Ifo Institute – Leibniz Institute for Economic Research at the University of Munich

ifo Working Papers

Fossil Resource Market Power
in General Equilibrium

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Ifo Working Paper No. 197

March 2015

Revised March 2020

Fossil Resource Market Power in General Equilibrium*

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First version: March 2015

This version: 31 March 2020

Abstract

We examine market power in the supply of a crucial exhaustible resource accounting for the resulting interplay between the resource and the capital market. Employing a two-country model with international trade we investigate new supply motives from the general-equilibrium feedbacks into the monopolist's extraction decision and from asset holdings of the resource-rich country. Recognizing the influence of resource supply on capital returns can lead the monopolist to accelerate or postpone extraction while the influence on capital accumulation poses an incentive to accelerate extraction and to exploit the importers' increased future resource addiction. Overall, in the reference calibration the conventional conservationist bias of resource market power is reversed. The general-equilibrium supply motives substantially alter the monopolist's reaction to more competitive capital-intensive resource substitutes, demonstrating the robustness of our observations to future technological change. Similarly, these supply motives may reverse the effects of a future tax on the exporting countries' asset holdings.

JEL codes: D42; D58; D9; Q3
Keywords: Market power, fossil resources, general equilibrium, capital market, sovereign wealth funds

*This work was supported by the German Federal Ministry of Education and Research (Project No. 01LA1120A).

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1 Introduction

Since the industrial revolution the use of fossil resources is playing a key role in the production of goods and driving economic growth in industrialized countries, as well as in emerging economies. This is especially true for oil but also for other non-renewable resources like rare earths which become increasingly important for the global economy due to the wide-spread diffusion of electronic devices and digital technologies. The substitutability of oil in the transportation sector, especially with regard to freight and air transport, or of rare earth metals in the production of many goods like permanent magnets for generators is still limited, in spite of technological advancements. From an economic perspective, the degree of complementarity between fossil resources and other production factors, in particular capital and labor, at the macro level, is still enormous. The use of these important resources increases the productivity of the other production factors and, thus, e.g. the returns on capital.[1] Also, fossil resources play an important role for capital accumulation and the long-term growth path.[2] In turn, a steep growth path, e.g. recently by emerging economies, fuels additional demand for the resources themselves and resulting price increases.[3] Overall, these particular fossil resources have widespread effects on incomes, prices and expected returns in the world economy.

At the same time, deposits of these non-renewable resources are geographically quite concentrated and their markets exhibit a great degree of supply-side market power.[4] In the present study we combine both aspects in a novel general equilibrium ("GE") approach. We account for the role of these resources in the global economy and study its implications for market power and the supply behavior of the exporting countries.[5]

[1]Cf. Hamilton (1983, 2013), Kang et al. (2014), Cunado and Perez de Gracia (2014), Kilian (2009).

[2]Cf. Berk and Yetkiner (2014), Stern and Kander (2012) (empirical), and Stiglitz (1974) (theoretical).

[3]Cf. Kilian and Hicks (2013) and Fouquet (2014).

[4]In 2017, the market share of OPEC in crude oil was 43.7%. Almost a third of that controlled by Saudi Arabia, giving it a high leverage within the cartel. Also considering countries, which coordinate with OPEC informally under the label "OPEC+" like Russia, raises the market share up to 64.9%. But OPEC's share of low-cost oil is higher and recent low oil prices raise the question if the U.S. market share (some 15%), based on more expensive shale oil, will be persistent (cf. EIA 2020). China's market share in rare earth metals was around 85% in 2016 (cf. Zhou et al. (2017)). But the long-term development of Chinese market power seems less clear because of possible alternative sources (cf. Massari and Ruberti (2013), Packey and Kingsnorth (2016), Pothen (2018)).

[5]To ensure a clear exposition and in order to focus on the general implications for market power

We identify and examine additional supply motives which go beyond a conventional partial-equilibrium ("PE") reasoning, and discuss the underlying mechanisms and the role of these motives for the supply policy theoretically and numerically. The profound differences between PE and GE which we find in our analysis of future technological progress with respect to the substitutability of the resource and for the effect of a capital income tax on the exporting country illustrates the policy relevance of our observations.[6]

Specifically, we introduce a two-period GE framework with a single resource-exporting country E with market power and a resource-importing country I, where final good production is taking place. The framework includes limited substitutability between the resource and capital as production inputs, and endogenous savings and accumulation of physical capital. Apart from the familiar own-price effect of resource supply on the resource price, one additional motive the monopolist takes into account is how her resource supply affects capital accumulation over time, and the resulting feedback effect on resource demand due to the complementarity of production factors. By fostering capital accumulation via resource supply, the monopolist can raise the importing country's resource "addiction" in the future. This "addiction motive" contributes to an acceleration of extraction as long as acceleration fosters capital accumulation.

As a second additional supply motive, the monopolist also considers the influence of her resource supply on the return on capital assets which the exporting country invests in the capital market. In contrast to Hillman and Long (1985), this influence runs only via resource market power and explicitly not by assuming that the resource monopolist has in addition capital market power. This "capital asset motive", as we call it, is especially important because the monopolist considers not only resource revenues when benevolently maximizing country E's utility, but also capital asset holdings of her country, which provide a second simultaneous income source. These capital holdings can repre-

independently of the kind of resource, we model a resource monopolist instead of a more complex, but less transparent market structure. In doing so, we speak of a "resource" in general. For the numerical examples in Sections 4 to 6, we calibrate the model to the oil market and use the label "oil" there.

[6]In an accompanying paper, which builds upon the present analysis, Marz and Pfeiffer (2019) show that accounting for the additional supply motives of an oil monopolist in GE can also fundamentally alter her supply reaction to future carbon taxation.

sent sovereign wealth funds, as well as privately held assets.[7] The fact that the chairman of Saudi Arabia's main sovereign wealth fund PIF has been recently appointed as head of the kingdom's oil company Saudi Aramco (cf. El Gamal and Barbuscia (2019)), the ownership of which is in turn set to be transferred to PIF as part of an overarching economic transformation plan (cf. Roll (2019)), underlines the plausibility of this integrated view on both income sources. Depending on the development of the resource exporting country's capital holdings over time, accounting for the effect of oil supply on country E's capital asset returns can provide an incentive to accelerate or postpone extraction.

Overall, the additional supply motives in GE can, in principle, postpone or accelerate resource extraction relative to a conventional monopolist in partial equilibrium (cf. Stiglitz (1976) and Dasgupta and Heal (1979) for PE fossil resource monopoly). The conservationist bias, which has inspired the phrase of the monopolist being "the conservationist's friend" (Solow, 1974) can be reinforced, dampened or reversed by the additional supply motives. For the reference calibration of our model, indeed, we find that for the full GE monopoly present extraction is about 10 percent higher than for a competitive resource market. The addiction motive strongly contributes to acceleration of extraction (+25 percent in present extraction rel. to competition), which is in turn dampened by the capital asset motive (-15 percent in present extraction rel. to competition) in this case.

We subsequently examine a scenario in which future technological progress (understood as an increase in substitutability of the scarce resource by rather abundant capital) alters the role of the resource in the world economy and capital-intensive substitutes (like renewable energy sources paired with electric vehicles in transport) become more competitive to the fossil resource sector, thus reducing the scope of resource market power. We show that the GE supply motives substantially affect how this kind of technological change impacts the timing of resource extraction. In the context of climate change, e.g., the timing of carbon emissions is a crucial determinant of overall climate damages. With

[7] Countries exporting fossil fuel resources often dispose of considerable sovereign wealth funds. In the case of oil, the funds of the United Arab Emirates ($ 1,213 billion) and Saudi Arabia ($ 835 billion) are the two biggest such sovereign asset stocks among OPEC countries (SWFI 2020). Beyond official sovereign wealth funds, all other kinds of petrodollar bank deposits are invested in some manner in the capital market, very often in the industrialized countries.

resource market power, extraction is postponed as future technological progress raises the elasticity of future resource demand[8], in contrast to an acceleration of extraction by a competitive resource sector which disregards the elasticity of demand and only reacts to a decrease in the future resource price. But a monopolist who accounts for GE feedbacks in her perception of the elasticity of resource demand (i.e., the addiction motive) exhibits a substantially weaker postponement of extraction than her PE counterpart: present extraction decreases by about a third less for an increase of the future elasticity of factor substitution from the reference calibration of 0.96605 to 1. Additionally accounting for the capital asset motive in GE leads to an even weaker postponement. It is only about half as strong as in PE in this example. This analysis also indicates that the discussed GE supply motives a likely to stay important even in a scenario where future technological progress substantially changes the role of the resource in the world economy.

Moreover, we show that the additional GE supply motives can significantly affect the impact of a future capital income tax by the resource importing countries on capital assets owned by the exporting countries relative to PE reasoning. This policy measure has been proposed by Sinn (2008) as an alternative to carbon taxation which is supposed to avoid the disadvantage of an undesired acceleration of extraction ("green paradox" effect). For the reference calibration and a future capital income tax of 20 percent, our GE monopolist in fact exhibits an increase in present extraction by some 10 percent in contrast to a decrease by approx. 3 percent by her PE counterpart.

For our analysis, we build upon previous steps towards a GE perspective in the literature on fossil resource extraction under market power. Hoel (1981) postulated an unspecified influence of a resource monopolist's decision on the interest rate in an otherwise PE model, disregarding the associated capital stock dynamics. Hassler et al. (2010) also incorporate an influence of the resource supplier on capital returns, but lack the intertemporal optimization of supply. Hillman and Long (1985) bring forward a GE model, where the interest rate is chosen by a resource exporter with market power on both, the resource

[8]The effect that a higher (exogenous) future elasticity of resource demand implies slower extraction by a resource monopolist has been already discussed by Stiglitz (1976) from a PE perspective.

and the capital market. However, the assumption of capital market power by a single or a group of countries like OPEC seems rather strong. Thus, they leave the impact of resource supply on the interest rate directly over the production technology, as well as the corresponding effect of capital on factor prices and all resulting repercussions out of the picture. But this interaction of resource and capital, which we are interested in, arises naturally in our GE framework. Moussavian and Samuelson (1984) incorporate a fossil resource monopolist's influence on the capital accumulation in their model. Our analysis of the "addiction motive" is consistent with this study and yields, in contrast to Moussavian and Samuelson (1984), unambiguous effects on extraction due to our finite time horizon. Besides the studies mentioned above, however, resource supply with market power is usually, from Stiglitz (1976) to Fischer and Laxminarayan (2005), analyzed with an exogenous and constant interest rate and capital stock. We, therefore, provide a comprehensive account of a resource monopolist's reasoning and extraction behavior in GE which builds on aspects from the previous literature on the special complementarity-driven role of the resource and identifies completely new aspects. Marz and Pfeiffer (2019) build upon the present analysis and study the implications which the supply motives, and the asset motive in particular, have for the supply reaction of the resource monopolist to (future) climate policy by the industrialized countries.

