OPEC, Shale Oil, and Global Warming*

On the importance of the order of extraction

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Abstract

OPEC's market power in the oil market affects global warming not only through the speed, but also through the composition of global fossil fuel supply. By marking up the price over marginal costs, OPEC enables producers of relatively expensive and dirty shale oil to start extracting before the OPEC reserves are depleted. We develop an oligopoly-fringe model of the oil market to examine this extraction *sequence* effect. In our calibrated model, that takes into account the damage caused by the accumulation of carbon emissions, we find that the sequence effect is substantial: it accounts for 97 percent of the social welfare loss due to imperfect competition. Because of the sequence effect, the recent boom in shale oil reserves may result in a decrease of social welfare. Renewables subsidies decrease current supply by OPEC, but increase current supply of shale oil. Hence, they increase the average carbon content of current extraction.

JEL codes: Q31, Q42, Q54, Q58

Keywords: cartel-fringe, climate policy, non-renewable resource, Herfindahl rule,

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limit pricing, oligopoly

NEW LONG. Market power in the oil market affects global warming not only through the speed, but also through the composition of global fossil fuel supply. which we model as made up of OPEC supply and supply from shale oil reserves. By marking up the price over marginal costs, OPEC enables producers of relatively expensive and dirty shale oil to start extracting before OPEC reserves are depleted. We develop an oligopoly-fringe model of the oil market to examine this extraction *sequence* effect. In our calibrated model that takes into account the damage caused by the accumulation of carbon emissions, we find that the sequence effect is substantial: While welfare under the oligopoly-fringe equilibrium can be significantly lower than under a first-best outcome, 97 percent of this welfare loss is due to the sequence effect. Keeping the same global supply path as under the oligopoly-fringe equilibrium and only following the efficient order of use would almost eliminate the welfare loss. Because of the sequence effect, (i) the recent boom in shale oil reserves may result in a decrease of social welfare, and (ii) renewables subsidies decrease current supply by OPEC, but increase current supply of shale oil at the expense of current OPEC supply which results in an increase of the average carbon content of current extraction.
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OLD SHORT. OPEC's market power in the oil market affects global warming not only through the speed, but also through the composition of global fossil fuel supply. By marking up the price over marginal costs, OPEC enables producers of relatively expensive and dirty shale oil to start extracting already before the OPEC reserves are depleted. We develop an oligopoly-fringe model of the oil market to examine this extraction *sequence* effect. In our calibrated model, we find that the sequence effect is substantial: it accounts for 97 percent of the social welfare loss due to imperfect competition. Because of the sequence effect, the recent shale oil revolution has not only increased climate damages, but may even decrease social welfare if the interest rate and the social cost of carbon are high enough. Future renewables subsidies decrease current supply by OPEC, but increase current supply of shale oil. Hence, they increase the average carbon content of current extraction.
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1 Introduction

An old adage says that "the monopolist is the conservationist's best friend" (e.g., Dasgupta and Heal, 1979, p. 329). Indeed, we know from non-renewable resource economics that market power typically leads to higher initial resource prices and slower resource depletion. The consequences of imperfect competition for the Earth's climate are not so evident, however, especially not if different types of fossil fuels with varying carbon contents are exploited. The reason is that imperfect competition does not only affect the speed, but also the order of extraction of different fossil fuel types (cf. Benchekroun et al., 2009, 2010). With OPEC producing 40 percent of global oil supply and owning 70 percent of world oil reserves, the oil market obviously is imperfectly competitive (EIA, 2017). Nevertheless, recent empirical evidence suggests that OPEC's market power is declining. One reason is that its members do no longer seem to act as a cohesive cartel (Almoguera et al., 2011; Brémond et al., 2012; Kisswani, 2016; Okullo and Reynès, 2016). Furthermore, the deployment of new hydraulic fracturing technologies has enabled a more than tenfold increase of shale oil and gas production in the US over the laste decade: the 'shale revolution' (McJeon et al., 2014; Behar and Ritz, 2016; EIA, 2017). In this paper we examine these two important features of the oil market (imperfect competition with the rise of a fringe's stocks) and their implications for global warming and welfare when the damage caused by the accumulation of carbon emissions is taken into account.

Our paper is related to three strands of literature, the first one studying resource use under imperfect competition. Important contributions to this field were made by Stiglitz (1976) on monopoly, Lewis and Schmalensee (1980) on oligopoly, Gilbert (1978) and Newbery (1981) on dominant firms. More recently, Groot et al. (2003), Benchekroun et al. (2009, 2010) and Benchekroun and Withagen (2012) have developed cartel-fringe models of the resource market. See also Withagen (2013) for a survey and the references therein. In the present paper we offer new insights in three respects. First of all, we take account of OPEC still being an important player on the market, but with less power than some decades ago. Almoguera et al. (2011, p. 144) conclude that "OPEC's behaviour is best described as Cournot competition in the face of a competitive fringe constituted by non-OPEC producers." In line with this conclusion, we model the market as a situation with a large number of price-taking mining firms and a set of oligopolists, which reduces to the cartel-fringe model if the number of oligopolists equals unity. Second, we take account of the existence of renewables that provide perfect substitutes for fossil fuel and that can be produced in unlimited amounts. This opens the possibility of a limit-pricing strategy by fossil fuel suppliers in equilibrium (see, e.g., Van der Meijden et al. (2015); Andrade de Sá and Daubanes (2016) and Van der Meijden and Withagen (2016) for recent work and Hoel (1978), Salant (l979) and Gilbert and Goldman (1978) for early contributions). Finally, we investigate the effect of climate change policies on the extraction paths as well as on welfare, allowing for damages from the accumulation of greenhouse gases.

Second, our article relates to the literature on the sequence of extraction of multiple non-renewable resource deposits with different unit extraction costs. Herfindahl (1967) and Solow and Wan (1976) show that these deposits are optimally extracted in order of increasing marginal extraction costs. The principle of extracting cheap resources before the more expensive ones has become known as the Herfindahl rule. Over the last decades, several refinements of this rule were proposed. Kemp and Long (1980) show that in general equilibrium, the Herfindahl rule may break down due to a consumption smoothing motive. Other reasons for deviations from the Herfindahl rule are heterogeneous resource demand (Chakravorty and Krulce, 1994), extraction capacity constraints (Amigues et al., 1998; Holland, 2003), upper bounds on pollution stocks (Chakravorty et al., 2008) and supply cost uncertainty (Gaudet and Lasserre, 2011). We contribute to this literature by examining how a violation of the Herfindahl rule due to imperfect competition affects global warming through the timing of carbon emissions.

The third field of research to which our study relates is the Green Paradox literature (cf. Sinclair, 1994; Sinn, 2008, 2012; Van der Ploeg and Withagen, 2015), in which it is shown that under perfect competition the announcement of stringent future climate policies (such as carbon taxes or subsidies for renewable energy) may cause an increase in current fossil fuel supply and therefore leads to an acceleration rather than a mitigation of global warming. We add to this active research field by demonstrating that, due to imperfect competition on the oil market, climate policies not only affect the level of current fossil use, but also the mix between relatively clean and dirty fuels. This provides an additional channel through which 'gradually greening policies' may increase current carbon emissions.

We establish the existence of an open-loop Nash-Cournot equilibrium on the oil market. We fully characterize the equilibrium and perform a sensitivity analysis for different policy measures and competitiveness indicators. In our numerical analysis, we take into account that conventional oil supplied by OPEC has lower marginal extraction costs and is relatively cleaner than the heavy oil, oil sands, and shale oil supplied by the fringe. Our main findings are as follows.

