and rearranging the resulting expression in terms of elasticities lead to:

$$\varepsilon_{a_2}^{q_1} = -\frac{a_2}{q_1} \frac{\mathrm{d}q_1}{\mathrm{d}a_2} = \frac{\left(-\epsilon_{a_2}^{P_2} + \eta_2 \epsilon_{a_2}^{\mathrm{d}P_2/\mathrm{d}q_2} \right)}{\frac{P_1}{P_2} \eta_1 (2-\kappa_1)(1+r) + \frac{q_1}{q_2} \eta_2 (2-\kappa_2)}$$

Substituting $P_2/P_1 = M_2(1+r)/M_1$ and writing the markups in terms of inverse price elasticities gives:

$$\begin{aligned}\varepsilon_{a_2}^{q_1} &= \frac{\left(-\epsilon_{a_2}^{P_2} + \eta_2 \epsilon_{a_2}^{\mathrm{d}P_2/\mathrm{d}q_2} \right)}{\frac{1-\eta_2}{1-\eta_1} \eta_1 (2-\kappa_1) + \frac{q_1}{q_2} \eta_2 (2-\kappa_2)}, \\ &= \frac{-\epsilon_{a_2}^{P_2} + \eta_2 \epsilon_{a_2}^{\mathrm{d}P_2/\mathrm{d}q_2}}{\left(\frac{1-\eta_2}{1-\eta_1} \right) \eta_1 (2-\kappa_1) + \left(\frac{1}{s-1} \right) \eta_2 (2-\kappa_2)},\end{aligned}$$

where the last line follows from $q_1/q_2 = 1/(s-1)$.

B.3 The intertemporal leakage rate for the competitive case

In the case of perfect competition, the system of FOCs reads as follows:

$$
\begin{aligned}
F^1(q_1, q_2, \lambda) = P_1 - \lambda &= 0, \\
F^2(q_1, q_2, \lambda) = P_2 - \lambda(1+r) &= 0, \\
F^3(q_1, q_2, \lambda) = q_1 + q_2 - S &= 0.
\end{aligned}
$$

The determinant of the Jacobien is given by:

$$
\begin{aligned}
|J| &= \begin{vmatrix} F^1_{q_1} & F^1_{q_2} & F^1_{\lambda} \\ F^2_{q_1} & F^2_{q_2} & F^2_{\lambda} \\ F^3_{q_1} & F^3_{q_2} & F^3_{\lambda} \end{vmatrix} = \begin{vmatrix} F^1_{q_1} & 0 & -1 \\ 0 & F^2_{q_2} & -(1+r) \\ 1 & 1 & 0 \end{vmatrix} \\
&= F^1_{q_1}(1+r) + F^2_{q_2} < 0
\end{aligned}
$$

Here, $F^t_{q_t}$ is given by $(\mathrm{d}P_t/\mathrm{d}q_t)\,(1+r)^t$. Other partial derivatives are easy to verify. Applying Cramer's rule gives:

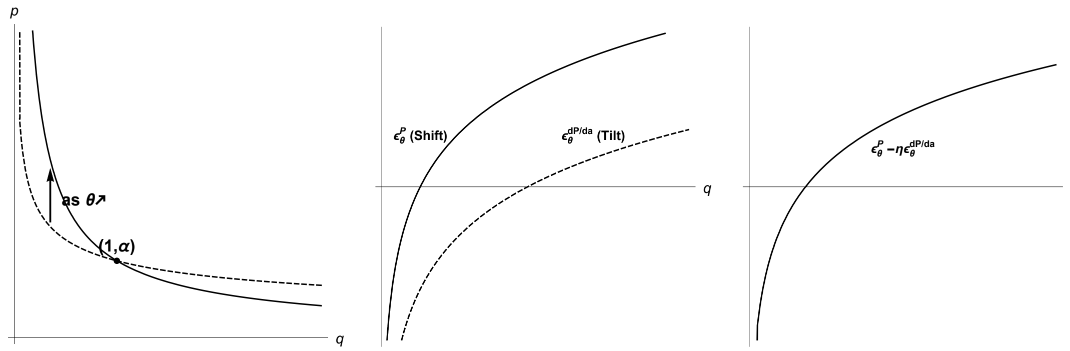
$$
\frac{\mathrm{d}q_1}{\mathrm{d}a_2} = \frac{F^2_{a_2}}{|J|}, \; \frac{\mathrm{d}q_2}{\mathrm{d}a_2} = -\frac{F^2_{a_2}}{|J|}, \; \frac{\mathrm{d}\lambda}{\mathrm{d}a_2} = \frac{F^1_{q_1} F^2_{a_2}}{|J|}.
$$

$F^2_{a_2}$ is given by $-\,(P_2/a_2)\,\epsilon^{P_2}_{a_2}$. Substituting this expression in the comparative static result leads to:

$$
\frac{\mathrm{d}q_1}{\mathrm{d}a_2} = \frac{F^2_{a_2}}{|J|} = \frac{\frac{P_2}{a_2}\left(-\epsilon^{P_2}_{a_2}\right)}{F^1_{q_1}(1+r) + F^2_{q_2}}
$$

Substituting $F^t_{q_t}$ and $P_2/P_1 = (1+r)$, and rearranging the resulting expression in terms of elasticities gives equation (13).