The GE settings of van der Meijden et al. (2015) and van der Ploeg (2016) are very close to ours, but feature perfectly competitive resource markets. Also, Long and Stähler (2014) addresses GE aspects under perfect competition. All three papers examine unintended consequences of climate policy and their focus on perfect competition prevents them from investigating implications of GE feedbacks for the resource supply behavior. Gaitan et al. (2006) also propose a GE model of a competitive resource market with a focus on iso-elastic resource demand instead of our more general approach.

We start by introducing the model and the novel approach of a "conditional market equilibrium" to derive equilibrium relationships between the resource supply path and market outcomes in Section 2. In Section 3, we examine the supply behavior of the resource monopolist and the identified general-equilibrium supply motives, followed by a numerical illustration in Section 4. In Sections 5 and 6 we investigate the implications of the new general-equilibrium supply motives for analyzing technological progress with respect to the substitutability of the resource and for the effects of capital income taxation on resource supply. Section 7 concludes.

2 Model

We consider a general equilibrium model with two countries $m \in \{E, I\}$ and two finite periods: $t \in 1, 2$. The global resource stock $\bar{S}$ is located in the resource exporting country E. Country E exports the resource to country I in exchange for consumption goods. All households derive utility from consuming the numeraire final good.

2.1 Resource Supply

Country E's government, or its public resource company, controls the world supply of the resource R_t from the given stock $\bar{S}$. To simplify we assume: 1) no extraction costs, and 2) a binding resource stock.[9] With zero extraction costs, resource exports yield $\pi_{tE} = p_t R_t$ with the resource price p_t. Section 3 focuses on the specific resource supply decision.

2.2 Final Goods Production

In country I final goods are produced competitively using physical capital K_t, resource R_t, and labor $L_t = L = 1$ – labor is inelastically supplied and constant over time – as input factors to the concave and constant-returns-to-scale production technology $F_t = F(K_t, R_t, L)$ with positive but decreasing marginal products $F_R, F_K > 0$, $F_{RR}, F_{KK} < 0$, and complementarity of capital and resources $F_{KR} > 0$.[10] With profit-maximizing competitive final goods producers, the first-order conditions for optimal factor use (implicitly)

[9]The latter considerably simplifies the characterization of the monopolist's supply behavior. In general, with a finite time horizon and market power, a binding resource stock and incomplete extraction could be distinguished, since the monopolist might want leave some resource in the ground if resource demand is inelastic. See also the corresponding discussion in Stiglitz (1976) and Tullock (1979), and Marz and Pfeiffer (2019) for an explicit characterization of the incomplete extraction case.

[10]We assume flexible wages under full employment here.

define resource R_t^d[11]

$$\frac{\partial F_t}{\partial R_t} = F_{tR}(K_t, R_t^d) = p_t \tag{1}$$

and capital demand K_t^d

$$\frac{\partial F_t}{\partial K_t} = F_{tK}(K_t^d, R_t) = i_t \tag{2}$$

with the capital rent i_t.

2.3 Households

We assume a constant population size of 1 for both countries. Households in both countries have symmetric homothetic preferences represented by the life-time utility function $U(c_{1m}, c_{2m}) = u(c_{1m}) + \beta u(c_{2m})$ with $u'(.) > 0$ and $u''(.) < 0$ and where $\beta < 1$ denotes the utility discount factor for the respective country $m \in \{E, I\}$. The government of country E benevolently distributes resource revenues π_t to the households. The budget constraints for both periods are given by

$$c_{1E} + s_{1E} = y_{1E} \quad \text{with} \quad y_{1E} = \pi_{1E} + (1 + i_1)s_{0E} \tag{3}$$

$$c_{2E} = \pi_{2E} + (1 + i_2)s_{1E} \tag{4}$$

In country I, the representative household receives the residual profits after remuneration of capital and the resource $\pi_{tI} = F_t - p_t R_t - i_t K_t$ as labor income. The budget constraints for country I households, therefore, are $c_{1I} + s_{1I} = y_{1I}$ – again with $y_{1I} = \pi_{1I} + (1 + i_1)s_{0I}$ – and $c_{2I} = \pi_{2I} + (1 + i_2)s_{1I}$. In period 1, households in both countries hold an exogenous, non-negative capital endowment s_{0m} and decide on savings $s_{(1,m)}$ to smooth consumption, i.e. to maximize life-time utility subject to the respective budget constraints according to the Euler equation $u'(c_{1m}) = \beta(1 + i_2)u'(c_{2m})$. The Euler equation implicitly defines optimal savings s_{1m} as a function of period incomes y_{1m} and π_{2m}, and the interest rate

[11] The superscript "s" indicates *supply*, while superscript "d" means *demand*.

i_2, which households take as given (cf. Appendix A.1)[12]:

$$s_{1m} = s_{1m}(y_{1m}, \pi^{\tau}_{2m}, i_2) \quad \text{with} \quad \frac{\partial s_{1m}}{\partial y_{1m}} > 0, \quad \frac{\partial s_{1m}}{\partial \pi_{2m}} < 0, \quad \frac{\partial s_{1m}}{\partial i_2} \gtrless 0 \tag{5}$$

Since we assume homothetic consumption preferences, the marginal savings reactions with respect to changes in period incomes are independent of the household's income level. They are determined only by the discount factor β, the intertemporal elasticity of substitution $\frac{1}{\eta}$, and the market interest rate i_2.

2.4 Capital Supply

The capital endowment in period 1 is given: $K_1^s = s_{0E} + s_{0I}$. Capital supply in period 2 derives from the aggregated endogenous household savings in both countries. Capital is available for consumption at the end of each period without depreciation. Positive capital accumulation therefore implies that $s_{1E} + s_{1I} > K_1$. Given the resource constraint, future capital supply K_2^s from aggregated savings can be stated as a function of the resource supply path and the interest rate i_2 only for homothetic preferences (cf. Appendix A.2):

$$K_2^s = K_2^s(R_2, i_2) \qquad \text{with} \qquad \frac{\partial K_2^s}{\partial R_2} < 0 \qquad \text{and} \qquad \frac{\partial K_2^s}{\partial i_2} > 0 \tag{6}$$

A shift of extraction to the future transfers output and aggregate income from the first to the second period, ceteris paribus. Given the saving propensities in (5), this reduces the incentive to save. Moreover, aggregate savings unambiguously increase with a rise in the interest rate i_2, ceteris paribus, because the income effect of a change in i_2 only has a redistributive effect which cancels out for symmetric homothetic preferences.

2.5 Conditional Market Equilibrium

We now introduce the "conditional market equilibrium" as a tool that allows us to derive and discuss the supply behavior of a GE resource monopolist. Equilibrium in all markets (resource, capital, final goods) is conditional on *any* resource supply path satisfying the

[12] We generally do not exclude negative savings.

binding resource constraint. Thus, we characterize the GE influence of the supply decision on market outcomes which the monopolist as a Stackelberg leader accounts for.

The *resource market equilibrium* is characterized by the market-clearing condition

$$R_t^d(p_t, i_t) = R_t^s \quad \text{for both periods } t = 1, 2 \tag{7}$$

with resource demand derived from competitive final goods production (cf. Equations (1) and (2)) for a binding resource constraint. With given capital endowments, the *capital market equilibrium* condition in period 1 is

$$K_1^d(p_1, i_1) = K_1 = s_{0E} + s_{0I} \tag{8}$$

with capital demand from Equations (1) and (2). In period 2, the capital market equilibrium is again characterized by the market-clearing condition

$$K_2^d(p_2, i_2) = K_2^s(R_2, i_2) \tag{9}$$

where capital supply is a function of R_2 and i_2 only (cf. Equation (6)). In equilibrium, aggregate consumption (and savings) has to equal aggregate consumption possibilities, which are given from production and the capital stock in both periods:

$$\begin{aligned} c_{1E} + c_{1I} + K_2 &= F_1(K_1, R_1) + K_1 \\ c_{2E} + c_{2I} &= F_2(K_2, R_2) + K_2 \end{aligned}$$

If the resource market and the capital market are in equilibrium, then, according to Walras' law, the *market for final goods* must be in equilibrium, too. These equations implicitly define equilibrium resource prices, capital rents, and the future capital stock as functions of resource supply only. A comparative statics analysis also implicitly characterizes the reaction functions for the analysis of monopolistic supply behavior. For period 1, we totally differentiate Equations (7) and (8) while taking into account Equations (1) and (2). Solving the two resulting equations together, we observe that

$$\frac{dp_1}{dR_1} = \frac{\partial p_1}{\partial R_1} = F_{1RR} < 0 \tag{10}$$

holds due to the concavity of the production technology. Moreover, by the complementarity of capital and resources in production

$$\frac{di_1}{dR_1} = \frac{\partial i_1}{\partial R_1} = F_{1KR} > 0 \tag{11}$$

In period 2, factor price reactions to changes in extraction also include the endogenous adjustment of the capital stock K_2, and are, therefore, more complex compared to (10) and (11). By totally differentiating Equations (6), (7), and (9) while taking into account the binding resource constraint, (1), and (2), and solving the resulting equations together (cf. Appendix A.3), the market price reactions can be decomposed as follows

$$\frac{dp_2}{dR_2} = \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} = F_{2RR} + F_{2RK}\frac{dK_2}{dR_2} < 0 \tag{12}$$

$$\frac{di_2}{dR_2} = \frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2} = F_{2KR} + F_{2KK}\frac{dK_2}{dR_2} > 0 \tag{13}$$

The overall reaction of the period 2 capital stock to an increase in R_2, e.g., a postponement of extraction, $\frac{dK_2}{dR_2}$ is determined by two counteracting effects, and is generally ambiguous (cf. Equation (A.3) in Appendix A.3): on the one hand, a postponement of resource extraction causes an according increase (decrease) in future (present) output and aggregate income, and thereby reduces savings incentives (cf. (5)). On the other hand, postponement of extraction also increases the productivity of capital in period 2, that is, the interest rate i_2. Even though the income effect of the interest rate change cancels out for symmetric homothetic preferences (cf. Appendix A.2), the increase in i_2 induces a substitution effect which induces an increase in savings.