First, the oligopolists and the fringe start out supplying simultaneously to the market, despite their constant but differing unit extraction costs. If the initial stock of the fringe is large relative to the oligopolists', the phase with simultaneous supply will be followed by a phase during which only the fringe is active (and the stocks of the oligopolists are depleted). In this case, there will be no limit-pricing behaviour. However, if the initial stock of the oligopolists is relatively large, the phase with simultaneous supply will be followed by a period during which only the oligopolists are supplying. During this period, the oligopolists either choose to price strictly below the price of renewables, in which case the price increases over time, or to perform a limit-pricing strategy of marginally undercutting the renewables price, in which case the price is constant over time. If marginal profits in a limit-pricing regime are non-positive, oligopolists will start with limit pricing as soon as the fringe's stock is depleted. However, if marginal profits during limit pricing are positive, the oligopolists will only start limit pricing after the fringe's stock is depleted and their own remaining stock is smaller than a certain threshold.

Second, when decomposing the global welfare loss due to imperfect competition into a 'conservation effect' (slower extraction due to a higher initial oil price) and a 'sequence effect' (front-loading of extraction of the relatively expensive and dirty resource), we find that the sequence effect, which so far has remained unexplored in the literature, is huge in our calibrated model. In the benchmark scenario, imperfect competition causes a social welfare loss of 14.5 percent, almost all of which (97 percent) is imputable to the inefficient order of use the resources, i.e. the sequence effect. Furthermore, imperfect competition increases the discounted value of climate damages by 5.2 percent. Without the sequence effect, imperfect competition would *decrease* climate damages by 4.8 percent, due to the conservation effect.

Third, in our benchmark scenario a renewables subsidy decreases OPEC's (relatively clean) initial supply, but increases the initial (relatively dirty) supply by the fringe. Hence, the average carbon content of initial resource extraction increases. Furthermore, initial aggregate emissions go up: a subsidy rate equal to 10 percent of renewables unit production costs increases initial carbon emissions by 12 percent (with equal emission factors the increase in initial emissions would have been 8.3 percent).

Fourth, the collapse of OPEC as a cartel—modeled as an increase in the number of oligopolists—has an ambiguous effect on climate damage. On the one hand, resource extraction will become less conservative, which increases climate damage. On the other hand, extraction of the relatively expensive and dirty resource owned by the fringe will be back-loaded in time, which slows down global warming and reduces climate damage.

Fifth, the shale oil revolution characterized by an increase in shale oil reserves and a decrease in shale oil extraction costs, has not only increased climate damages, but may also have lowered 'grey welfare' because the relatively expensive shale oil partially crowds out early extraction of cheap oil by the oligopolists. We numerically investigate conditions under which the recent boom in shale oil reserves reduces global welfare.

Our numerical results are obtained within a calibrated stylized model. A caveat is therefore in order. The numbers we obtain are useful only to gain insights into the possible relative magnitudes of the different effects examined. Some remarks on the scope of our study are in order at this point as well. Because imperfect competition is a salient feature of the global oil market, but not of the markets for gas and coal, we restrict our analysis of climate damage to the use of oil, although coal is "potentially a much bigger threat to climate change than oil" (Van der Ploeg and Withagen, 2012, p. 62). Furthermore, in our model cumulative extraction remains unchanged due to linear extraction costs: climate damage effects merely result from changes in the timing of extraction of different types of fossil fuels. Therefore, our analysis mainly applies to the extraction of relatively cheap oil that is available at roughly constant marginal costs and in finite amounts (and not to more expensive oil that is available in larger amounts and at higher, reserve-dependent extraction costs). Still, the initial aggregate proven oil reserves that we use in our calibrated model contain 839 tonnes of CO_2 (EIA, 2017), which already is about 84 percent of the remaining carbon budget corresponding to the scenario of keeping the average global temperature rise below 2 degrees Celsius with a 50 percent probability (McGlade and Ekins, 2015). Our results show that even with fixed cumulative emissions, the change in the timing of extraction of the proven oil reserves due to imperfect competition, the shale oil revolution, and policy measures already generate substantial climate damage and welfare effects.

The remainder of the paper is structured as follows. Section 2 outlines the model. Section 3 characterizes the open-loop Nash-Cournot equilibrium and provides a comparative statics analysis. Section 4 discusses welfare effects. Finally, Section 5 concludes.

2 The model

A non-renewable resource is jointly supplied by a price-taking fringe and a group of n suppliers with market power, referred to as oligopolists. The fringe is endowed with an aggregate initial stock S_0^f and has a constant per unit extraction cost k^f. The initial stock of oligopolist i is denoted by S_{0i}^c with $i = 1, .., n$, where the superscript c refers to the Cournot players, since we assume that the oligopolists compete in quantity à la Cournot. The per unit extraction cost of oligopolist i is constant and denoted by k_i^c. Extraction rates at time $t \geq 0$ by the fringe and oligopolist i are $q^f(t)$ and $q_i^c(t)$, respectively. The time argument will be dropped when possible. Aggregate supply by the oligopolists reads $q^c \equiv \sum_i q_i^c$. The inverse demand of the non-renewable resource is given by $p + \tau = \alpha - \beta(q^f + q^c)$, with $\alpha > 0$ and $\beta > 0$, where τ denotes a constant specific tax on resource consumption and p is the price received by suppliers of the resource. Hence, $p + \tau$ is the consumer price. A perfect substitute for the resource can be produced, indefinitely, at marginal cost $b > 0$, by using a backstop technology. We abstract from technological progress (cf. Fischer and Salant, 2014), as well as from set-up costs. Consumption of the substitute is subsidized at a constant specific rate σ.[1] Define $\hat{b} \equiv b - \sigma - \tau$ and denote the interest rate by $r > 0$.

[1]The constancy of the tax can be motivated by constant marginal damages of emissions. Constancy of the renewables subsidy is convenient for the results' exposition.

The fringe maximizes its discounted profits,

$$\int_0^\infty e^{-rt}(p(t) - k^f)q^f(t)dt, \tag{1}$$

taking the price path as given, subject to its resource constraint

$$\dot{S}^f(t) = -q^f(t), S^f(t) \geq 0 \text{ for all } t \geq 0, \text{ and } S^f(0) = S_0^f. \tag{2}$$

Each oligopolist i is aware of its influence on the equilibrium price and maximizes

$$\int_0^\infty e^{-rt}(\alpha - \beta(q^f(t) + q^c(t)) - \tau - k_i^c)q_i^c(t)dt, \tag{3}$$

taking the time paths of q^f and q_j^c ($j \neq i$) as given, subject to its resource constraint

$$\dot{S}_i^c(t) = -q_i^c(t), S_i^c(t) \geq 0 \text{ for all } t \geq 0, \text{ and } S_i^c(0) = S_{0i}^c. \tag{4}$$

Moreover, the existence of the perfect substitute effectively implies an upper limit on the price oligopolists can ask, yielding the additional constraint

$$\alpha - \beta(q^f(t) + q^c(t)) - \tau \leq \hat{b}. \tag{5}$$

We make the following two assumptions.

Assumption 1 (Symmetric oligopolists) *For all $i = 1, .., n$ we have:*

(i) $k_i^c = k^c$.

(ii) $S_{0i}^c = \frac{S_0^c}{n}$ *where S_0^c represents the total stock owned by the oligopolists.*

Assumption 2 (Relative costs) *We impose:*

(i) $k^c + \tau < k^f + \tau < b - \sigma < \alpha$.

(ii) $k^f < (\alpha - \tau + nk^c)/(1 + n)$.

Assumption 1 allows us to focus on the interaction of market power and the fringe when facing a competing backstop technology. Asymmetry of oligopolists can deliver interesting insights, but would obscure the source behind the novelty of the results of the paper. Assumption 2 enables us to restrict our attention to cases that we think are empirically relevant. Part (i) ensures that the tax-inclusive marginal production costs of the non-renewable resource are lower than the after-subsidy marginal production costs of the backstop technology, and that the after-tax and after-subsidy marginal production costs are below the choke price. Part (ii) makes sure that the marginal extraction costs of the fringe are below the profit-maximizing price of the oligopolists.[2]

3 Oligopoly-Fringe equilibrium

Our problem is a hybrid version of the cartel-fringe framework where the cartel announces a price path and the fringe chooses an extraction path, and the oligopoly framework where each player chooses an extraction strategy. In this section, we first introduce the equilibrium concept. Subsequently, after describing different extraction phases we provide a full characterization of the oligopoly-fringe equilibrium. Finally, we perform a comparative statics analysis.