Figure 11: Comparative Statics with Constant Markup



C Example: Constant demand elasticity

Consider the constant price elasticity demand function given by $P(q) = \alpha q^{-\theta}$. The elasticity and convexity are given by $\eta = \theta$ and $\kappa = 1 + \theta$, respectively. The markup is equal to $1/(1-\theta)$ which is increasing in θ. Therefore, when demand is less responsive, the supplier charges a higher markup at any given q. On the other hand, the level parameter, α, does not affect the elasticity and markup. Let's conduct this analysis in terms of the shift and the tilt. First, consider an increase in α. The shift and the tilt are given by $\epsilon_\alpha^P = -1$ and $\epsilon_\alpha^{\mathrm{d}P/\mathrm{d}q} = -1$, respectively. As a result, the market power effect vanishes. The term in equation (10) given by $\epsilon_\alpha^P - \eta\epsilon_\alpha^{\partial P/\partial q}$ is equal to $\theta - 1$ which is always negative. Therefore, F_α is always positive.

Second, consider an increase in θ, which means that the demand becomes less responsive. Now, the shift and the tilt are given by $\epsilon_\theta^P = \theta \log q$ and $\epsilon_\theta^{\partial P/\partial q} = \theta \ln q - 1$, respectively. The difference is equal to one, and the markup effect is given by $\epsilon_\theta^M = -\theta/(1-\theta)$, which is constant and negative. As can be seen in Figure 11, an increase in θ tilts the demand curve around the point $(\alpha, 1)$ in the (q, p) space. There is no local shift at this point. When $q > 1$, the change in willingness to pay is negative. That is, the absolute shift is negative $(\partial P/\partial\theta < 0)$ and the shock elasticity of the demand curve is positive $(\epsilon_\theta^P > 0)$. The tilt changes sign at a critical level given by $\bar{q}(\theta) = e^{(1/\theta)} > 1$. The second panel in Figure 11 illustrates this situation for $\theta = 0.75$. For $q < 1$, both terms are negative. For $0 < q < (\bar{q}(\theta) = 3.8)$, they have opposite signs. For $q > \bar{q}(\theta)$, they are both positive, and the shift is dampened by the tilt. In all these cases, the difference is constant and equal to 1.

The term $\epsilon_\theta^P - \eta\epsilon_\theta^{\partial P/\partial q}$ is equal to $\theta\left(1+(1-\theta)\ln q\right)$. This is negative for low values of q and θ where both the shift and the tilt have negative signs. In particular, when $q < 1/e$, there is a solution to $\theta\left(1+(1-\theta)\log q\right) = 0$ for any value of $\theta \in (0,1)$. The third panel in Figure 11 illustrates this situation. At high values of q, an increase in θ reduces the willingess to pay ($\epsilon_\theta^P > 0$). Since the markup is increasing everywhere ($\epsilon_\theta^M < 0$), F_θ is negative. At low q values, the decrease in willingness to pay is smaller, or even positive. In a somewhat restrictive space, this situation can lead to a negative F_θ while there is an increase in the willingness to pay. This is a contrasting situation with the case of perfect competition as follows: in the case of perfect competition, an increase in θ does not affect price. However, quantity changes due to the shift in the demand curve, $\epsilon_\theta^P = \theta\log q$. The tilt does not play a role, as there is no markup in the pricing decision. Therefore, the sign of the partial adjustment, F_θ, is always determined by the sign of the shift.

D Market competition and strategic complementarities

In order to analyze a shock to the substitute price, we can simply substitute $p = P(q,x)$ for the demand function, where x is the supply schedule of the substitute good. Here, x is not an equilibrium outcome and it depends on the assumed market structure. It can be considered as the reaction function of the competitor. This treatment covers widely employed competition structures as we will briefly discuss in the following.