The signs of (12) and (13) are unambiguous irrespectively of the sign of $\frac{dK_2}{dR_2}$ if both countries have symmetric preferences. Thus, the direct effects of resource supply on resource price and interest rate if the capital stock was kept constant ($\frac{\partial p_2}{\partial R_2}$ and $\frac{\partial i_2}{\partial R_2}$) always outweigh the respective indirect price effects from the endogeneity of capital.

3 Resource Supply Behavior

Any changes in resource supply in either period directly influence market prices in both, the resource and the capital market, capital accumulation, or, in short, the overall equilibrium of the world economy. The conditional market analysis in Section 2.5 above illustrates this. These widespread interactions capture the particular importance of the resource as input to the world economy. We now examine the implications for the supply behavior of a supplier with resource market power. To simplify the exposition, we assume that country E, or its resource ministry/public resource company, is making the supply decision as a Stackelberg leader in the world economy to benevolently maximize the utility of households in country E.[13] The reactions of the followers are summarized and characterized by the comparative statics of the conditional market equilibrium above.

Technically, the monopolist seeks to maximize the utility of households in country E

$$\max_{R_1,R_2} u(c_{1E}) + \beta u(c_{2E}) \tag{14}$$

subject to the budget constraints (3) and (4) and the conditional market equilibrium represented by Equations (7), (8), and (9) and the corresponding equilibrium relationships between second-period resource supply and factor market prices (Equations (12) and (13)). Due to the assumption of a binding resource constraint, the monopolist's optimization problem is one-dimensional ($R_2 = \bar{S} - R_1$). Moreover, the representative household in country E makes optimal saving decisions for any set of resource income streams and interest rates taking them as given. Therefore, the Euler equation holds for

[13]It seems plausible that public resource companies are managed to serve further political goals beyond mere profit maximization. The appointment of the head of Saudi Arabia's main sovereign wealth fund as chairman of the oil company Saudi Aramco and the plan to transfer the firm to the ownership of the fund and partly privatize it as a part of the "Saudi Vision 2030" supports the idea of a common strategy integrating resource income and capital income (cf. El Gamal and Barbuscia (2019), Roll (2019)).

any resource supply path chosen by the omniscient monopolist. Thus, substituting the Euler equation into the first-order condition and simplifying the latter for the optimal resource supply path gives the modified Hotelling rule

$$(1+i_2)\left[p_1 + \frac{\partial p_1}{\partial R_1} R_1 + \frac{\partial i_1}{\partial R_1} s_{0E}\right] = p_2 + \frac{dp_2}{dR_2} R_2 + \frac{di_2}{dR_2} s_{1E} \tag{15}$$

First, note that for the familiar PE resource monopolist maximizing household life-time utility and maximizing the sum of discounted resource profits by a private resource firm is equivalent, because households smooth consumption in a separate savings decision (see also Hoel (1981)). In GE, however, this equivalence of profit maximization and utility maximization, breaks down, because the utility maximizing monopolist, apart from resource income, also considers the capital income of her constituency and her influence on capital returns, thus pursuing a twofold strategy.[14]

To better understand the implications of the GE feedback effects for the monopolist's extraction behavior, we first relate the modified Hotelling rule to monopolistic resource supply in a conventional PE setting (Stiglitz, 1976). Using (12) and (13), we rewrite condition (15) to separate familiar terms from new ones, which we discuss in the following:

$$(1+i_2)p_1\left[1 - \frac{1}{\epsilon_{R_1,p_1}}\right] + (1+i_2)\frac{\partial i_1}{\partial R_1} s_{0E} = p_2\left[1 - \frac{1}{\epsilon_{R_2,p_2}}\right] + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} R_2 + \frac{di_2}{dR_2} s_{1E}$$

where the price elasticity of (resource) demand is positively defined as

$$\epsilon_{R_t,p_t} = -\frac{1}{\frac{\partial p_t}{\partial R_t}\frac{R_t}{p_t}} \tag{16}$$

[14] Still, there appears no derivative of the market discount factor $(1+i_2)$ in the modified Hotelling rule (15), since $(1+i_2)$ stems from the Euler equation and separate savings decision of the households who act as price takers on the capital market. By contrast, a profit maximizing monopolist who recognizes her cross-market influence on the capital market would directly take into account that postponing extraction increases the interest rate i_2, but would neglect her influence on households' capital income and would not pursue the capital asset motive. The Hotelling rule for such a profit maximizing monopolist reads

$$(1+i_2)\left(p_1 + \frac{\partial p_1}{\partial R_1} R_1\right) = p_2 + \frac{dp_2}{dR_2} R_2 - \frac{p_2 R_2}{1+i_2}\frac{di_2}{dR_2}$$

The third term on the right captures the marginal increase in the market discount factor, reduces the future marginal resource value, and, thus, contributes to an acceleration of extraction.

Obviously, the monopolist takes into account the own-price effect of resource supply which gives an incentive to deviate from the competitive market supply path if $\epsilon_{R_1,p_1} \neq \epsilon_{R_2,p_2}$. If $\epsilon_{R_1,p_1} < \epsilon_{R_2,p_2}$ in the competitive outcome (and $\frac{\partial \epsilon_{R_t,p_t}}{\partial R_t} < 0$), the PE monopolist extracts more slowly than the competitive market. This observation has inspired the phrase of the monopolist as the "conservationist's friend" (Solow, 1974). In contrast, for iso-elastic demand ($\epsilon_{R_1,p_1} = \epsilon_{R_2,p_2}$) and no extraction costs in PE, this incentive to deviate disappears. With respect to the bracketed terms on both sides of the modified Hotelling condition, these considerations in principle still hold, even though the inequality in the elasticity of resource demand along the competitive supply path may not only arise from $R_1 \neq R_2$ but also from $K_1 \neq K_2$. However, a resource supplier with market power who only accounts for the own-price effect of supply in GE would have to be considered "naive" (like in Moussavian and Samuelson (1984)).

3.1 The Endogeneity of the Future Resource Demand Curve and the Addiction Motive

We now examine the supply incentive from accounting for the endogenous reaction of the future capital stock K_2 to supply changes (cf. Equation (A.3) in Appendix A.3) and for the complementarity of capital and resources in production. Neglecting the savings related terms in (15), the Hotelling condition simplifies to

$$(1+i_2)p_1\left[1-\frac{1}{\epsilon_{R_1,p_1}}\right] = p_2\left[1-\frac{1}{e_{R_2,p_2}}\right] \tag{17}$$

In a more consistent way, we can derive this Hotelling condition by assuming that the monopolist only understands the actual relationship between resource supply and demand defined by (12), but not her cross-market influence on the interest rate. The "effective" price elasticity of resource demand e_{R_2,p_2}, which in contrast to ϵ_{R_2,p_2} from (16) also includes the feedback effect from the capital dynamics, is defined using (12)

$$e_{R_2,p_2} = -\frac{1}{\left(\frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2}\right)\frac{R_2}{p_2}} \gtrless -\frac{1}{\frac{\partial p_2}{\partial R_2}\frac{R_2}{p_2}} = \epsilon_{R_2,p_2} \qquad for \quad \frac{dK_2}{dR_2} \gtrless 0 \tag{18}$$

Since $\frac{\partial p_2}{\partial K_2} > 0$ due to the complementarity of resources and capital, effective resource demand becomes less (more) elastic if the monopolist accounts for the endogeneity of K_2 and $\frac{dK_2}{dR_2} < 0$ ($\frac{dK_2}{dR_2} > 0$). This observation yields the following proposition:

Proposition 1. *Taking into account the feedback of capital dynamics on inverse resource demand establishes an incentive to accelerate (postpone) extraction if* $\frac{dK_2}{dR_2} < 0$ *(*$\frac{dK_2}{dR_2} > 0$*).*

From (12) we know that $\frac{dp_2}{dR_2} < 0$ for countries with symmetric homothetic preferences, irrespective of the sign of $\frac{dK_2}{dR_2}$. However, if the future capital stock negatively depends on future resource supply ($\frac{dK_2}{dR_2} < 0$), then the effective negative own-price effect that the "non-naive" monopolist considers is even stronger than the familiar partial equilibrium own-price effect as discussed before, and vice versa. This is directly reflected in the corresponding difference between the effective and the partial price elasticity of resource demand (e_{R_2,p_2} vs. ϵ_{R_2,p_2}). The incentive to unambiguously accelerate extraction arises in this case because by doing so the monopolist boosts production and savings in period 1 and takes advantage of the increase in resource demand in period 2. The indirect feedback via the endogeneity of capital accumulation enables the monopolist not only to exploit but even to manipulate the dependency or "addiction" of the resource importing countries on fossil resources and introduces what we may call an "addiction motive".

That a negative relationship between capital accumulation and future resource supply constitutes an incentive to accelerate extraction, in principle, has also been pointed out by Moussavian and Samuelson (1984)with a much simpler representation of the capital dynamics: They assume that a fixed share of present income is saved and adds to the existing capital stock. Thus, accelerating (postponing) extraction always increases (decreases) the future capital stock without depreciation. In our framework, in contrast, savings are a function of first and second period income and the interest rate (cf. (A.1) in Appendix A.1), so that $\frac{dK_2}{dR_2}$ may, in general, be positive or negative. This implies that the extraction incentive established by the explicit consideration of the capital dynamics in our setting can also run in the opposite direction: If the capital stock increased with a postponement of extraction ($\frac{dK_2}{dR_2} > 0$), the induced upward shift in resource demand would attenuate the negative own-price effect, and the monopolist would have an incentive to postpone extraction relative to her naive counterpart. Thus, depending on the sign of $\frac{dK_2}{dR_2}$, we find unambiguous extraction incentives from internalizing the endogeneity of the future capital stock. This is in contrast to Moussavian and Samuelson (1984) due to their infinite time horizon, even though they focus on the case $\frac{dK_2}{dR_2} < 0$.[15]

The additional supply incentive in period 2 has direct implications for the comparison between the monopolistic and the competitive resource market outcome. In particular, if we have $\epsilon_{R_1,p_1} < \epsilon_{R_2,p_2}$ (and $\frac{\partial \epsilon_{R_t,p_t}}{\partial R_t} < 0$) along the competitive supply path, the monopolist should extract more conservatively from the traditional or familiar perspective. However, this needs no longer hold true if the monopolist accounts for the capital dynamics and we have $\frac{dK_2}{dR_2} < 0$. The conservationist bias from market power is at least attenuated, or even completely reversed depending on the strength of the additional feedback effect from capital dynamics. Moreover, the coincidence of monopolistic and competitive resource supply for iso-elastic resource demand in the sense that $\epsilon_{R_1,p_1} = \epsilon_{R_2,p_2}$ breaks down, as can directly be observed from (18).