3.1 Equilibrium concept

Each oligopolist chooses an extraction strategy, taking the extraction strategies of all the other players, including the fringe, as given while the fringe takes the price path as given and chooses its extraction strategy. For tractability we focus on open-loop strategies, where the strategy of each oligopolist is an extraction *path*.

Definition 1 *A vector of functions $q \equiv (q_1^c, ..., q_n^c, q^f)$ with $q(t) \geq 0$ for all $t \geq 0$ is an Open-Loop Oligopoly-Fringe Equilibrium (OL-OFE) if*

(i) each extraction path of the vector $(q_1^c, ..., q_n^c, q^f)$ satisfies the corresponding resource constraint,

[2]To see this, consider the extreme case with an infinitely large S_0^c, implying a zero scarcity rent. Instantaneous marginal profits of the oligopolists (if $q^f = 0$) are then given by $\alpha - \tau - \beta q^c(1 + 1/n) - k^c$. Hence, the profit-maximizing price is $p^* = (\alpha - \tau)\frac{1}{1+n} + k^c\frac{n}{1+n}$. Condition (ii) in Assumption 2 implies $k^f < p^*$.

(ii) for all $i = 1, 2, ..., n$

$$\int_0^\infty e^{-rs}\left[\alpha - \beta\left(q^c(s) + q^f(s)\right) - \tau - k^c\right] q_i^c(s)ds$$
$$\geq \int_0^\infty e^{-rs}\left[\alpha - \beta\left(\sum_{j\neq i} q_j^c(s) + \hat{q}_i^c(s) - q^f(s)\right) - \tau - k^c\right] \hat{q}_i^c(s)ds$$

for all $\hat{q}_i^c$ *satisfying the resource constraint, and*

(iii)

$$\int_0^\infty e^{-rs}\left[p\left(s\right) - k^c\right] q^f(s)ds \geq \int_0^\infty e^{-rs}\left[p\left(s\right) - k^c\right] \hat{q}^f(s)ds,$$

where $p\left(s\right) = \alpha - \tau - \beta\left(q^c(s) + q^f(s)\right)$, *for all* $\hat{q}^f$ *satisfying the resource constraint.*

We use an optimal control approach to characterize an OL-OFE. The Hamiltonian associated with the fringe's problem reads

$$\mathcal{H}^f = e^{-rt}(p(t) - k^f)q^f(t) + \lambda^f(t)[-q^f(t)]. \tag{6}$$

The necessary conditions include

$$p(t) = \alpha - \tau - \beta(q^f(t) + q^c(t)) \leq k^f + \lambda^f e^{rt}, \tag{7}$$
$$[k^f + \lambda^f e^{rt} - (\alpha - \tau) + \beta(q^f(t) + q^c(t))]q^f(t) = 0, \tag{8}$$
$$\dot{\lambda}^f = 0. \tag{9}$$

Here, λ^f is the fringe's shadow price of the resource stock. Hence, (7)-(9) say that in an equilibrium with positive supply of the fringe, the producer price satisfies Hotelling's rule: the net price, $p - k^f$, increases over time at the rate of interest.

The Lagrangian associated with oligopolist i's problem is given by

$$\mathcal{L}_i^c = e^{-rt}\left[\alpha - \tau - \beta\left(q^f(t) + q^c(t)\right) - \tau - k^c\right] q_i^c(t) + \lambda_i^c[-q_i^c(t)]$$
$$+ \mu_i^c(t)\left[b - \sigma - \alpha + \beta\left(q^f(t) + q^c(t)\right)\right]. \tag{10}$$

Due to Assumption 1 we can focus on the conditions that characterize an equilibrium where the extraction paths of the oligopolists are identical, $q_i^c = q^c/n$, $\lambda_i^c = \lambda^c$, $\mu_i^c = \mu^c$

and $T_i^c = T^c$ for all $i = 1, .., n$, where T_i^c denotes the date at which oligopolist i's resource is depleted. The necessary conditions then include

$$\alpha - \tau - \beta(q^f(t) + \left(1 + \frac{1}{n}\right) q^c(t)) \leq k^c + \lambda^c e^{rt} - \mu^c \beta e^{rt}, \quad (11)$$

$$\left[k^c + \lambda^c e^{rt} - \mu^c \beta e^{rt} - \alpha + \tau + \beta \left(q^f(t) + \left(1 + \frac{1}{n}\right) q^c(t)\right)\right] q^c(t) = 0, \quad (12)$$

$$\mu^c(t)[b - \sigma - \alpha + \beta(q^f(t) + q^c(t)] = 0; \; \mu^c(t) \geq 0, \quad (13)$$

$$\dot{\lambda}^c = 0, \quad (14)$$

where λ^c denotes the shadow price of the resource stock of the oligopolists and μ^c is the Lagrange multiplier associated with restriction (5). Hence, conditions (11)-(14) imply that as long as $p < \hat{b}$ (i.e., as long as restriction (5) is non-binding) and $q^c > 0$, marginal profit of the oligopolists increases over time at the rate of interest. Because the oligopolists are free to choose the moment of depletion of their stocks, in equilibrium the Hamiltonian vanishes at date T^c, implying

$$\left(p(T^c) - k^c - \lambda^c e^{rT^c}\right) \frac{q^c(T^c)}{n} = 0. \quad (15)$$

3.2 Phases of resource extraction

In the OL-OFE, different phases of resource extraction exist. By F, C, S and L we denote phases with only the fringe supplying, only the oligopolists supplying, at a price strictly below b, simultaneous supply, and supply by the oligopolists at the backstop price (i.e., limit pricing), respectively.

We first summarize the necessary conditions that hold in each phase (Lemma 1) and then proceed by elimination of specific sequences of phases (Lemma 2). From these two lemmata we proceed to characterize an OL-OFE in Section 3.3.

Lemma 1 *Along F we have*

$$p(t) = \alpha - \tau - \beta q^f(t) = k^f + \lambda^f e^{rt}, \quad (16)$$

$$p(t) = \alpha - \tau - \beta q^f(t) \leq k^c + \lambda^c e^{rt}, \quad (17)$$

$$q^f(t) = \frac{1}{\beta}(\alpha - \tau - k^f - \lambda^f e^{rt}). \quad (18)$$

Along S we have

$$p(t) = \alpha - \tau - \beta(q^f(t) + q^c(t)) = k^f + \lambda^f e^{rt}, \tag{19}$$

$$\alpha - \tau - \beta(q^f(t) + \left(1 + \frac{1}{n}\right) q^c(t)) = k^c + \lambda^c e^{rt}, \tag{20}$$

$$q^f(t) = \frac{1}{\beta}\left(\alpha - \tau - (n+1)(k^f + \lambda^f e^{rt}) + n(k^c + \lambda^c e^{rt})\right), \tag{21}$$

$$q^c(t) = \frac{n}{\beta}\left(k^f + \lambda^f e^{rt} - k^c - \lambda^c e^{rt}\right). \tag{22}$$

Along C we have

$$p(t) = \alpha - \tau - \beta q^c(t)) \leq k^f + \lambda^f e^{rt}, \tag{23}$$

$$\alpha - \tau - \left(1 + \frac{1}{n}\right) \beta q^c(t)) = k^c + \lambda^c e^{rt}, \tag{24}$$

$$q^c(t) = \frac{1}{\beta}\frac{n}{n+1}(\alpha - \tau - k^c - \lambda^c e^{rt}). \tag{25}$$