Let's analyze the implication of assumed market structure for the inverse price elasticity. The explicit formulation is given by:

$$\eta = -\left(\frac{\partial\ln P}{\partial\ln q} + \frac{\partial\ln P}{\partial\ln x}\frac{\mathrm{d}\ln x}{\mathrm{d}\ln q}\right) - \left(\frac{\partial\ln P}{\partial\ln m}\frac{\mathrm{d}\ln m}{\mathrm{d}\ln q}\right),$$

where we express the elasticities in logarithmic terms for brevity. Consider the cases of monopolistic and Cournot competition where firms are not large enough to affect expenditure ($\mathrm{d}m/\mathrm{d}q = 0$) and maximize profits for given quantity supplied by the competitor. That is, the conjecture about the competitor's behavior entails $\mathrm{d}x/\mathrm{d}q = 0$. This leads to $\eta = -\partial \ln P(q,x)/\partial \ln q$. That is, the total and the partial inverse price elasticities are equal. Note that the evaluation of the resulting expression still depends on the assumed competition structure and the demand function.

Now, consider the relevant term for our discussion which is about the partial adjustment in the second period (F_a), and set $a = p^x$, which leads to

$$\begin{aligned} F_{p^x} &= -\frac{P}{p^x}\left(\epsilon^P_{p^x} - \epsilon^M_{p^x}\right). \\ &= -\frac{P}{p^x}\left(\epsilon^P_{p^x} - \eta\epsilon^{\partial P/\partial q}_{p^x}\right). \end{aligned}$$

In general, both $\epsilon^P_{p^x}$ and $\epsilon^M_{p^x}$ in the first row are positive. Therefore, this term can be arbitrarily small and our results in Section 3 apply to the case of a shock to the substitute price. Given this result and given that the substitute good is produced with the same conjecture, such that $\mathrm{d}q/\mathrm{d}x = 0$, we have:

$$\epsilon^P_{p^x} = -\frac{\partial \ln P}{\partial \ln x}\frac{\partial \ln x}{\partial \ln p^x} \text{ and } \epsilon^{\partial P/\partial q}_{p^x} = -\frac{\partial \ln\left(\partial P/\partial q\right)}{\partial \ln x}\frac{\partial \ln x}{\partial \ln p^x}$$

Substituting these expresions back leads to:

$$F_{p^x} = M\frac{P}{p^x}\epsilon^x_{p^x}\left(-\frac{\partial \ln P}{\partial \ln x} - \frac{\partial \ln P}{\partial \ln q}\frac{\partial \ln\left(\partial P/\partial q\right)}{\partial \ln x}\right),$$

where $\varepsilon^x_{p^x} > 0$ is the price elasticity of the substitute good. As in the case of own price elasticity, evaluation of these partial effects still depends on the market structure and the assumed demand schedule. For example, in case of monopolistic competition with constant elasticity of substitution demand schedule, the partial effects of x are zero. As a result, there is no cross-price effects. For non-zero cross-price effects, one has to depart either from the monopolistic competition as in Atkeson and Burstein (2008) or from the CES demand assumption as in Melitz and Ottaviano (2008).

As long as the oil supplier do not internalize the change in the competitors' supply decision, the same formula applies for the case that the substitute is produced competitively. First, in our model in Section 4, we go beyond the assumption of the myopic conjecture of $\mathrm{d}x/\mathrm{d}q = 0$, and assume that the oil supplier internalizes the effect of its supply decision on the supply of the alternative resource owner. Hence, the total elasticity for the oil market is given by

$$\eta = -\left(\frac{\partial \ln P}{\partial \ln q} + \frac{\partial \ln P}{\partial \ln x}\frac{\mathrm{d}\ln x}{\mathrm{d}\ln q}\right).$$

The crucial assumption is that the competing good is produced competitively which is a reasonable and common assumption in our applied case. Hence, the supply of the alternative resource does not depend on strategic consideration. Finally, we mantain the assumption that the supply decision does not affect the energy expenditure. This is consistent with the empirical evidence that energy expenditure shares are more or less constant over time (see Hassler et al. (2012)).

E Derivations and Proofs in Section 4

E.1 Derivation of the Inverse Price Elasticity and the Markup Function

Demand schedules and market shares. The market for final energy is perfectly competitive, which leads to the usual demand and inverse demand functions for the inputs given by

$$
\begin{aligned}
q &= (1-\gamma)^{\sigma} p^{-\sigma} (P^Z)^{\sigma-1} E^Z, \\
p &= (1-\gamma) q^{-\frac{1}{\sigma}} Z^{-\frac{\sigma-1}{\sigma}} E^Z, \\
x &= \gamma^{\sigma} a^{\sigma-1} \left(p^x\right)^{-\sigma} \left(P^Z\right)^{\sigma-1} E^Z, \\
p^x &= \gamma a^{\frac{\sigma-1}{\sigma}} x^{-\frac{1}{\sigma}} Z^{-\frac{\sigma-1}{\sigma}} E^Z.
\end{aligned}
$$