3.2 The Capital Asset Motive

The last terms in the modified Hotelling condition (15) reflect that the benevolent monopolist recognizes that additional resource supply in either period increases the marginal productivity of capital and, thereby, generates a higher return on her constituency's capital asset holdings. We call this capital income component in the benevolent monopolist's supply decision the "(capital) asset motive".

With the asset motive the marginal resource value MV_t to the monopolist in either period

[15] With an infinite time horizon in Moussavian and Samuelson (1984), a shift in the extraction path does not only trigger a change the subsequent period's capital stock but in all future periods. Due to rising marginal resource productivity over time, a postponement of extraction might lead to more, but also later, capital accumulation in the future. Trading-off these counteracting effects may lead the monopolist to slow down extraction compared to the naive monopolist, and thereby to reverse the addiction motive.

is no longer given by the (effective) marginal resource revenue MR_t only:

$$MV_t = p_t + \frac{dp_t}{dR_t} R_t + \frac{di_t}{dR_t} s_{(t-1)E} = MR_t + \frac{di_t}{dR_t} s_{(t-1)E} \tag{19}$$

with $\frac{dp_1}{dR_1}$ from (10), $\frac{di_1}{dR_1}$ from (11), $\frac{dp_2}{dR_2}$ from (12), $\frac{di_2}{dR_2}$ from (13). With no closed-form solution for the optimal extraction path, we characterize the additional intertemporal trade-off by comparison to the Hotelling condition (17) and find the following:

Proposition 2. *In each period, the asset motive introduces an incentive to extract more (less) if $s_{(t-1)E} > 0$ ($s_{(t-1)E} < 0$). The intertemporal effect on extraction incentives depends on the development of the resource income component over time relative to that of the (effective) marginal resource revenue. A redistribution of capital endowments to country E always creates an incentive to accelerate extraction.*

From a static perspective, as long as the monopolist's constituency has positive capital holdings abroad ($s_{(t-1)E} > 0$), the asset motive adds to the marginal resource revenue MR_t and thereby creates an incentive for the monopolist to increase period resource supply.[16] The opposite holds true for a debt position of country E, which due to the binding budget constraints, however, is only possible in one period.

With a binding resource constraint increasing resource supply in both periods is, of course, not feasible. The asset motive, therefore, introduces an additional intertemporal trade-off to the monopolist's supply decision and provides a new perspective[17] on the role of by now significant capital holdings of resource rich countries.[18] To discuss the implications of this asset related intertemporal trade-off and the second part of the above proposition,

[16]Calvo and Findlay (1978) and Hassler et al. (2010) also note this for positive capital holdings.

[17]A relationship between the capital asset holdings and the (dynamic or intertemporal) supply decision of resource owners has also been pointed out by van den Bremer et al. (2014). However, they consider a competitive resource market and show that with uncertain but correlated future resource prices and capital market returns the value of the resource stock underground should optimally be considered as part of the asset portfolio which resource rich countries hold. But this reasoning is completely different to the asset motive of a resource supplier with market power and her internalized influence on the capital interest rate, which we analyze here.

[18]The publicly available information about the volume of the sovereign wealth funds (cf. SWFI (2020)) provides presumably a lower bound estimate of total capital asset holdings of resource-rich countries as it does not contain private capital holdings.

we rewrite condition (15) using (16) and (18):

$$(1+i_2)p_1\left[1-\frac{1}{\epsilon_{R_1,p_1}}\right]-p_2\left[1-\frac{1}{e_{R_2,p_2}}\right]=\frac{di_2}{dR_2}s_{1E}-(1+i_2)\frac{\partial i_1}{\partial R_1}s_{0E} \tag{20}$$

If Hotelling condition (17) holds, the left side of this equation will be zero which implies that the (effective) marginal resource revenue grows at the rate of interest i_2 over time. The right side will be zero only if the present value of the future capital income component corresponds to that of the present capital income component, that is, if the capital income component grows exactly at the rate of interest i_2 over time, too. However, for example, if the monopolist's constituency does not hold capital assets in the first period (i.e. $s_{0E}=0$) and households still save for reasons of consumption smoothing ($s_{1E}>0$) the right side will be positive. The asset motive then only adds to the second period marginal resource revenue. This implies that the marginal value of the resource in terms of gains in capital income grows more strongly over time than the marginal resource revenue, and future resource supply is more valuable to the monopolist with pursuing the asset motive than without. In this case, the asset motive unambiguously establishes an incentive to postpone extraction to the second period. In general, however, the right side of Equation (20) may be positive or negative if extraction is such that Hotelling condition (17) holds.

To understand the role of a redistribution of capital endowments to country E again assume that Hotelling condition (17) holds and the monopolist's constituency does not hold capital assets in the first period (i.e. $s_{0E}=0$). The left side of Equation (20) will be zero while the right side will be positive (for $s_{1E}>0$) so that the monopolist pursuing the asset motive has an incentive to deviate and to postpone extraction. Due to homothetic symmetric consumption preferences in both countries, if we redistribute some of the given capital endowments K_1 to country E this redistribution alone will not affect any of the aggregate, or macro, variables in the economy, i.e. market prices and capital stock K_2. Thus, the left side of (20) does not change but the right side does. The reason is that while neutral at the aggregate level, the redistribution changes the savings of both countries: Because country E gains capital income in the first period at the expense of country I, households in country E save more while households in country I reduce their savings exactly by the same amount, given the savings propensities derived in Appendix A.1. Note that the redistribution capital endowments is also neutral with respect to the savings reactions to income changes as they only depend on market prices and income streams.[19] Therefore, we can decompose the second-period asset holdings of country E as a linear function of its asset endowment for a given extraction path and given K_1:

$$s_{1E}(s_{0E}) = s_{1E}(0) + \frac{\partial s_{1E}}{\partial s_{0E}} s_{0E} = s_{1E}(0) + \frac{\partial s_{1E}}{\partial y_{1E}} \frac{\partial y_{1E}}{\partial s_{0E}} s_{0E} = s_{1E}(0) + \frac{\partial s_{1E}}{\partial y_{1E}} (1 + i_1) s_{0E}$$

with the savings level for a zero capital endowment of country E $s_{1E}(0)$. Country E's savings reaction to increases in the first period income $\frac{\partial s_{1E}}{\partial y_{1E}}$ is a positive constant (lower than unity) for a given extraction path. Using this relationship between capital endowment and savings, we find that[20]

$$\left. \frac{\partial \left(\frac{s_{1E}}{s_{0E}} \right)}{\partial s_{0E}} \right|_{K_1} = \frac{1}{s_{0E}} \left[\frac{\partial s_{1E}}{\partial y_{1E}} (1 + i_1) - \frac{s_{1E}}{s_{0E}} \right] = - \frac{s_{1E}(0)}{s_{0E}^2} < 0 \tag{21}$$

Overall, increasing country E's first-period capital holdings s_{0E} upon redistribution increases both elements on the right side of Equation (20) but disproportionally strengthens the capital income component in the present over the one in the future because households only save a fraction of the additional first-period income. Thus, given our original assumptions, the right side of Equation (20) overall decreases upon redistribution of capital endowments. This implies that the redistribution *reduces* the incentive of the monopolist pursuing the asset motive to deviate from Hotelling condition (17) and to postpone extraction. Due to the unambiguous sign in (21) and the universal neutrality of the endowment redistribution with respect to market prices and the capital stock K_2 resulting from the assumption of symmetric homothetic preferences in both countries, this obser-

[19] In fact, holding some extraction path (R_1, R_2) fixed determines every variable in the model like the market prices, the capital stock in period 2, and the sensitivity of the interest rate with respect to resource supply for symmetric countries (cf. (13)), except for the households' savings in both countries $(s_{1E},\ s_{1I})$.

[20] We use the notation $|_{K_1}$ here to point out that we consider a redistribution of capital endowments and no increase in aggregate capital endowment.

vation holds true irrespective of the original level of s_{0E} and s_{1E}, and also irrespective of the original extraction path.

Finally, to briefly elaborate on the implications with respect to the deviation from the competitive outcome introduced by market power consider (20) again but assume that $(1+i_2)p_1 = p_2$, i.e. that the competitive market equilibrium holds. Obviously, the benevolent monopolist following Hotelling condition (15) potentially has two separate incentives to deviate from the competitive outcome: 1) the development of the price elasticity of resource demand over time, and 2) the development of the capital income component, or asset motive, over time. Even if we have $\epsilon_{R_1,p_1} = e_{R_2,p_2}$ along the competitive extraction path, so that the left side of (20) would be zero, and the non-benevolent monopolist from section 3.1 would choose the competitive extraction path, the asset motive could still constitute an incentive either to postpone or to accelerate extraction.

Overall, the extraction behavior of the benevolent monopolist is characterized of three separate components which may or may not be counteracting and may or may not establish a monopolistic extraction bias. As a result, the consideration of the familiar own-price effects of resource supply, of the addiction motive, and of the asset motive together can strengthen, dampen, or reverse the conservationist bias of monopolistic resource extraction relative to the competitive outcome which was pointed out in the early resource economics literature. Moreover, without extraction costs, iso-elastic demand, neither in the more traditional sense of $\epsilon_{R_1,p_1} = \epsilon_{R_2,p_2}$ nor in the sense of $\epsilon_{R_1,p_1} = e_{R_2,p_2}$, is sufficient for the monopolist's supply to coincide with the competitive outcome.