Along L we have

$$p(t) = \hat{b}, \tag{26}$$

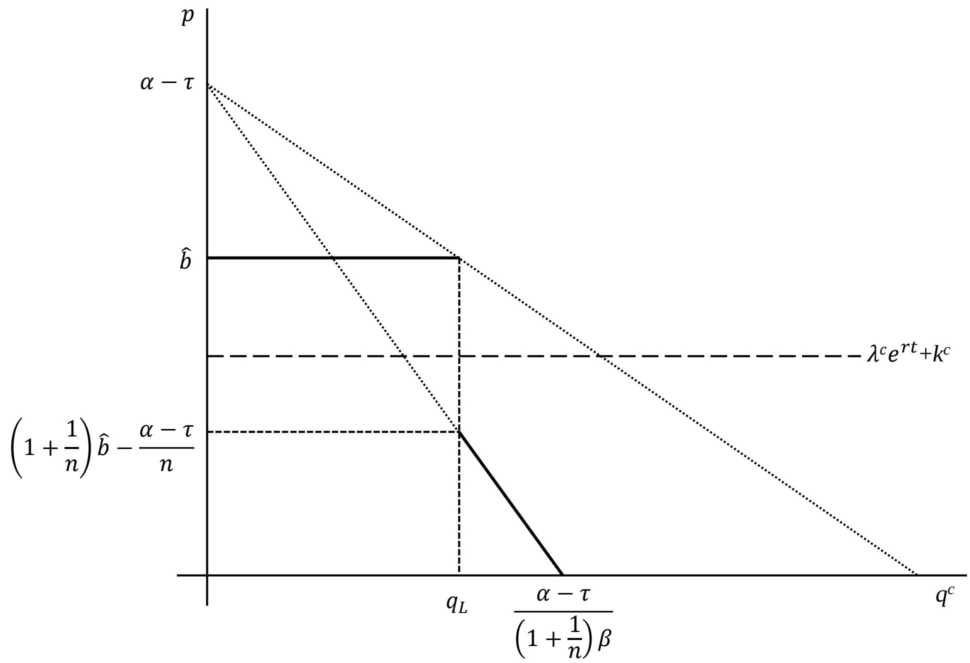
$$q^c(t) = q_L \equiv \frac{\alpha - \tau - \hat{b}}{\beta}, \tag{27}$$

$$k^c + \lambda^c e^{rt} > \alpha - \tau - \left(1 + \frac{1}{n}\right) \beta q_L = \left(1 + \frac{1}{n}\right) \hat{b} - \frac{\alpha - \tau}{n}. \tag{28}$$

Proof. Straightforward from the application of the Maximum Principle to the problem of each oligopolist and the fringe and using symmetry. Rewriting conditions (7), (8), (11), (12), (13) and (15) in each phase yields the results. Expression (28) is obtained from (12) with $\mu^c > 0$ imposed. $\square$

During the limit-pricing phase L, the producer price is constant and equal to $\hat{b}$ and therefore (16) and (19) cannot hold: the fringe's production is nil. Condition (28) is illustrated in Figure 1, which exhibits marginal revenue (discontinuous solid line) and marginal costs (dashed line). Marginal revenue jumps at $q = q_L$, and when $\hat{b} \geq k^c + \lambda^c e^{rt} \geq (1 + \frac{1}{n})\hat{b} - \frac{\alpha - \tau}{n}$ marginal revenue is not smaller (not larger) than the full marginal cost for $q < (>) q_L$, implying that the profit maximizing quantity is q_L. When $\hat{b} = k^c + \lambda^c e^{rt}$, marginal revenue equals full marginal cost for any $q \in [0, q_L]$. However, the symmetric oligopolistic outcome yields q_L because of discounting.

Figure 1: Discontinuous marginal revenue and limit pricing



We denote the oligopolists' marginal profit during limit pricing by[3]

$$\hat{\pi} \equiv \left(1 + \frac{1}{n}\right)\hat{b} - \frac{\alpha - \tau}{n} - k^c. \tag{29}$$

If $\hat{\pi} \leq 0$, condition (28) always holds. Therefore, as soon as the stock of the fringe is exhausted the equilibrium will be limit pricing. Intuitively, if marginal profits remain non-positive for all $p \leq \hat{b}$, once the fringe's stock is depleted the oligopolists will set the highest possible price (of course, given that they still have a positive remaining stock). If $\hat{\pi} > 0$, we get from (12) and (15) that the duration of the limit-pricing phase can be at most

$$\hat{\Delta} \equiv \frac{1}{r} \ln\left(\frac{\hat{b} - k^c}{\hat{\pi}}\right), \tag{30}$$

where the term between brackets equals average profits over marginal profits during

[3]Define marginal profits of oligopolist i as $\pi(q_i^c; q^c, q^f) \equiv \alpha - \beta(q^c + q^f) - k^c - \tau - \beta q_i^c$. Evaluate at $q^f = 0$ and $nq_i^c = q^c = q_L = \frac{\alpha-\tau-\hat{b}}{\beta}$ to get $\hat{\pi} = \pi(q_L/n, q_L, 0) = \left(1 + \frac{1}{n}\right)\hat{b} - \frac{\alpha-\tau}{n} - k^c$.

limit pricing. We denote a limit-pricing phase of duration $\hat{\Delta}$ by $\hat{L}$. The phase $\hat{L}$ also requires a minimum amount of stock: $\hat{S}_L \equiv q_L \hat{Delta}$. A limit-pricing phase with a duration different from $\hat{Delta}$ is denoted by $\tilde{L}_{LM}$.

We proceed by investigating which sequences of phases are possible in equilibrium. Lemma 2 lists all sequences of phases that can be ruled out because they violate the necessary conditions.

Lemma 2 *In an OL-OFE*

(i) A direct transition from C to F or vice versa is excluded.

(ii) The initial regime is not C.

(iii) F before S is excluded.

(iv) $F \to \hat{L}$ and $F \to \tilde{L}$ are excluded.

Proof. See Appendix B.1. □

Intuitively, (i) must hold in equilibrium because a direct transition from C to F or vice versa with a continuous price would imply a jump in q^f and therefore a jump in marginal profits of the oligopolists at the moment of the transition. Furthermore, (ii) must hold in equilibrium because if only the oligopolists are extracting, Assumption 2 ensures that the oil price exceeds the unit extraction costs of the fringe and that the net price of the fringe, $p - k^f$, is growing at a rate lower than the rate of interest. Therefore, the fringe prefers current extraction over future extraction and will undercut the oligopolists, implying that a C-phase cannot occur before depletion of the fringe's stock. Similarly, (iii) and (iv) must hold; indeed suppose there is a phase where the fringe is the sole supplier before the oligopolists' stock is depleted. During that phase the fringe's net price growth rate equals the interest rate. Because the unit extraction costs of the oligopolists are smaller than the fringe's unit extraction cost, this would imply that the oligopolists' net price, $p - k^c$ (which equals their marginal profit if $q^c = 0$), grows at a rate lower than the rate of interest. Hence, the oligopolists prefer current extraction over future extraction and will undercut the fringe.

3.3 Characterization of an OL-OFE

The strategy to characterize an OL-OFE is to consider for a given stock S_0^f which phases occur in equilibrium depending on the stock S_0^c. To this end it will be helpful to define two threshold stocks S_{0S}^c and $\hat{S}_0^c$. We first identify the conditions to obtain an OL-OFE that consists of only S.