By using these input demand schedules, we express the market share of the energy inputs in terms of quantities and prices as follows:

$$
\begin{aligned}
\mu &= \frac{pq}{P^Z Z} == (1-\gamma)^{\sigma} \left(\frac{p}{P^Z}\right)^{1-\sigma} = (1-\gamma)\left(\frac{q}{Z}\right)^{\frac{\sigma-1}{\sigma}} \\
\mu^x &= \frac{p^x x}{P^Z Z} = \gamma^{\sigma} \left(\frac{p^x}{aP^Z}\right)^{1-\sigma} = \gamma \left(\frac{ax}{Z}\right)^{\frac{\sigma-1}{\sigma}}
\end{aligned}
$$

Inverse price elasticity. The inverse price elasticity is calculated as follows:

$$
\eta \equiv \varepsilon_q^P = -\frac{\mathrm{d}\ln P}{\mathrm{d}\ln q} = -\frac{\mathrm{d}\ln\left((1-\gamma)q^{-\frac{1}{\sigma}} Z^{-\frac{\sigma-1}{\sigma}} E^Z\right)}{\mathrm{d}\ln q} = \frac{1}{\sigma} - \frac{\sigma-1}{\sigma}\varepsilon_q^Z,
$$

which is the expression given by equation (15). The elasticity of the CES aggregator (ε_q^Z) is calculated as:

$$
\begin{aligned}
\varepsilon_q^Z &= -\frac{q}{Z}\frac{\mathrm{d}Z}{\mathrm{d}q} = -\frac{q}{Z}\frac{\mathrm{d}}{\mathrm{d}q}\left[\gamma\left(a_t x_t\right)^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\left(q_t\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \\
&= -\frac{q}{Z^{\frac{\sigma-1}{\sigma}}}\left[\gamma\frac{\left(a_t x_t\right)^{\frac{\sigma-1}{\sigma}}}{a}\frac{a}{x}\frac{\mathrm{d}x}{\mathrm{d}q} + (1-\gamma)\left(q_t\right)^{-\frac{1}{\sigma}}\right], \\
&= -\left[\gamma\left(\frac{a_t x_t}{Z}\right)^{\frac{\sigma-1}{\sigma}}\frac{q}{x}\frac{\mathrm{d}x}{\mathrm{d}q} + (1-\gamma)\left(\frac{q}{Z}\right)^{\frac{\sigma-1}{\sigma}}\right], \\
&= -\mu + (1-\mu)\varepsilon_q^x.
\end{aligned}
$$

In the third line, we rearrange the expression in the second line in terms of market shares, which results in the final expression. Here, ε_q^x denotes the effect of a change in oil supply on the supply of the alternative resource. It is given by

$$\begin{aligned}\varepsilon_q^x &= -\frac{\mathrm{d}\ln x}{\mathrm{d}\ln q} = -\frac{\mathrm{d}\ln\left(\gamma^\sigma a^{\sigma-1}\left(p^x\right)^{-\sigma}\left(P^Z\right)^{\sigma-1}E^Z\right)}{\mathrm{d}\ln q},\\ &= (\sigma-1)\frac{\mathrm{d}\ln P^Z}{\mathrm{d}\ln q} = (\sigma-1)\varepsilon_q^{P^Z}.\end{aligned}$$

Note that the alternative resource market is perfectly competitive. Hence, p^x do not adjust. The elasticity of CES price index ($\varepsilon_q^{P^Z}$) can be calculated as follows:

$$\begin{aligned}\varepsilon_q^{P^Z} &= -\frac{q}{P^Z}\frac{\mathrm{d}P^Z}{\mathrm{d}q} = -\frac{q}{P^Z}\frac{\mathrm{d}}{\mathrm{d}q}\left(\gamma^\sigma\left(\frac{p_t^X}{a_t}\right)^{1-\sigma} + (1-\gamma)^\sigma(p_t)^{1-\sigma}\right)^{\frac{1}{1-\sigma}}\\ &= -\left((1-\gamma)^\sigma\left(\frac{p}{P^Z}\right)^{1-\sigma}\frac{q}{p}\frac{\mathrm{d}p}{\mathrm{d}q}\right) = \mu\varepsilon_q^P\end{aligned}$$

The expressions for ε_q^P, ε_q^Z, ε_q^x, and $\varepsilon_q^{P^Z}$ constitute a system of four equations with four unknowns. By using $\mu^x = 1-\mu$, all elasticities can be expressed as a function of μ as follows:

$$\begin{aligned}\eta &= \frac{1}{(1-\mu)\sigma+\mu},\\ \varepsilon_q^Z &= -\varepsilon_q^{P^Z} = -\frac{\mu}{(1-\mu)\sigma+\mu},\\ \varepsilon_q^x &= \frac{\mu(\sigma-1)}{(1-\mu)\sigma+\mu}.\end{aligned}$$

The first line is the expression in equation (16).