4 Numerical Analysis

To illustrate the results in a numerical exercise we assume CES production $F(K_t, R_t) = A\left[\gamma K_t^{\frac{\sigma-1}{\sigma}} + \lambda R_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma-\lambda)L^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$ with oil as the exhaustible resource, total factor productivity $A > 0$, and the elasticity of factor substitution σ. The period utility function is symmetric and homothetic: $u(c_{tm}) = \frac{c_{tm}^{1-\eta}-1}{1-\eta}$ for $\eta \neq 1$ and $u(c_{tm}) = ln(c_{tm})$ for $\eta = 1$ with the constant elasticity of intertemporal substitution $1/\eta$. Table 1 shows the magnitudes of present extraction for a reference ballpark calibration (for details, see Appendix C) and a corresponding setting with Cobb-Douglas production ($\sigma = 1$). The

		Reference case $\sigma = 0.96605$				**Cobb-Douglas** $\sigma = 1$			
		R_1	K_2	s_{1E}	i_2	R_1	K_2	s_{1E}	i_2
A	Full GE monopoly	**0.2210**	406.7	8.67	2.99	0.2097	464.5	11.1	3.79
B	GE mon. w/o assets	**0.2498**	459.9	6.43	2.24	0.2188	476.2	11.2	3.75
B_{PM}	$\rightarrow$ corr. PE mon.	**0.1593**	459.9	6.43	2.24	0.2048	476.2	11.2	3.75
B_{PC}	$\rightarrow$ corr. PE comp.	**0.1875**	459.9	6.43	2.24	0.2048	476.2	11.2	3.75
C	GE competition	**0.2002**	400.4	8.92	3.08	0.2053	463.4	11.1	3.81

Table 1: Equilibrium outcomes of different market configurations for the reference calibration and Cobb-Douglas production (total resource stock $\bar{S} = 0.25$). The "corresponding PE" cases are constructed with K_2 and i_2 as exogenous inputs.

full GE monopoly (A) with all discussed supply motives (cf. (15)) exhibits lower present extraction R_1 than a GE monopolist who neglects oil supply's influence on her own capital asset returns (B), i.e. the "capital asset motive", (thereby following condition (17)) in both parameter settings. The capital asset motive contributes to a slow down of extraction here because the benefits outweigh the costs: the benefit from a higher future capital return (as $\frac{di_2}{dR_2} > 0$), which, in addition, rewards higher savings s_{1E} by the exporting country, is larger than the disutility from a deviation from period oil incomes of (B) and from a reduction in present capital income (due to $\frac{\partial i_1}{\partial R_1} > 0$). But, nevertheless, both variants of the GE monopolist extract oil more quickly than the competitive oil market in GE (C).[21] Therefore, the additional GE supply motives reverse the notion of the monopolist as "the conservationist's friend" here. To show the effect of the monopolist internalizing capital accumulation and the implications for oil demand ("addiction motive"), we compare the GE and PE variants of oil monopoly while neglecting the asset motive, i.e. we compare (B) to (B_{PM}). We construct the corresponding PE monopoly (B_{PM}) by using the equilibrium future capital stock K_2 and interest rate i_2 of its GE counterpart as an exogenous input to block the effects of deviating capital accumulation. The comparison shows that the GE addiction motive contributes to a substantial acceleration of extraction (+25 percent in present extraction R_1 relative to the competitive

[21]Setting (C) largely corresponds to van der Meijden et al. (2015), who do not employ market power and assume asymmetric preferences (and a different calibration) to study the effects of climate policy.

case) which fosters capital accumulation. The latter compensates the monopolist for a lower future oil quantity sold and a lower present oil rent by a higher future scarcity rent.

In the Cobb-Douglas case, the magnitudes differ, but the general relation of the different cases to each other is pretty similar. In addition, we see, that PE monopoly (B_{PM}) and PE competition (B_{PC}) – which correspond in their (exogenous) future capital stock K_2 and the resulting demand curves to the GE monopolist without asset motive (B) – do exhibit the same extraction path due to iso-elastic oil demand for Cobb-Douglas technology in PE (in contrast to the reference case). But the corresponding GE monopolist (B) deviates from that since in GE future oil demand incorporates the capital market dynamics and is, therefore, not iso-elastic, as discussed in Section 3.

5 The Role of Future Technological Progress

We have shown that, by considering GE feedback effects between the resource market and the capital market, a resource supplier with market power obtains additional supply motives, which substantially modify her extraction path. Now we illustrate how these GE supply motives also change the impact of a specific kind of future technological progress, namely an increase in the substitutability of the scarce resource by rather abundant capital, and of a resulting change in the role of the resource in the world economy on the timing of resource extraction. In the context of the climate debate and fossil fuels like oil, the timing of carbon emissions is an important determinant of overall climate damages. The progressing spread of electric vehicles in transport and of renewable energy sources for power and heating are examples for an increasing competitiveness of capital-intensive substitutes which more and more challenges the powerful role of oil in the global economy and reduces OPEC's market power.[22] This is likely to change the interaction of oil market and capital market, but also the nature of oil demand itself. At the same time, the material use of oil in petrochemical products can remain for a longer period of

[22]Resource market power can be constrained by additional resource suppliers or by improving substitutes from outside the specific resource market. Since we deal primarily with interactions of the resource market and the capital market, we focus on changes in these interactions here.

time. We capture this kind of developments by assuming an exogenous increase in the future elasticity of substitution of oil by capital σ_2 in the aggregate (CES) production function. At the same time the following exercise shows that the additional GE supply motives continue to play a significant role even in this scenario of technological change.

Starting with the different market structures at the reference calibration of Table 1, Figure 1 illustrates the effects of an increase in the future elasticity of substitution σ_2 on present extraction R_1. An increase in σ_2 reduces the future marginal product, i.e. price, of oil. Thus, in a competitive market, extraction shifts to the present to satisfy the competitive Hotelling rule (red curves, panels (a) and (b)). Since the capital endowment is much larger than the resource endowment (cf. Appendix C), the increase in factor substitutability also boosts future output and globally diminishes the incentive to save. The reduction in the future capital stock K_2 additionally reinforces the resource price reduction via complementarity of factors. Thus, the GE reaction of the competitive market ((C), solid red curves) is around ten times stronger than its PE counterpart where the future capital stock K_2 is assumed to stay fixed ((C_{PK}), dashed red curves).

At the same time, the increase in σ_2 makes future oil demand more elastic, i.e., a marginal increase in supply goes along with a smaller marginal decrease in the price on the infra-marginal units and the marginal oil revenue turns out higher than before. Accounting for that, the monopolist (panels (c) and (d)) postpones oil extraction (similar to the discussion of an exogenous change in the demand elasticity by Stiglitz (1976)). When "switching" from PE to GE for the monopoly, not only the capital market (i_1, i_2, K_2) becomes endogenous, but also the strategic reasoning of the monopolist, i.e. her Hotelling rule, changes by accounting for the additional GE feedbacks.[23] Both aspects influence the extraction decision and the monopolist's reaction to future technological progress in σ_2. We disentangle them graphically in the following.

We first compare the GE monopolist without an asset motive (B)[24] with a PE monopolist

[23]By contrast, the Hotelling rule of competitive price takers does not change from PE to GE.

[24]Since there is no equivalent to the capital asset motive in PE, it makes more sense to compare the GE and PE versions of the monopoly without an asset motive to allow for transparent conclusions.

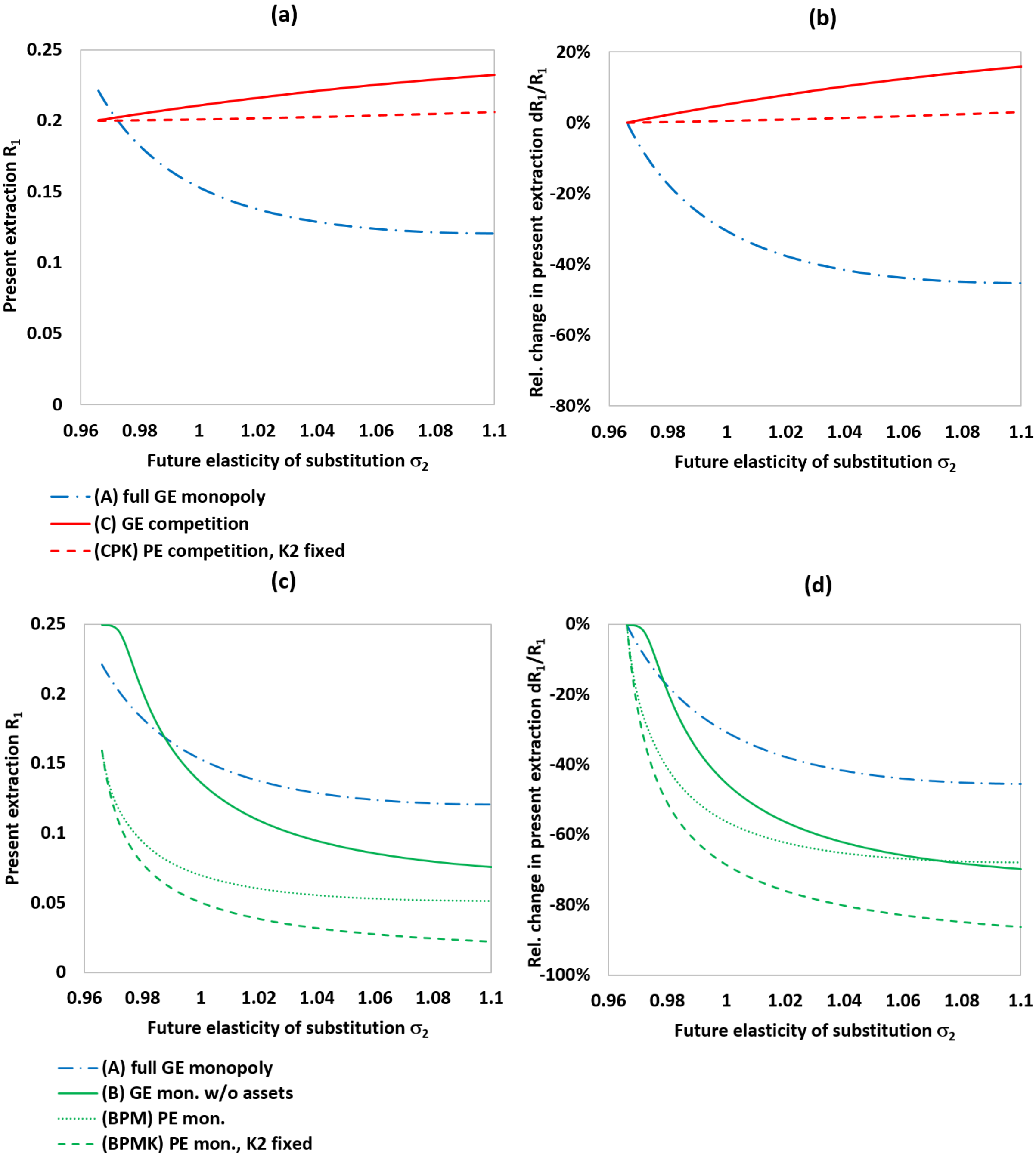

Figure 1: Effects of future technological progress (increases in σ_2) on present extraction R_1 in absolute terms (left panels (a) and (c)) and in percentage terms $\frac{\Delta R_1}{R_1}$ (right panels (b) and (d)) for competition (upper panels) and monopoly (lower panels). The full GE monopoly with the capital asset motive is shown in each panel for comparison.

who faces a fixed future capital stock K_2 (B_{PMK}, dashed green curves) at the level of the starting point ($\sigma_2 = 0.96605$), where K_2 is identical for the GE and the PE monopoly.[25] Panel (d) shows that with a PE approach with a fixed capital stock (B_{PMK}) the extraction reaction to future technological progress is significantly overestimated compared to GE. For an increase of σ_2 from 0.96605 to 1, e.g., the resulting GE postponement reaction of monopolist (B) is about a third weaker than in PE (B_{PMK}).