Lemma 3 *Suppose the OL-OFE consists of only S, with final time T_S. Then*

$$r\beta S_0^f = (\hat{b} + nk^c - (n+1)k^f)(rT_S - 1 + e^{-rT_S}) + (\alpha - \tau - \hat{b})rT_S, \tag{31}$$

$$r\beta S_0^c = n(k^f - k^c)(rT_S - 1 + e^{-rT_S}). \tag{32}$$

Proof. See Appendix B.2. □

This system defines a one to one relationship between S_0^f and S_0^c that yields an equilibrium S. Given S_0^f the system defines a unique $S_{0S}^c = \Phi\left(S_0^f\right)$ such that the equilibrium is S when the initial stocks are $\left(S_0^f, S_{0S}^c\right)$. It can be shown that the function Φ is strictly increasing. So for each S_0^c we have an equilibrium that reads S when $S_{0S}^f = \Phi^{-1}\left(S_0^c\right)$. Hence, we have established the following result.

Lemma 4 *For each S_0^f there exists a unique S_{0S}^c such that the equilibrium reads S.*[4]

3.3.1 When the fringe depletes last

We investigate the equilibrium outcome when, for a given S_0^f, we have $S_0^c < S_{0S}^c$. We establish that the sequence of regimes reads $S \to F$.

Lemma 5 *Given S_0^f, the equilibrium reads $S \to F$ when $S_0^c < S_{0S}^c$. When S_0^c approaches S_{0S}^c from below, the duration of the F-phase tends to zero.*

Proof. See Appendix B.3. □

[4]Note that S_{0S}^c is a function of S_0^f. However, for the ease of exposition we omit the argument and only use the notation S_{0S}^c throughout the rest of the paper.

3.3.2 When the fringe depletes first

Here we examine the possible outcomes when, given S_0^f, we have $S_0^c > S_{0S}^c$. We establish that there will then be a final limit-pricing phase. We start by considering the special case of the equilibrium $S \to \hat{L}$.

Lemma 6 *Suppose the equilibrium sequence reads $S \to \hat{L}$ with transition at $\hat{T}_S$ and final time $\hat{T}_L$. Then*

$$
\begin{aligned}
r\beta S_0^f &= (\alpha - \tau + nk^c - (n+1)k^f)(r\hat{T}_S - 1 + e^{-r\hat{T}_S}), && (33)\\
r\beta S_0^c &= (\hat{b} - (\alpha - \tau) + n(k^f - k^c))(r\hat{T}_S - 1 + e^{-r\hat{T}_S}) \\
&\quad + (\alpha - \tau - \hat{b})r\hat{T}_L, && (34)\\
(\hat{b} - k^c)e^{-r\hat{T}_L} &= \left[\left(1 + \frac{1}{n}\right)\hat{b} - \frac{\alpha - \tau}{n} - k^c\right] e^{-r\hat{T}_S}. && (35)
\end{aligned}
$$

Proof. See Appendix B.4. □

We show in the next lemma that for any given initial stock of the fringe, the existence of this equilibrium requires a unique initial stock of the oligopolists. Moreover, the length of the S-phase is larger than in the equilibrium where there is only an S-phase (Lemma 4). We will distinguish cases with positive (Lemma 7-9) and negative (Lemma 10) marginal profits of the oligopolists during limit-pricing.

Lemma 7 *Suppose marginal profits during limit pricing are positive, i.e., $\hat{\pi} > 0$. Then:*

(i) For each S_0^f, there exists a unique $\hat{S}_0^c$ such that the equilibrium reads $S \to \hat{L}$.

(ii) $\hat{T}_S > T_S$ and $\hat{S}_0^c > S_{0S}^c + \hat{S}_L$.

Proof. See Appendix B.5. □

Note that the duration of the limit-pricing phase depends on the marginal profit of the oligopolists at the end of the S-phase. This can be seen by combining (12) and (15), yielding

$$
\tilde{\Delta} = \frac{1}{r}\ln\left(\frac{\hat{b} - k^c}{\hat{b} - \beta\frac{q^c(T^-)}{n} - k^c}\right), \tag{36}
$$

where $\tilde{\Delta}$ denotes the duration of limit pricing and $T^- \equiv \lim_{t\uparrow T} t$ denotes the end of the S-phase. It follows from Lemma 7 that if S_0^c equals the threshold $\hat{S}_0^c$, we have $\tilde{\Delta} = \hat{\Delta}$. Substitution into (30) then makes clear that the oligopolists serve the entire market at the end of the S-phase, i.e., $q^c(T^-) = q_L$ and $q^f(T^-) = 0$.

The next lemma provides the equilibrium when the initial stock of the oligopolists exceeds the threshold $\hat{S}_0^c$.

Lemma 8 *Suppose marginal profits during limit pricing are positive, i.e., $\hat{\pi} > 0$. Given S_0^f then for any $S_0^c \geq \hat{S}_0^c$ the equilibrium reads $S \to C \to \hat{L}$.*

Proof. See Appendix B.6. □

Intuitively, compared to the equilibrium in Lemma 7, the duration of the limit-pricing phase cannot increase, as is clear from (36), because the oligopolists are already serving the entire market at the end of the S-phase. As a result, the increase in the initial stock of the oligopolists gives rise to the occurrence of an intermediate C-phase before limit-pricing starts.

Lemma 9 characterizes the equilibrium when, given S_0^f, the initial stock of the oligopolists falls short of the threshold $\hat{S}_0^c$, but still exceeds S_{0S}^c.

Lemma 9 *Suppose marginal profits during limit pricing are positive, i.e., $\hat{\pi} > 0$. Given S_0^f then for any $S_0^c \in \left(S_{0S}^c, \hat{S}_0^c\right)$ the equilibrium reads $S \to \tilde{L}$.*

Proof. See Appendix B.7. □

In this case, the oligopolists still have a positive remaining stock at the end of the S-phase, but the remaining stock size is insufficient to have a final limit-pricing phase $\hat{L}$ of duration $\hat{\Delta}$. As a result, there will be limit pricing for a shorter period of time. Therefore, the market share of the oligopolists at the end of the S-phase, q^c/q_L, in this equilibrium will be smaller than in the equilibria described in the previous two lemmata. Moreover, this market share will converge to zero if S_0^c converges to S_{0S}^c (and therefore $\tilde{\Delta}$ converges to zero), as can be noticed from (36).

We now consider the case where $\hat{\pi} \leq 0$.

Lemma 10 *Suppose marginal profits during limit pricing are non-positive, i.e., $\hat{\pi} \leq 0$. Then for any $S_0^c \geq S_{0S}^c$ the equilibrium reads $S \to \tilde{L}$.*

Proof. See Appendix B.8. □

Intuitively, if the oligopolists have an initial stock large enough to end up with a positive remaining stock at the moment when the fringe's stock is depleted, non-positive marginal profits imply that they will maximize profits by adopting a limit-pricing strategy from that moment onwards until depletion, irrespective of the size of their remaining resource stock.

3.3.3 Full characterization

We are now ready to give a full characterization of the OL-OFE. The results from Lemma 1-10 can be collected into Proposition 1.

Proposition 1 (Characterization of the equilibrium)

(i) *Suppose marginal profits during limit pricing are non-positive, i.e.,* $\hat{\pi} \leq 0$. *Then for any given* $S_0^f \geq 0$*, there exists a unique* S_{0S}^c *such that:*