Markup function. The markup function follows from substituting η in equation (3). The markup function for the case of oligopolistically competitive behavior can be calculated by following the same steps and using the conjecture that $\varepsilon_q^x = 0$.

E.2 Derivation of Markup Elasticity and Convexity

Convexity and demand manifold By Lemma 8, convexity of a demand function can be expressed as follows:

$$\kappa = 1 + \eta + \varepsilon_q^\eta,$$

where ε_q^η is the elasticity of inverse price elasticity given by:

$$\varepsilon_q^\eta = -\frac{q}{\eta}\frac{\mathrm{d}\eta}{\mathrm{d}\mu}\frac{\mathrm{d}\mu}{\mathrm{d}q} = -\varepsilon_\mu^\eta \varepsilon_q^\mu \tag{24}$$

Here, ε_μ^η is given by

$$\varepsilon_\mu^\eta = -\frac{\mu}{\eta}\frac{\mathrm{d}}{\mathrm{d}\mu}\left(\frac{1}{(1-\mu)\sigma + \mu}\right) = -\mu\eta(\sigma - 1).$$

We express our results for ε_q^μ in the following lemma:

Lemma 9. $\varepsilon_q^\mu = \eta - 1 < 0$. *That is, μ is increasing in q.*

Proof. ε_q^μ is calculated as follows:

$$\begin{aligned}\varepsilon_q^\mu &= -\frac{\mathrm{d}\ln\mu}{\mathrm{d}\ln q} = -\frac{\mathrm{d}}{\mathrm{d}\ln q}\ln\left((1-\gamma)\left(\frac{q}{Z}\right)^{\frac{\sigma-1}{\sigma}}\right)\\ &= -\frac{\sigma-1}{\sigma}\left(\frac{\mathrm{d}\ln q}{\mathrm{d}\ln q} - \frac{\mathrm{d}\ln Z}{\mathrm{d}\ln q}\right) = -\frac{\sigma-1}{\sigma}\left(1 + \varepsilon_q^Z\right)\end{aligned}$$

Substituting ε_q^Z from equation (15) gives the expression for ε_q^μ as stated in the lemma. □

Substituting equation ε_μ^η and ε_q^μ in equation (24) gives

$$\varepsilon_q^\eta = -\varepsilon_\mu^\eta \varepsilon_q^\mu = \mu\eta(\sigma-1)(\eta-1) > 0.$$

Given this result and the expression for η given by equation (16), convexity reads as follows:

$$\kappa = 1 - \frac{(1-\mu)\mu(\sigma-1)^2}{((1-\mu)\sigma+\mu)^3},$$

which is smaller than 2, in line with Assumption 2(i). Solving the expression given by equation (16) for μ and substituting in κ gives the manifold illustrated in Figure 3.

Markup elasticity By using equation (3), the markup elasticity can be expressed as follows:

$$\varepsilon_q^M = M\eta\varepsilon_q^\eta = M\eta\left(\kappa - 1 - \eta\right).$$

By substitution, we obtain:

$$\varepsilon_q^M = -\frac{\mu(\sigma-1)}{((1-\mu)\sigma+\mu)^2},$$

which can be expressed as $\varepsilon_q^M = \eta(1-\sigma\eta)$ as stated in the main text.

E.3 Derivation of the Shift and the Tilt in the Demand Curve

The shift and the elasticity of markup with respect to the shock The shift term is given by

$$\begin{aligned}\epsilon_a^P &= -\frac{\partial \ln P}{\partial \ln a} = -\frac{\partial \ln\left((1-\gamma)q^{-\frac{1}{\sigma}}Z^{-\frac{\sigma-1}{\sigma}}E^Z\right)}{\partial \ln a}, \\ &= \frac{\sigma-1}{\sigma}\frac{\partial \ln Z}{\partial \ln a} = -\frac{\sigma-1}{\sigma}\epsilon_a^Z.\end{aligned}$$

The elasticity of markup with respect to a is given by

$$\epsilon_a^M = -\frac{a}{M}\frac{\partial M}{\partial \mu}\frac{\partial \mu}{\partial a} = -\frac{\partial \ln M}{\partial \ln a} = -\epsilon_\mu^M \epsilon_a^\mu$$

ϵ_a^μ can be expressed in terms of ε_a^Z as follows:

$$\begin{aligned}\epsilon_a^\mu &= -\frac{\partial \ln \mu}{\partial \ln a} = -\frac{\partial}{\partial \ln a}\ln\left((1-\gamma)\left(\frac{q}{Z}\right)^{\frac{\sigma-1}{\sigma}}\right) \\ &= -\frac{\sigma-1}{\sigma}\left(-\frac{\partial \ln Z}{\partial \ln a}\right) = -\frac{\sigma-1}{\sigma}\varepsilon_a^Z\end{aligned}$$

Substituting these expressions in F_a gives:

$$\begin{aligned}
F_a &= \frac{P}{a}\left(-\epsilon_a^P + \epsilon_a^M\right) \\
&= \frac{P}{a}\left(\frac{\sigma-1}{\sigma}\epsilon_a^Z + \epsilon_\mu^M \frac{\sigma-1}{\sigma}\varepsilon_a^Z\right) \\
&= \frac{P}{a}\frac{\sigma-1}{\sigma}\epsilon_a^Z\left(1+\epsilon_\mu^M\right)
\end{aligned}$$

Here, it is seen that the market power effect always dampens the shift as $\epsilon_\mu^M < 0$ by Lemma 7.