In addition, we construct another PE monopolist (B_{PM}, dotted green curve), who at each point of the curve (exogenously) faces the same future capital stock K_2 and resulting oil demand as the GE monopolist (B) does in the equilibrium for the respective value of σ_2 (instead of a fixed initial K_2 value). This intermediate step shows that a big part of the extraction difference between PE and GE monopoly stems from the change in actual strategic reasoning of the monopolist, and not just the endogeneity of the capital stock.

Finally, accounting for the capital asset motive ((A), blue curve) dampens the postponement of extraction even further, so that, for a shift of σ_2 from 0.96605 to 1, it turns out only about half as strong as in PE (cf. panel (d)). The loss in future oil income (cf. above) triggers an increase in savings of country E and, thus, actually provides an additional incentive to postpone extraction on top of the increasing elasticity of future oil demand. But the reduction in R_1 increases oil's effect on present capital returns $\frac{\partial i_1}{\partial R_1}$, while the higher R_2 decreases oil's effect on future capital returns $\frac{di_2}{dR_2}$. Thus, the asset motive in the present is strengthened and the one in the future is weakened by postponing extraction. This creates an additional incentive to dampen the postponement.

As the future elasticity of substitution continues to rise, the roles of the endogenous capital market and of the asset motive in GE remain robust. The additional GE supply motives of Section 3, therefore, still play a role in the future, even if better substitutes become available and reduce the degree of the OPEC's market power.

[25] For the "starting point" $\sigma_2 = 0.96605$ the future capital stock K_2 in PE is exogenously set to its equilibrium level for a GE monopolist without asset motive (B). But, since the Hotelling rules in PE and GE differ, note that the initial extraction rates are nevertheless different (cf. panel (c) in Figure 1).

6 Policy Discussion: Capital Income Tax

To further illustrate the potential relevance of our approach to resource market power, we now discuss the impact of the GE supply motives on the extraction path for a policy which has been discussed by Sinn (2008) and van der Ploeg (2016) in the context of the debate on climate change. Unintended consequences of climate policy measures, like an undesired acceleration of extraction, have been discussed in the according strand of the environmental economic literature under the term "green paradox" since Sinn (2008) (cf. Jensen et al. (2015), van der Ploeg and Withagen (2015), and van der Werf and Di Maria (2012) for overviews of the according strand of literature). In a parallel follow-up paper to the present one, Marz and Pfeiffer (2019) contribute to this literature by showing how a future carbon tax policy and the according increase in own capital assets by the oil exporting monopolist strengthens her capital asset motive in the second period, which we introduce in the present paper (cf. Section 3.2). This can trigger an overall postponement of oil extraction by the monopolist, in contrast to the conventional acceleration in partial-equilibrium models with a competitive oil market.

To avoid an unintended acceleration of the extraction of fossil resources, Sinn (2008) suggests a capital income tax by the oil importing countries on capital investments which the exporting countries can hardly avoid making in the importing countries. In his competitive framework, such a policy-driven reduction in the exporting countries' capital returns slows down extraction, which corresponds to a reduction in climate damages. In our general equilibrium setup with oil market power, we now investigate how the new additional supply motives affect the supply-side reaction to such a capital income tax. The oil importing country levies a tax κ_2 on the capital returns of country E's assets in period 2 (only). Capital assets of country E, thus, yield an effective interest rate of $i_2(1-\kappa_2)$. Households in country I are not taxed. The tax revenues are distributed in a lump-sum fashion in country I. The reaction of the monopolist's extraction path to an increase in the future capital income tax κ_2 is determined by several counteracting effects. The sign of the overall reaction is ambiguous:

$$\frac{dR_2^*}{d\kappa_2} = \frac{\frac{\partial}{\partial \kappa_2}\left(\frac{dp_2}{dR_2}\right) R_2 + \frac{\partial}{\partial \kappa_2}\left(\frac{di_2}{dR_2}\right) s_{1E} + \frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \kappa_2} + i_2 MV_1}{\frac{d[(1+i_2(1-\kappa_2))MV_1]}{dR_2} - \frac{dMV_2^{\kappa}}{dR_2}} \gtreqless 0 \tag{22}$$

To derive the comparative statics (22), we totally differentiate (15) with respect to R_2 and κ_2 taking into account $dR_1 = -dR_2$ by the binding resource constraint and (10), (11), (12), and (13). The denominator of (22) is strictly positive (cf. Appendix (B)). Like in Sinn (2008), a decrease in the effective interest rate for country E contributes to a postponement of extraction (positive term $i_2 MV_1$). Due to the asset motive and the endogeneity of savings in both countries, however, there are additional effects of a capital income tax. First, the capital income holdings in country E may increase or decrease due to an income effect and a counteracting substitution effect induced by the capital income tax (ambiguous term $\frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \kappa_2}$). If an increase in the future capital income tax leads to a decrease (an increase) in capital assets of country E, then it weakens (strengthens) the second period's capital asset motive and creates an incentive to accelerate (postpone) oil extraction. Second, the aggregate capital stock K_2 unambiguously decreases, but only due to the substitution effect in country E. The income effect only implies a redistribution of income from country E to country I, which is neutral due to symmetric homothetic preferences. The reduction of the capital stock K_2 affects both, the slope of the oil demand curve $\frac{dp_2}{dR_2}$ and the influence of oil supply on the interest rate $\frac{di_2}{dR_2}$ (cf. (12) and (13)). However, both terms ($\frac{\partial}{\partial \kappa_2}\left(\frac{dp_2}{dR_2}\right)$ and $\frac{\partial}{\partial \kappa_2}\left(\frac{di_2}{dR_2}\right)$) have ambiguous signs. Thus, the sign of (22) is ambiguous and we resort to a numerical analysis.

Figure 2 shows the effects of a future capital income tax κ_2 on country E's capital assets for the reference calibration. For the competitive oil market, the decrease in the intertemporal discount rate indeed leads to a postponement of extraction, even though the decrease in K_2 reduces future inverse oil demand. For the PE monopolist with a fixed capital stock ("B_{PMK}")[26] the same mechanism leads to a slow down of extraction

[26]Like in Section 5 above, at the starting point ($\kappa_2 = 0$) the PE monopolist exogenously faces the future capital stock as the GE monopolist without asset motive ("B"). While in GE the future capital stock changes with κ_2, it remains fixed for the PE monopolist.

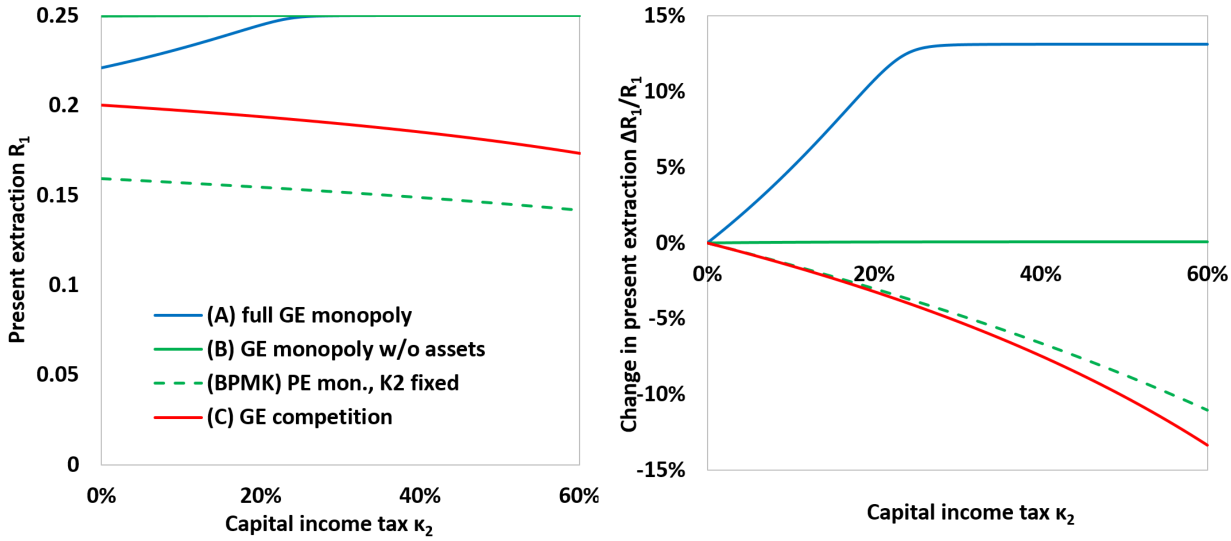

Figure 2: Present extraction R_1 (left) and percentage change in present extraction $\frac{\Delta R_1}{R_1}$ (right) for different levels of future capital income tax κ_2 on country E's capital assets.

(of course for fixed oil demand). But the GE monopolist, who accounts for the influence of capital market dynamics on oil demand ("B"), does not postpone extraction, but slightly increases extraction in period 1 (barely visible in Figure 2). Since R_1 is already very high in this case, substantial further acceleration of extraction is not easy. Once the GE monopolist also accounts for the capital asset motive ("A"), the initial equilibrium is different and present extraction is accelerated substantially. The additional GE supply motives, therefore, entirely reverse the effect of this policy on the extraction path compared to a PE analysis. In contrast to the recommendation of Sinn (2008), here a capital income tax on the assets of the resource exporting country would yield exactly the opposite of the intended outcome.