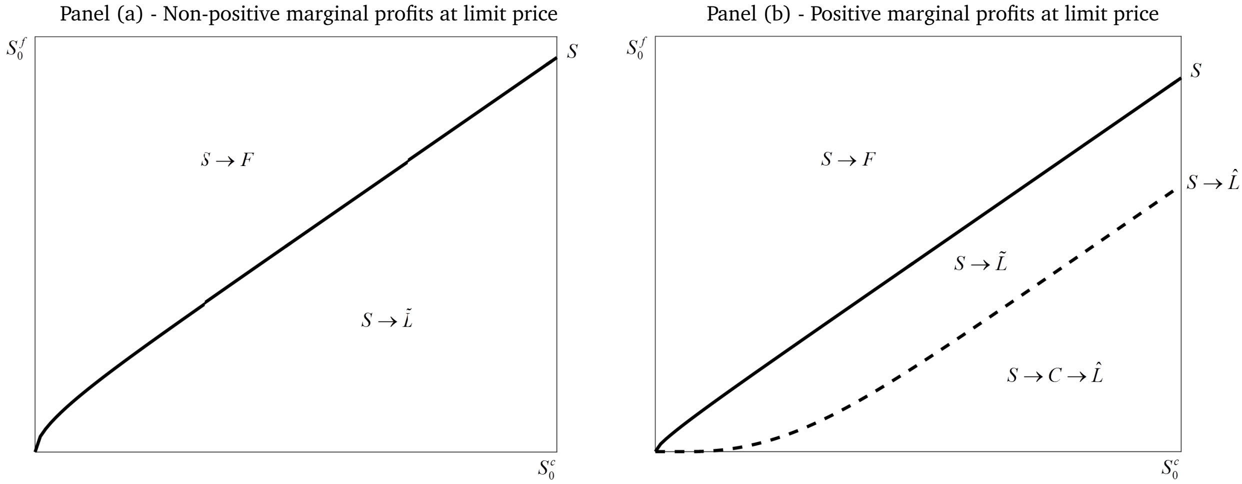
- (a) *If* $S_0^c < S_{0S}^c$ *the equilibrium reads* $S \rightarrow F$*,*
- (b) *If* $S_0^c = S_{0S}^c$ *the equilibrium reads* S*,*
- (c) *If* $S_0^c > S_{0S}^c$ *the equilibrium reads* $S \rightarrow \tilde{L}$*.*

(ii) *Suppose marginal profits during limit pricing are positive, i.e.,* $\hat{\pi} > 0$. *Then for any given* $S_0^f \geq 0$*, there exists a unique* S_{0S}^c *and a unique* $\hat{S}_0^c > S_{0S}^c$*, such that:*

- (a) *If* $S_0^c < S_{0S}^c$ *the equilibrium reads* $S \rightarrow F$*,*
- (b) *If* $S_0^c = S_{0S}^c$ *the equilibrium reads* S*,*
- (c) *If* $S_0^c \in (S_{0S}^c, \hat{S}_0^c)$ *the equilibrium reads* $S \rightarrow \tilde{L}$*,*
- (d) *If* $S_0^c = \hat{S}_0^c$ *the equilibrium reads* $S \rightarrow \hat{L}$*,*
- (e) *If* $S_0^c > \hat{S}_0^c$ *then the equilibrium reads* $S \rightarrow C \rightarrow \hat{L}$*.*

Figure 2 illustrates the equilibrium sequence for different combinations of the initial resource stock of the oligopolists (horizontal axis) and the fringe (vertical axis). Panel (a) shows the case with non-positive marginal profits during limit pricing (part (i) of the proposition), whereas panel (b) shows the case with positive marginal profits during limit pricing (part (ii) of the proposition).

Figure 2: Characterization of the equilibrium



3.4 Comparative statics

We apply our analysis in the context of climate change and examine the effect of specific climate change policies on the equilibrium outcomes. In an oligopoly-fringe market, the effects of climate change policies differ markedly from those under the extreme circumstances of perfect competition and monopoly. In this section, we investigate these effects.

Proposition 2 discusses the effect of a renewables subsidy on initial oil extraction.

Proposition 2 (Renewables subsidy and initial extraction)

(i) If the equilibrium reads $S \to F$, a marginal increase in the renewables subsidy increases initial extraction by the fringe and does not affect initial extraction by the oligopolists.

(ii) If the equilibrium reads $S \to C \to \hat{L}$, a marginal increase in the renewables subsidy does not affect initial extraction by the fringe. If $n = 1$, a marginal increase in the renewables subsidy decreases initial extraction by the oligopolist.

Proof. See Appendix B.9. □

To understand the results in Proposition 2, it is helpful to consider the extreme cases of perfect competition and pure monopoly on the resource market. Under perfect competition, a subsidy for renewables increases initial extraction. This is the standard

Green Paradox effect discussed by Sinn (2008, 2012). The reason is that by making renewables cheaper, the subsidy lowers the future market price of oil. As a result, resource owners respond by depleting their stock more rapidly, which increases initial extraction. With monopolistic resource supply, on the contrary, the resource owner responds to a renewables subsidy by increasing the initial price and thereby lowering extraction (as long as she does not adopt limit pricing from the beginning). So doing, the monopolist effectively postpones entry of renewables producers (cf. Gilbert and Goldman, 1978; Hoel, 1983; Van der Meijden and Withagen, 2016).

As long as the initial aggregate stock of the oligopolists is small relative to that of the fringe, the equilibrium reads $S \to F$ (Proposition 1, parts (ia) and (iia)). In this case, the perfectly competitive mechanism dominates, implying that initial supply goes up in response to an increase in the renewables subsidy (part (i) of Proposition 2). However, if the initial aggregate stock of the oligopolists is relatively large and if marginal profits during limit pricing are positive, the equilibrium sequence reads $S \to C \to \hat{L}$ (Proposition 1, part (iie)). In that case, for $n = 1$ the monopolistic mechanism dominates and initial extraction decreases upon a rise in the renewables subsidy (part (ii) of Proposition 2). For $n > 1$, the degree of imperfect competition may be too low to generate a decrease in initial extraction.

In the intermediate $S \to \tilde{L}$ equilibrium (Proposition 1, parts (ic) and (iic)) the effect of a renewables subsidy on initial extraction is ambiguous. In Section 4.4, we numerically analyze this case.

Proposition 3 considers the effects of climate policy on the duration of limit pricing and the time of depletion.

Proposition 3 (Policy and extraction duration)

(i) If the equilibrium reads $S \to C \to \hat{L}$, a marginal increase in the renewables subsidy and/or the carbon tax decreases the duration of the $\hat{L}$-phase.

(ii) If the equilibrium reads $S \to F$ or $S \to C \to \hat{L}$, a marginal increase in the renewables subsidy (carbon tax) decreases (postpones) the time of depletion.

Proof. See Appendix B.10. □

The result in part (i) can be understood by noting from (30) that the duration of the limit-pricing phase depends on the proportional difference between average profits and marginal profits at the after-tax-and-subsidy renewables price $\hat{b}$. Both a renewables subsidy and a carbon tax lower this proportional difference and thus shorten the duration of the limit-pricing phase.

Part (ii) says that irrespective of the relative initial stocks of the oligopolists and the fringe, an increase in the renewables subsidy brings forward the time of depletion, whereas a carbon tax postpones it. In the perfectly competitive case, the renewables subsidy shifts down (up) the entire resource price (extraction) path, which implies that depletion occurs sooner. Under pure monopoly, although initial extraction goes down, supply during the limit pricing phase goes up. On balance, the depletion time goes down. To understand the increase in the time of depletion upon an increase of the carbon tax, note that the carbon tax effectively increases marginal extraction costs, implying more conservative extraction.

4 Welfare implications of the OL-OFE

We now exploit our analysis above to examine the importance of imperfect competition and the order of extraction of resources in the context of fossil fuels and their contribution to global warming. In our framework, the fact that the fringe may start extracting before the low cost resource is exhausted is a source of inefficiency. This inefficiency is further amplified when we consider the emissions of pollution generated by fossil fuels and their impact on global warming. In this section we calibrate our model to examine the relative importance, in terms of welfare, of the inefficient order of use of fossil fuel reserves. Our calibrated model also allows us to examine the net welfare impact of the shale oil revolution.