Details on ϵ_a^Z Various elasticities with respect to a, including ϵ_a^Z, are given by

$$\begin{aligned}
\epsilon_a^P &= -\frac{(\sigma-1)}{\sigma}\epsilon_a^Z, \\
\epsilon_a^Z &= -(1-\mu)\left(1-\epsilon_a^x\right), \\
\epsilon_a^x &= -(\sigma-1)\left(1-\epsilon_a^{PZ}\right), \\
\epsilon_a^{PZ} &= \mu\epsilon_a^P + (1-\mu).
\end{aligned}$$

Solving these four equations leads to

$$\epsilon_a^P = 1 - \frac{1}{\sigma-(\sigma-1)\mu}, \tag{25}$$

$$\epsilon_a^Z = -\epsilon_a^{PZ} = -\frac{\sigma(1-\mu)}{(1-\mu)\sigma+\mu} \tag{26}$$

$$\epsilon_a^x = -\frac{(\sigma-1)\mu}{(1-\mu)\sigma+\mu} \tag{27}$$

It is easy to see that $\epsilon_a^Z < 0$. Its derivative with respect to μ is given by

$$\frac{\partial\epsilon_a^Z}{\partial\mu} = \frac{\sigma}{((1-\mu)\sigma+\mu)^2},$$

which is positive.

E.4 Proof of Proposition 5

ϵ_μ^M can be calculated as follows:

$$\begin{aligned}\epsilon_\mu^M &= -\frac{\mu}{M}\frac{\partial}{\partial\mu}\left(1+\frac{1}{(\sigma-1)(1-\mu_t)}\right)\\ &= -\frac{\mu}{(1-\mu)((1-\mu)\sigma+\mu)}\end{aligned}$$

The critical value is given by $1+\epsilon_\mu^M=0$, which leads to

$$1-\frac{\mu}{(1-\mu)((1-\mu)\sigma+\mu)}=\left(\mu-\frac{\sigma-\sqrt{\sigma}}{\sigma-1}\right)\left(\mu-\frac{\sigma+\sqrt{\sigma}}{\sigma-1}\right)=0.$$

This equality holds if and only if

$$\mu=\frac{\sigma-\sqrt{\sigma}}{\sigma-1}<1 \text{ or} \mu=\frac{\sigma+\sqrt{\sigma}}{\sigma-1}>1.$$

The second solution cannot hold as it is higher than 1. Therefore, $1+\epsilon_\mu^M$ changes sign in the admissable space only at

$$\bar{\mu}(\sigma)=\frac{\sigma-\sqrt{\sigma}}{\sigma-1}.$$

E.5 Proof of Proposition 6

Substitute the markup function given by equation (20), and rearrange the resulting expression as follows:

$$\begin{aligned}\bar{s} &= \frac{D(\mu_2)}{D(\mu_1)},\\ &\text{where } D(\mu)=\frac{\mu}{M(\sigma-1)}=\frac{\mu\,(1-\mu)}{(1-\mu)\sigma+\mu}.\end{aligned}$$

Lemma 10. $D(\mu)$ is increasing for $\mu < \bar{\mu}$ and decreasing for $\mu > \bar{\mu}$. That is,

$$D'(\mu) \begin{cases} > 0 & \Leftrightarrow 0 < \mu < \bar{\mu} \\ < 0 & \Leftrightarrow \bar{\mu} < \mu < 1. \end{cases}$$

Proof. The derivative of $D(\mu)$ with respect to μ is given by

$$D'(\mu) = \frac{\mu^2(\sigma-1) - 2\mu\sigma + \sigma}{((1-\mu)\sigma + \mu)^2}.$$

The term in the denominator is positive in the admissable range. Therefore, $D'(\mu) = 0$ if and only if the numerator is zero:

$$(\sigma - 1)\mu^2 - 2\sigma\mu + \sigma = 0.$$

Solving $(\sigma-1)\mu^2 - 2\sigma\mu + \sigma = 0$ for μ gives two real solutions:

$$\mu^s = \frac{2\sigma \pm \sqrt{4\sigma^2 - 4(\sigma-1)\sigma}}{2(\sigma-1)} = \frac{\sigma \pm \sqrt{\sigma}}{\sigma - 1}.$$