7 Conclusion

We provide a comprehensive analysis of market power in a market for a crucial exhaustible resource like oil or rare earths in general equilibrium ("GE"). Our model captures the impact of resource extraction on the endogenous interest rate, output and capital accumulation, as well as the resulting feedback effects on resource demand and again on the interest rate. The different interactions between the resource market and the capital market introduce additional supply motives to the monopolist's reasoning: considering how present resource supply fuels capital accumulation in the importing country and its future reliance on and demand for the resource ("addiction motive") poses an incentive for the monopolist to accelerate extraction. The resource monopolist not only focuses on resource revenues, but also on capital asset returns as a second income stream for her country and on the positive influence of resource supply on her own country's capital returns via the complementarity of the resource and capital in production. Thus, the monopolist faces an additional intertemporal trade-off (apart from marginal resource revenues) in her dynamic resource supply decision, which we call "capital asset motive". Depending on the development of the exporter's capital assets over time, the asset motive can contribute to acceleration, as well as postponement of extraction. The conservationist extraction bias of a monopolist relative to a competitive resource market, which has led to the well-known phrase of the monopolist as "the conservationist's friend", can be amplified, dampened or even reversed by the GE supply motives. For the reference calibration indeed the monopolist extracts more quickly than the competitive market.

Further, we examine a scenario in which future technological progress increases the substitutability of the (scarce) resource by (rather abundant) capital and makes future resource demand more elastic. Even though the resource-capital interaction in the world economy changes and the scope of the resource exporting country's market power is constrained in this way, our numerical analysis shows that the influence of the GE supply motives remains relevant. The postponement of extraction under resource market power, which is driven by the rising resource demand elasticity, turns out about a third weaker in GE than in PE for the reference calibration, and even about a half weaker if the capital asset motive is also accounted for. Moreover, a capital income tax on the exporting country's capital assets, discussed in the literature as an alternative to carbon taxation supposedly avoiding an undesired acceleration of resource extraction, does not postpone, but in fact accelerate extraction due to our additional general equilibrium supply motives.

The present framework is a good basis for further research. To clearly show the complex interplay of resource market power and the GE feedback effects independently of the resource in question, we employed a resource monopoly. Market power can be constrained by additional suppliers within the same resource market or by the development of a substitute to the resource in the overarching production technology. Since our present focus lies on the GE interactions between resource market and capital market, we investigate the latter market power constraint through technological progress which affects this interaction. Adding also a more complex market structure within the resource market would, furthermore, have to involve heterogeneity not only of resource stocks (thinking of the dominant role of Saudi Arabia), but also of capital asset stocks. This is beyond the scope of this paper and is left for future research. But an intermediate level of resource market power, i.e. between the extremes of monopoly and perfect competition, can be expected to lead to qualitatively similar results with smaller magnitudes.

Accounting for the capital asset motive visualizes dynamic changes in the role of a resource exporter with market power, which could be exploited in future work, e.g. on the planned (semi-)privatization of Saudi Aramco. Starting with a focus on resource revenues, with a growing asset stock over time the exporter acquires a double role as resource supplier and capital investor with influence on the capital market via her resource supply. Over time, resource revenues may even lose their role as the primary source of income.

Appendix

A Model Details

A.1 Household Capital Supply Behavior

The Euler equation implicitly gives savings as a function of period incomes and the interest rate i_2.

$$s_{1m} = s_{1m}(y_{1m}, \pi_{2m}, i_2) \tag{A.1}$$

From the total derivative of the Euler equation with respect to changes in period incomes and the interest rate, we derive the savings reactions

$$\begin{aligned}
\frac{\partial s_{1m}}{\partial y_{1m}} &= \frac{[\beta(1+i_2)]^{\frac{1}{\eta}}}{1+i_2+[\beta(1+i_2)]^{\frac{1}{\eta}}} > 0 \\
\frac{\partial s_{1m}}{\partial \pi_{2m}} &= \frac{\partial s_{1m}}{\partial \pi_{2m}} = -\frac{1}{1+i_2+[\beta(1+i_2)]^{\frac{1}{\eta}}} < 0 \\
\frac{\partial s_{1m}}{\partial i_2} &= -\frac{\beta u'(c_{2m})}{u''(c_{1m})+\beta(1+i_2)^2 u''(c_{2m})} + \frac{\partial s_{1m}}{\partial \pi_{2m}} s_{1m} \\
&= \frac{1}{\eta(1+i_2)} \frac{\pi_{2m}+(1-\eta)(1+i_2)s_{1m}}{1+i_2+[\beta(1+i_2)]^{\frac{1}{\eta}}} \gtreqless 0
\end{aligned} \tag{A.2}$$

A.2 Aggregate Capital Supply with Homothetic Preferences

We show in the following that capital supply is a function of the resource extraction path and the interest rate i_2 only as long as we assume symmetric (and homothetic) consumption preferences. In case of an unit resource tax, the derivation is completely analogue.

Totally differentiating $K_2^s = s_{1E} + s_{1I}$ and taking into account (5) yields

$$dK_2^s = \frac{\partial s_{1E}}{\partial y_{1E}} dy_{1E} + \frac{\partial s_{1E}}{\partial d\pi_{2E}} d\pi_{2E}^{\tau} + \frac{\partial s_{1E}}{\partial i_2} di_2 + \frac{\partial s_{1I}}{\partial y_{1I}} dy_{1I} + \frac{\partial s_{1I}}{\partial \pi_{2I}} d\pi_{2I}^{\tau} + \frac{\partial s_{1I}}{\partial i_2} di_2$$

as $s_{1m} = s_{1m}(y_{1m}, \pi_{2m}, i_2)$ by the Euler equation of the respective country $m = E, I$.

The changes in the period income streams in both countries can be further decomposed with respect to resource inputs and factor prices. Taking into account the binding resource constraint and Equations (1) and (2) and $\frac{\partial s_{1E}}{\partial y_{1E}} = \frac{\partial s_{1I}}{\partial y_{1I}}$ and $\frac{\partial s_{1E}}{\partial \pi_{2E}} = \frac{\partial s_{1I}}{\partial \pi_{2I}}$ for symmetric homothetic preferences yields

$$dK_2^s = \left[\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1\right] dR_2 + SE di_2$$

where we use (A.2) to derive the aggregate substitution effect:

$$\begin{aligned} SE &= \frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}} K_2 \\ &= -\left[\frac{\beta u'(c_{2E})}{u''(c_{1E}) + \beta(1+i_2)^2 u''(c_{2E})} + \frac{\beta u'(c_{2I})}{u''(c_{1I}) + \beta(1+i_2)^2 u''(c_{2I})}\right] > 0 \end{aligned}$$

A.3 Comparative Statics of Conditional Market Equilibrium

To determine the sign of $\frac{dp_2}{dR_2}$, we totally differentiate the market equilibrium conditions (7) and (9), solve for the market price reactions $\frac{dp_2}{dR_2}$ and $\frac{di_2}{dR_2}$ and obtain

$$\frac{dp_2}{dR_2} = \frac{F_{2RR} - \Gamma_2 SE + F_{2KR}\left(\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1\right)}{1 - F_{2KK} SE} < 0$$

with $\Gamma_t = F_{tRR} F_{tKK} - F_{tKR}^2$, while $SE = \frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}} K_2$ is the aggregated substitution effect from a change in the interest rate i_2, as defined in Appendix A.2. The negative sign unambiguously holds as $F_{2RR} < 0$, $F_{2KK} < 0$, and $\Gamma_2 > 0$ due to the concavity of the production technology, $F_{2KR} > 0$ due to the complementarity of production factors, and $SE > 0$ as shown in Appendix A.2, as well as $\frac{\partial s_{1E}}{\partial \pi_{2E}} < 0$, and $\frac{\partial s_{1E}}{\partial y_{1E}} > 0$ according to (5). This also implies that the general equilibrium change in the interest rate

$$\frac{di_2}{dR_2} = \frac{F_{2KR} + F_{2KK}\left(\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial \pi_{2E}} p_1\right)}{1 - F_{2KK} SE} > 0$$

is unambiguously positive. Using the total derivative of (6), derived in Appendix A.2, substituting for $\frac{di_2}{dR_2}$ yields

$$\frac{dK_2}{dR_2} = \frac{\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + F_{2KR} SE}{1 - F_{2KK} SE} \tag{A.3}$$

The denominator captures the feedback effect of a change in the second-period capital stock on savings incentives. A higher capital stock K_2 decreases, ceteris paribus, the marginal productivity of capital due to the concavity of the production technology and thus the interest rate i_2 in capital market equilibrium, which induces households to substitute savings for present consumption. Recall that the income effects induced in both countries by this decrease in the interest rate exactly offset each other in case of symmetric and homothetic consumption preferences. Due to the concavity of the production technology and the positive substitution effect SE, the denominator is unambiguously positive.

A.4 Equilibrium Capital Accumulation with Symmetric Preferences

From (A.3) we know that

$$\frac{dK_2}{dR_2} = \frac{\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + F_{2KR} SE}{1 - F_{2KK} SE}$$

where $SE = \frac{\partial s_{1E}}{\partial y_{1E}} \frac{c_{1E}+c_{1I}}{\eta(1+i_2)}$, as derived in Section A.2. Since the denominator is unambiguously positive, the sign of the capital reaction depends solely on the numerator. From the final goods market equilibrium and the symmetric Euler equation it follows that

$$c_{1E} + c_{1I} = F_1 + K_1 - K_2 = \frac{c_{2E} + c_{2I}}{[\beta(1+i_2)]^{\frac{1}{\eta}}} = \frac{F_2 + K_2}{[\beta(1+i_2)]^{\frac{1}{\eta}}}$$

Moreover, since $\frac{\partial s_{1E}}{\partial y_{1E}} = -\frac{\partial s_{1E}}{\partial \pi_{2E}} [\beta(1+i_2)]^{\frac{1}{\eta}}$ from (5), we can rearrange the numerator and conclude that capital accumulation will react negatively to a shift of resources to the future period if

$$\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 \left\{ 1 + [\beta(1+i_2)]^{\frac{1}{\eta}} \frac{p_1}{p_2} - \frac{1}{\eta\sigma} \frac{i_2(F_2 + K_2)}{F_2(1+i_2)} \right\} < 0$$

and therefore if

$$\frac{1+i_2}{\theta_{2K}+i_2} \left\{ 1 + [\beta(1+i_2)]^{\frac{1}{\eta}} \frac{p_1}{p_2} \right\} > \frac{1}{\sigma\eta}$$

Since the left side is greater than unity ($\theta_{2K} < 1$), this implies that $\sigma\eta \geq 1$ is a sufficient condition for $\frac{dK_2}{dR_2} < 0$.[27]

B The Monopolist's Second-Order Condition

Consider the maximization problem of the omniscient benevolent monopolist (14).

$$\begin{aligned} \max U(c_{1E}, c_{2E}) &= u(c_{1E}) + \beta u(c_{2E}) \\ &= u[p_1 R_1 + (1+i_1)s_{0E} - s_{1E}] + \beta u[\tilde{p}_2 R_2 + (1+i_2)s_{1E}] \end{aligned}$$

The omniscient monopolist is aware that

$$p_t = F_{tR}(K_t, R_t) \quad \text{with } \frac{dp_2}{dR_2} = \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} \quad \text{from (12)}$$

$$i_t = F_{tK}(K_t, R_t) \quad \text{with } \frac{di_2}{dR_2} = \frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2} \quad \text{from (13)}$$

K_1 given

$$K_2 = K_2(R_2) \quad \text{from (A.3)}$$

$$s_{1E} = s_{1E}(y_{1E}, \pi_{2E}, i_2) \quad \text{with } \frac{ds_{1E}}{dR_2} = -\frac{\partial s_{1E}}{\partial y_{1E}}\frac{\partial y_{1E}}{\partial R_1} + \frac{\partial s_{1E}}{\partial \pi_{2E}}\frac{d\pi_{2E}}{dR_2} + \frac{\partial s_{1E}}{\partial i_2}\frac{di_2}{dR_2}$$

[27] The elasticity of substitution measures how easily capital and oil can be substituted in production. It thus also captures how strongly capital demand reacts to a change in resource input. The intertemporal elasticity of substitution, in turn, indicates how sensitive households' savings and, therefore, capital supply are to changes in the interest rate i_2. Thus, intuitively, if $\sigma > \frac{1}{\eta}$, shifting resources to the second period lowers the resource price, and thereby capital demand, to such an extent that the strong reduction in capital demand outweighs the incentive to increase savings derived from the complementarity-driven rise in the interest rate i_2.