We define 'grey' welfare, W^G, as the discounted sum of consumer surplus, producer surplus and tax revenue, minus subsidy costs:[5]

$$W^G \equiv \int_0^{\bar{T}} e^{-rt} \left[\alpha(q^c + q^f) - \frac{1}{2}\beta(q^c + q^f)^2 - k^c q^c - k^f q^f \right] dt$$
$$+ \frac{e^{-r\bar{T}}}{r} \left[\frac{\alpha - b}{\beta}(\alpha - \tau - \hat{b}) - \frac{1}{2}\frac{1}{\beta}(\alpha - \tau - \hat{b})^2 \right],$$

where $\bar{T}$ denotes the moment at which the last resource stock is depleted.[6]

The atmospheric stock of carbon, E, evolves according to

$$\dot{E}(t) = \omega^c q^c(t) + \omega^f q^f(t),$$

where ω^c and ω^f denote the emission factors of the oligopolists and the fringe, respectively. We follow Hoel (2011) and Van der Ploeg (2016) by assuming that climate damages are linear in the stock of atmospheric carbon. The discounted value of climate damage is given by:

$$D(t) = \int_t^{\infty} e^{-r(s-t)} \psi E(s) ds,$$

where $\psi > 0$ denotes the instantaneous and constant marginal damage of carbon. Hence, the social cost of carbon (SCC), i.e., the discounted value of current and future marginal damages, is equal to

$$SCC(t) = \int_t^{\infty} e^{-r(s-t)} \psi ds = \frac{\psi}{r}. \quad (37)$$

Social welfare, W, is defined as the difference between grey welfare and climate damage: $W \equiv W^G - D$.

Firms ignore the damage caused by their activity. Thus in our framework we have two sources of market failure: imperfect competition and a negative climate externality. The evaluation of the impact of market failure cannot entirely be captured by the level of the industry's output alone; it should also take into account the composition of aggregate extraction. Indeed, for a given path of aggregate extraction, the equilibrium

[5]Alternatively, we could define a the quasi-linear utility function $U(q^c + q^f + x) = \alpha(q^c + q^f + x) - \frac{1}{2}\beta(q^c + q^f + x)^2 + M$ (which gives rise to our linear demand function), where x denotes renewables consumption and M expenditure on a *numeraire* good. This results in the same expression for W^G.

[6]In our welfare calculations, we assume that the renewables subsidy remains in place after depletion at time $\bar{T}$.

involves an S-phase during which extraction of the high cost source occurs before the low cost reserve is exhausted. We seek to determine the relative importance of the failure due to the inefficient order of use of resources. For this purpose we compare the OL-OFE exhibited above, with three cases: the socially optimal extraction of reserves also referred to as the first-best (FB), the perfectly competitive (PC) scenario where the owners of the low cost reserves are assumed to be price takers, and the 'Herfindahl scenario'. In this latter scenario, we take the extraction paths of the OL-OFE, but impose the order of resource use of the first-best: first extraction by the oligopolists until their stocks are depleted and then extraction by the fringe until depletion. Hence, total extraction at each instant of time in the Herfindahl scenario is the same as in the OL-OFE, but the extraction sequence differs. This allows us to decompose the deviation of the OL-OFE from the first-best into a 'conservation effect' (i.e., the deviation of the Herfindahl scenario from the first-best) and a 'sequence effect' (i.e., the deviation of the OL-OFE from the Herfindahl scenario).

4.1 Calibration

We calibrate our model by using data on proven oil reserves, global oil consumption, extraction costs, the oil price, the price elasticity of oil demand, and carbon emission factors for different types of oil. Proven reserves owned by OPEC are 1212 billion barrels (EIA, 2017). In the rest of the world, proven reserves excluding shale oil equal 438 billion barrels (EIA, 2017). Furthermore, according to the EIA (2013) shale oil reserves amount to 10 percent of total proven reserves, which implies another 181.5 barrels of oil for the rest of the world. For the parameters of the demand function, we use $\alpha = \frac{2480}{11}$ US$/bbl and $\beta = \frac{800}{184}$ US$/bbl to get an initial oil demand of 44 billion barrels and an initial price of 80 dollars per barrel (roughly equal to the average crude oil consumption and crude oil price over the last decade (EIA, 2017)) and an initial price elasticity of demand of 0.55, which is within the range of long-run price elasticities reported by Hamilton (2009).[7]

For the marginal extraction costs of OPEC, we use the Middle East and North African

[7]By using the price elasticity of demand $\varepsilon \equiv -\frac{dq/q}{dp/(p+\tau)} = \frac{\alpha-\beta q}{\beta q}$ together with the demand function, by imposing $\tau = 0$ we obtain $\alpha = \frac{\varepsilon+1}{\varepsilon}p$ and $\beta = \frac{p}{\varepsilon q}$, yielding values for α and β in terms of the observed initial p, q, and ε.

Table 1: Benchmark calibration

parameters	**description**	**value**	**unit**
α	choke price	2480/11	US$/bbl
β	slope inverse demand function	800/184	US$/bbl
b	renewables price	102.5	US$/BOE
k^c	marginal extraction cost oligopolists	18	US$/bbl
k^f	marginal extraction cost fringe	62.5	US$/bbl
n	number of oligopolists	1	number
r	interest rate	0.028	perunage
S_0^c	initial (aggregate) stock oligopolists	1212	billion bbl
S_0^f	initial stock fringe	619.5	billion bbl
ω^c	emission factor oligopolists	0.11083	tC/bbl
ω^f	emission factor fringe	0.1525	tC/bbl
$SCC = \psi/r$	social costs of carbon	619.5	uS$/tC
implied values	**description**	**value**	**unit**
$q^c(0) + q^f(0)$	initial oil consumption	34	billion bbl
$p(0)$	initial oil price	80	US$/bbl
$\varepsilon(q^c(0) + q^f(0))$	initial price elasticity of demand	0.55	elasticity

oil (MENA) estimate of 18 US$ per barrel reported in Fischer and Salant (2017). For the unit extraction costs of the fringe, we use a weighted average (with the oil reserves as weights)[8] of the other types of oil in Fischer and Salant (2017), which gives 62.5 US$ per barrel. Similarly, for the relative emission factor of the fringe (compared to OPEC) we use a weighted average of the relative emission factors of the different types of oil (excluding the MENA oil) in Fischer and Salant (2017), yielding $\omega^f/\omega^c = 1.376$. For the carbon content of crude oil, we use $\omega^c = 0.11083$ ton carbon per barrel (EPA, 2015).

In all benchmark scenarios, we choose $n = 1$, implying that OPEC is acting as a cohesive cartel. Because of the recent evidence of imperfect cartelization of OPEC (cf. Almoguera et al., 2011; Brémond et al., 2012; Kisswani, 2016; Okullo and Reynès, 2016), we provide a sensitivity analysis with respect to n. Finally, for the renewables unit cost parameter we use $b = 102.5$ US$/BOE ('barrels of oil equivalent') to indeed get an initial oil use equal to 34 billion barrels in equilibrium. Our renewables unit cost corresponds to the unit costs of biofuels after 30 years in Fischer and Salant (2017).[9]

[8]Fischer and Salant (2017) use estimates for the ultimately recoverable resources reported by the IEA (2013), instead of the proven oil reserves.