Rearrange and denote these solutions as follows:

$$\mu^{s1} = 1 - \frac{1}{\sqrt{\sigma}+1} \text{ and } \mu^{s2} = \frac{1}{\sqrt{\sigma}-1} + 1.$$

Since the denominator of $D'(\mu)$ is convex in μ, we have:

$$D'(\mu) \begin{cases} > 0 & \Leftrightarrow 0 < \mu < 1 - \frac{1}{\sqrt{\sigma}+1} \text{ or } 1 < 1 + \frac{1}{\sqrt{\sigma}-1} < \mu \\ < 0 & \Leftrightarrow 0 < \underbrace{1 - \frac{1}{\sqrt{\sigma}+1}}_{\bar{\mu}} < \mu < 1 < 1 + \frac{1}{\sqrt{\sigma}-1}. \end{cases}$$

Since $\mu^{s2} > 1$, $D'(\mu)$ changes sign only at μ^{s1} which is equal to $\bar{\mu}$. $\square$

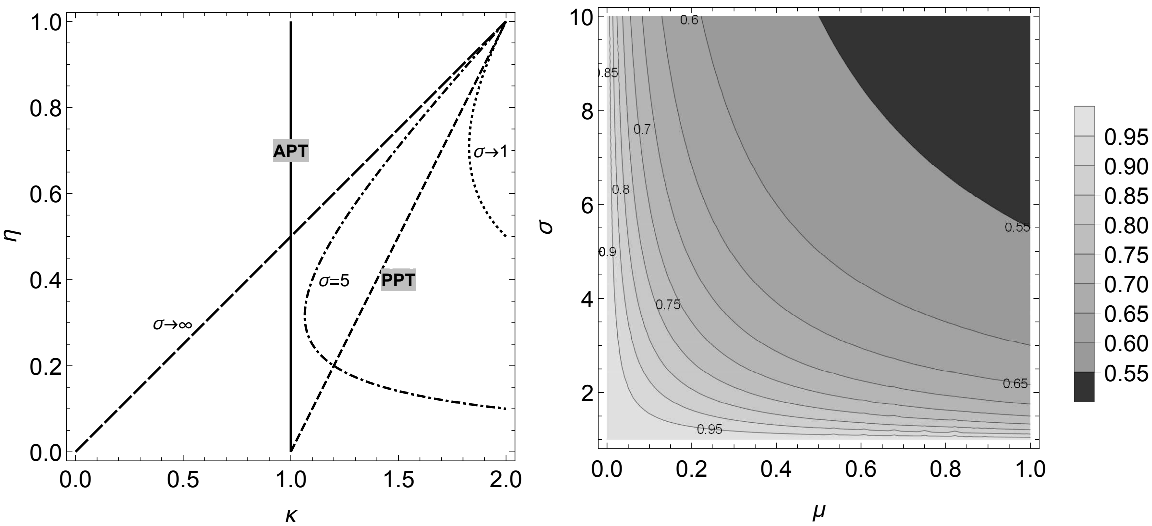
Assume that $\bar{s} < 1$ and $\mu_2 > \bar{\mu}$. First, by inspection, $\bar{s} < 1 \Leftrightarrow D(\mu_2) < D(\mu_1)$. Second, by Lemma 7, we must have $\mu_1 > \mu_2 > \bar{\mu}$. These conditions hold together, only if $D'(\mu) > 0$. By Lemma 10, $D'(\mu) > 0$ and $\mu_2 > \bar{\mu}$ is a contradiction. Therefore, when $\bar{s} < 1$, $\mu_2 > \bar{\mu}$ cannot hold. This result completes the proof of Proposition 6. That is, when $\bar{s} < 1$, a reversal is not possible, and if a solution exists, it is characterized by Green Paradox.

F Markup Elasticity and Convexity with Alternative Competition Structures

In this section, we discuss the implications of the benchmark behavioral assumptions for markup elasticity and convexity. In the case of monopolistically competitive behavior, the elasticity and the convexity are given by $1/\sigma$ and $1 + 1/\sigma$, respectively, which implies that $\kappa = 1 + \eta$. Therefore, the markup elasticity is zero. This situation is represented by the threshold line where the markup elasticity changes sign in Figure 1. Therefore, a marginal cost shock causes one-to-one proportional pass-through. As the supply takes place to the right of the unit convexity line, the absolute pass-through is even higher than one to one. In other words, a marginal cost shock is not dampened in absolute terms. The dampening into consumer prices is negative and given by $-1/(\sigma - 1)$.