Additionally taking into account the budget constraints (3) and (4) and the resource constraint reduces (14) to a one-dimensional optimization problem. Thus, for the necessary first-order condition, we obtain

$$\frac{dU}{dR_2} = u'(c_{1E})\left[\underbrace{\left(p_1 + \frac{\partial p_1}{\partial R_1}R_1 + \frac{\partial i_1}{\partial R_1}s_{0E}\right)}_{MV_1}\frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2}\right] + \beta u'(c_{2E})\left[\underbrace{\tilde{p}_2 + \frac{d\tilde{p}_2}{dR_2}R_2 + \frac{di_2}{dR_2}s_{1E}}_{MV_2} + (1+i_2)\frac{ds_{1E}}{dR_2}\right] \stackrel{!}{=} 0$$

where $u'(c_{tE}) = \frac{\partial u}{\partial c_{tE}}$. The second-order condition for a (local) welfare maximum then reads

$$\begin{aligned}\frac{d^2U}{(dR_2)^2} = u''(c_{1E})\left[MV_1\frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2}\right]^2 + u'(c_{1E})\left[\frac{\partial MV_1}{\partial R_1}\left(\frac{dR_1}{dR_2}\right)^2 - \frac{d^2 s_{1E}}{(dR_2)^2}\right] \\ + \beta u''(c_{2E})\left[MV_2 + (1+i_2)\frac{ds_{1E}}{dR_2}\right]^2 \\ + \beta u'(c_{2E})\left[\frac{dMV_2}{dR_2} + \frac{di_2}{dR_2}\frac{ds_{1E}}{dR_2} + (1+i_2)\frac{d^2 s_{1E}}{(dR_2)^2}\right]\end{aligned} \quad \text{(B.1)}$$

where

$$\begin{aligned}\frac{\partial MV_1}{\partial R_1} &= 2\frac{\partial p_1}{\partial R_1} + \frac{\partial^2 p_1}{(\partial R_1)^2}R_1 + \frac{\partial^2 i_1}{(\partial R_1)^2}s_{0E} \\ \frac{dMV_2}{dR_2} &= 2\frac{d\tilde{p}_2}{dR_2} + \frac{d^2\tilde{p}_2}{(dR_2)^2}R_2 + \frac{d^2 i_2}{(dR_2)^2}s_{1E} + \frac{di_2}{dR_2}\frac{ds_{1E}}{dR_2}\end{aligned}$$

From the savings decision of the representative household, we know that the Euler equation

$$\frac{u'(c_{1E})}{\beta u'(c_{2E})} = 1 + i_2$$

holds in the optimal equilibrium outcome. This implies, on the one hand, that the necessary first-order condition of the monopolist's utility maximization problem (14)

$$-u'(c_{1E})\left[p_1+\frac{\partial p_1}{\partial R_1}R_1+\frac{\partial i_1}{\partial R_1}s_{0E}\right]+u'(c_{2E})\left[\tilde{p}_2+\frac{d\tilde{p}_2}{dR_2}R_2+\frac{di_2}{dR_2}s_{1E}\right]=0$$

can be reduced to the modified Hotelling rule (15), i.e.,

$$(1+i_2)MV_1=MV_2$$

On the other hand, we can also conclude that for any extraction path in the conditional market equilibrium the Euler equation has to hold. Thus, from the total derivative of the Euler equation with respect to R_2 we obtain

$$u''(c_{1E})\left[MV_1\frac{dR_1}{dR_2}-\frac{ds_{1E}}{dR_2}\right]=\beta u'(c_{2E})\frac{di_2}{dR_2}+\beta(1+i_2)u''(c_{2E})\left[MV_2+(1+i_2)\frac{ds_{1E}}{dR_2}\right]$$

This allows us to substitute the first term in (B.1) and, upon rearranging, arrive at

$$\begin{aligned}\frac{d^2U}{(\partial R_2)^2}&=\left[MV_1\frac{dR_1}{dR_2}-\frac{ds_{1E}}{dR_2}\right]\left[\beta u'(c_{2E})\frac{di_2}{dR_2}+\beta(1+i_2)u''(c_{2E})\left(MV_2+(1+i_2)\frac{ds_{1E}}{dR_2}\right)\right]\\&\quad+\beta u'(c_{2E})\left[(1+i_2)\frac{\partial MV_1}{\partial R_1}\left(\frac{dR_1}{dR_2}\right)^2+\frac{dMV_2}{dR_2}\right]+\beta u'(c_{2E})\frac{di_2}{dR_2}\frac{ds_{1E}}{dR_2}\\&\quad+\beta u''(c_{2E})\left[MV_2+(1+i_2)\frac{ds_{1E}}{dR_2}\right]^2\\&=\beta u'(c_{2E})\left[(1+i_2)\frac{\partial MV_1}{\partial R_1}+MV_1\frac{dR_1}{dR_2}\frac{di_2}{dR_2}+\frac{dMV_2}{dR_2}\right]\end{aligned}$$

For a welfare maximum we must have $\frac{d^2U}{(dR_2)^2}<0$ and therefore, since $\beta u'(c_{2E})>0$,

$$(1+i_2)\frac{\partial MV_1}{\partial R_1}+MV_1\frac{dR_1}{dR_2}\frac{di_2}{dR_2}+\frac{dMV_2}{dR_2}<0$$

Given that $\frac{dR_1}{dR_2}=-1$ by the resource constraint, this also implies that

$$\frac{d[(1+i_2)MV_1]}{dR_2}-\frac{dMV_2}{dR_2}=(1+i_2)\frac{\partial MV_1}{\partial R_1}\frac{dR_1}{dR_2}+\frac{di_2}{dR_2}MV_1-\frac{dMV_2}{dR_2}>0$$

C Reference Calibration

Table 2 gives an overview of the model parameters in the reference calibration to data from the oil market and oil exporting countries. The capital endowment of 383 units

Capital endowment K_1	383
Country E's share of capital endowment $\frac{s_{0E}}{K_1}$	0.02
Oil stock $\bar{S}$	0.25
Labor L	1
Total factor productivity A	230
Elasticity of substitution σ	0.96605
Productivity parameter of oil λ	0.03
Productivity parameter of capital γ	0.5-λ
Discount factor β	0.3
Elasticity of intertemporal substitution $1/\eta$	0.5

Table 2: Reference parameter setting

corresponds to an estimate of global aggregate physical capital of approximately US \$383 trillion in 2014 in the Penn World Table (cf. Feenstra et al. (2015)). Accordingly, one unit of output in our model corresponds to US \$1 trillion. By adding the available figures for the size of OPEC countries' sovereign wealth funds SWFI (2020) and a private wealth estimate for these countries by Credit Suisse (2018) we obtain approximately US \$7 trillion for the sum of assets of OPEC countries. We take this as the basis for a share of country E in the capital endowment $\frac{s_{0E}}{K_1}$ of 0.02. Taking 2014 as the middle of our model period 1 and assuming that year's world GDP of US \$79.6 trillion (cf. CIA 2014) as the average annual output level yields a length of period 1 (with an output of $F_1 = 3068$) of 38.4 years. Thus, period 1 can be seen as stretching approximately from the mid-1990s to the 2030s. As a result, a utility discount factor of $\beta = 0.3$ between period 1 and 2 implies a rate of time preference of 0.037.

Following the literature on economic growth and fossil resources the elasticity of substitution σ between an essential fossil resource, which is not fully substitutable, and capital must be slightly below 1. At the same time the elasticity of substitution and the elasticity of oil demand are positively correlated. The empirical evidence on the elasticity of oil demand in the very long run is not quite clear. Especially on the time scale that we are looking at (over 38 years) the demand elasticity is higher than the available estimates, which are in addition biased towards zero, closer to, and possibly even higher than, one. This also implies an elasticity of factor substitution close to, but below one. Our choice of $\sigma = 0.96605$ is within that range.

For the productivity parameters of oil and capital the underlying assumption is that $\lambda + \gamma = 0.5$ while the parameter of labor is fixed at 0.5. This is motivated by the fact that the income share of labor in global GDP amounts to at least 50% according to OECD (2015). The TFP parameter $A = 230$ and the size of the oil stock ($\bar{S} = 0.25$, corresponding to a global stock of 150 billion tons of carbon in the form of oil reserves, cf. Abdul-Hamid et al. 2013) were chosen such that the resulting length of period one is below 40 years and the ratio of values of the capital endowment and the oil endowment in the reference case $\frac{K_1}{p_1 \bar{S}} = 3.2$ lies in a realistic range: the value ratio of the global physical capital stock from above and the oil stock is $\frac{383 \cdot 10^{12} \$}{70 \frac{\$}{\text{barrel}} \cdot 1696 \cdot 10^9 barrels} = 3.22$ with an oil stock of 1696.6 billion barrels (cf. BP 2018) at an oil price of 70 \$ per barrel. Both parameters, the length of period 1 and the ratio of endowment values can not be chosen independently from the income share of oil θ_R, which realistically lies between 2 and 6 percent of GDP. For the reference calibration oil's income share is $\theta_R = 0.0347$.

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