In the case of a Cournot oligopoly, the markup elasticity is given by $\varepsilon_q^M = -((\sigma-1)/\sigma)\mu$, and is always negative for $\sigma > 1$. That is, it is again characterized by a proportional pass-through that is lower than unity. The convexity is given by $\kappa = 2\eta + (1-\eta)/(\eta\sigma)$. It can be shown that $1/\sigma < \eta < 1$, and, hence, $\kappa > 0$. Figure 12 illustrates the relation between κ and η for $\sigma = 5$. The diagonal line represents the relation for $\sigma \to \infty$. Therefore, $\kappa < 2\eta$ always holds. In the limiting case when $\sigma \to 1$, we have $\kappa > 1 + \eta$. The part of the curve below the proportional pass-through line is ruled out by $1/\sigma < \eta$. Therefore, supply is always realized in the triangular area. It appears that absolute dampening is not likely when σ is low. The right panel illustrates the level sets for the proportional cost pass-through rate

Figure 12: Elasticity and Convexity in the Case of Cournot Oligopoly



Notes: APT and PPT stand for one-to-one absolute and proportional cost pass-through into prices, respectively. The left panel illustrates the demand manifold in the case of oligopolistically competitive behavior. The right panel illustrates the implied cost pass-through rates into prices.

$((1-\eta)/(2-\kappa))$ in the (σ, μ) space.

G Data Description

We construct our dataset mainly from the reported figures and tables in the World Energy Outlook published by the IEA (IEA, 2017) and OPEC Annual Statistical Bulletin (OPEC, 2017).

Market shares. We calculate the share of oil in global expenditure on energy based on Figure 19 in WEO (IEA (2017), Chapter 2). Corresponding tables are available online[18] and the required input from these tables are presented in Table 1. According to OPEC (2017), OPEC's share in global oil supply is 0.45 in 2016 (Table 3.6). We assume that this share applies in all scenarios. Applying this ratio to Table 1 leads to the market shares presented in Table 1.

[18]See Annex A in WEO 2017 IEA (2017) .

Table 1: Global Energy Expenditure by Fuel and WEO Scenario (bln. $ 2016)

	NPS				SDS			
	Oil	Electricity	Coal	Gas	Oil	Electricity	Coal	Gas
2016	2758.2	2355.6	232.8	515.3	2758.2	2355.6	232.8	515.3
2025	4291.4	3206.1	294.9	848.7	4003.2	3232.3	369.0	839.5
2030	4659.2	3617.7	305.2	968.0	3866.8	3746.5	427.8	989.4
2035	4919.7	3991.6	307.4	1076.1	3525.3	4139.2	429.8	1133.6
2040	5164.6	4294.7	305.1	1175.9	3205.9	4519.6	414.9	1212.7

Table 2: OPEC's Market Share

	Excluding Electricity		Including Electricity	
	NPS	SDS	NPS	SDS
2016	0.353	0.353	0.212	0.212
2025	0.355	0.346	0.223	0.213
2030	0.353	0.329	0.219	0.193
2035	0.351	0.312	0.215	0.172
2040	0.349	0.298	0.212	0.154

Table 3: Oil Demand (mega barrels/day)

	2016	2025	2040
NPS	93.9	100.3	104.9
CPS	93.9	104.1	118.8
SDS	93.9	92.4	72.9

Annual extraction. Table 4.1. in WEO (IEA, 2017) presents current and future oil demand by WEO scenarios for 2016, 2025 and 2040. This information is summarized in Table 3. According to the figures in OPEC (2017), OPEC's average crude oil production in 2016 was 33280 thousand barrel/day, which corresponds to an annual oil production of 12 billion barrels. This corresponds to 35% of global oil demand in 2016 (see Table 3). We assume that this share applies in all scenarios, and obtain OPEC's extraction in 2025 and 2040 by future WEO scenarios. We obtain the extration for the years in between by linear interpolation.

Reserves to extraction ratio. According to OPEC (2017, page 6), global proven crude oil reserves is 1492 billion barrels at the end of 2016, and OPEC Members own 81.5% of this reserves amounting to 1217 billion barrels at the end of 2016. Given OPEC's annual oil production of 12 billion barrels in 2016, the reserves-to-extraction ratio for OPEC is over 100 years. There are various concerns about these reported reserve levels. According to Owen et al. (2010), the calculation of remaining reserves depends on the grade and type of oil, as well as on the reporting framework. Furthermore, financial or political agendas, OPEC's reserve dependent production quota rule, and lack of third party auditing on these figures might result in intentional mis-reporting. Hence, Owen et al. (2010) argue that the volume of commercially-exploitable oil will decline much more rapidly. In our calculations, we use the estimations for proved and probable oil reserves (most likely estimates for existing oil fields) by Rystad, which is 387 billion barrels.[19]

[19] `https://www.rystadenergy.com/newsevents/news/press-releases/2017-annual-oil-recoverable-resource-review`

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