[9]In their benchmark scenario, Fischer and Salant (2017) assume that the backstop cost initially equals

For the social cost of carbon, we take 250 US$/tC (or 68 US$/tCO_2), which is within the Nordhaus-Stern range of about 31 to 85 US$/t$CO_2$ (Stern, 2007; Nordhaus, 2017).[10]

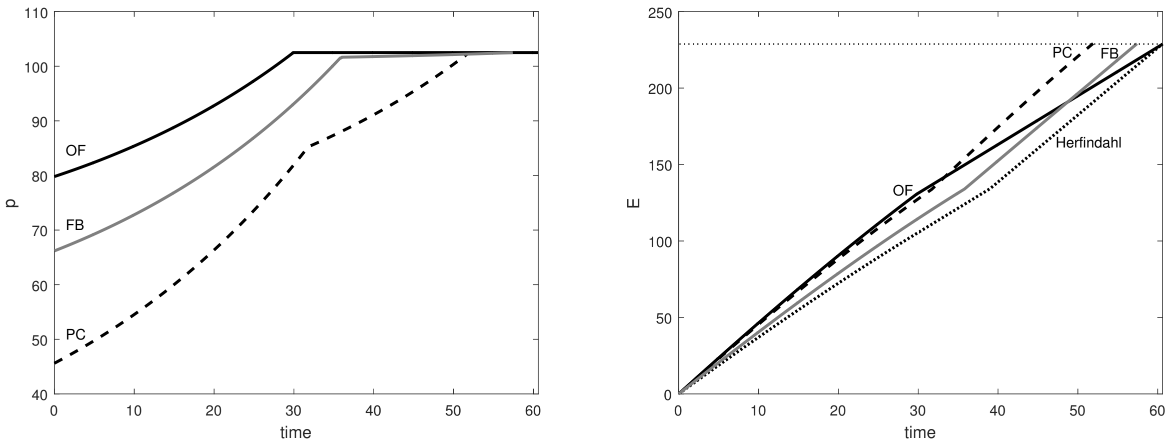
An overview of our benchmark calibration and the implied equilibrium values is provided in Table 1.[11] The equilibrium of the calibrated model is characterized by $\hat{\pi} < 0$ and the sequence $S \to \tilde{L}$.

4.2 The effects of imperfect competition

In this section, we discuss the effects of imperfect competition by comparing the OL-OFE with the outcome under perfect competition, the first-best, and the Herfindahl scenario (i.e., the OL-OFE without the sequence effect).

Figure 3: Time profiles

Panel (a) - Oil price　　　　Panel (b) - Carbon stock



Notes: The figure shows the time profiles of the oil price (panel (a)) and the carbon stock (panel (b)). The solid (dashed) black curves correspond to the oligopoly-fringe, OF (perfectly competitive, PC) equilibrium. The grey curves indicate the first-best outcome, FB. The dotted line in panel (b) represents the Herfindahl scenario. Parameters are set at their benchmark values, as shown in Table 1.

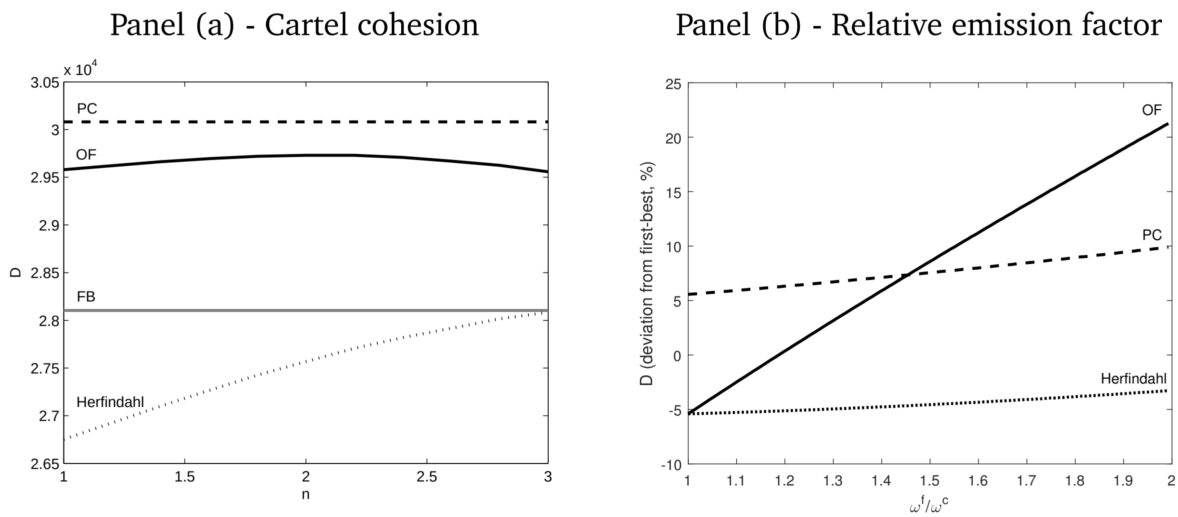
Figure 3 shows the time profiles of the oil price (panel (a)) and the carbon stock (panel (b)) for the benchmark calibration. The black solid and dashed curves represent the OL-OFE and the perfectly competitive equilibrium, respectively. The solid grey line corresponds to the first-best and the dotted line represents the Herfindahl scenario. As

115 US$/BOE and gradually falls over time, due to technological change.

[10]We have $SCC = \frac{\psi}{r}$. Hence, in the benchmark scenario we set $\psi = 250 \cdot 0.028 = 7$ US$/tC.

[11]We use tC to denote 'metric tonnes of carbon', bbl for 'barrels of oil' (one barrel contains about 159 litres) and BOE for 'barrels of oil equivalent'.

Figure 4: Climate damage



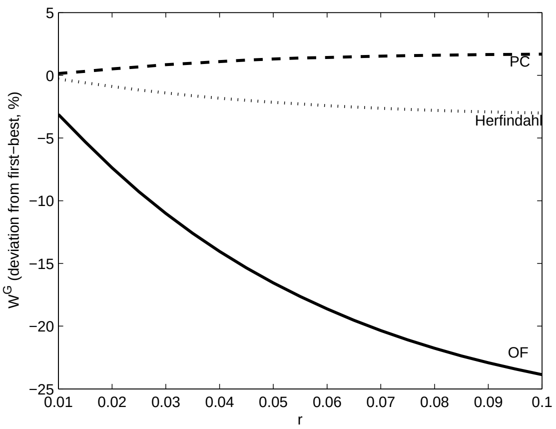
Notes: The figure shows climate damage for various values of n (panels (a)) and ω^f/ω^c (panel (b)). The solid (dashed) black curves correspond to the oligopoly-fringe, OF (perfectly competitive, PC) equilibrium. The grey curves indicate the first-best outcome, FB. The dotted curves represent the Herfindahl scenario. Parameters are set at their benchmark values, as shown in Table 1.

marginal profits during limit pricing are negative and the initial stock of the oligopolists exceeds S^c_{0S} in our calibration, the OL-OFE sequence is $S \to \tilde{L}$ (see Proposition 1 (i,c)): the cartel follows a limit-pricing strategy as soon as the fringe's stock is depleted. In the perfectly competitive equilibrium and in the first-best, the equilibrium sequence reads $C \to F$, implying that the Herfindahl rule is satisfied. The curves in panel (a) show that the time profile of the resource price in the OL-OFE is entirely located above the perfectly competitive one, and even above the one corresponding to the first-best. Still, panel (b) shows that initially the carbon stock grows more rapidly in the OL-OFE than under perfect competition and the first-best. The reason is that although extraction is initially lower in the OL-OFE due to the higher oil price (conservation effect), extraction of relatively dirty oil by the fringe is front-loaded in time in the OL-OFE (sequence effect). The dotted line shows that if we would eliminate the sequence effect, the OL-OFE would generate a carbon stock time profile below the one generated by each of the other cases.

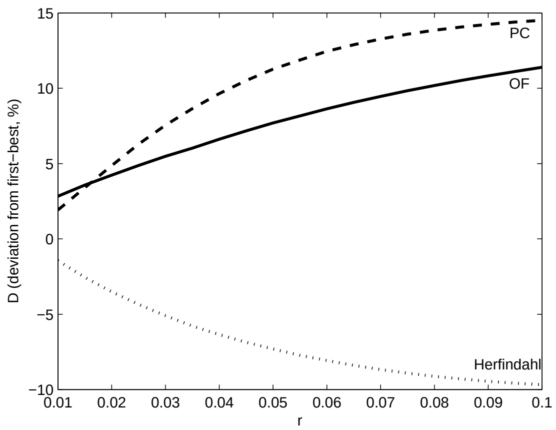
Panel (a) of Figure 4 shows that increasing competition by raising the number of oligopolists above 1 has a non-monotonic effect on climate damages. Damages first go up if n increases from 1 tot 2, because the conservation effect weakens. However,

Figure 5: Welfare deviations from first-best

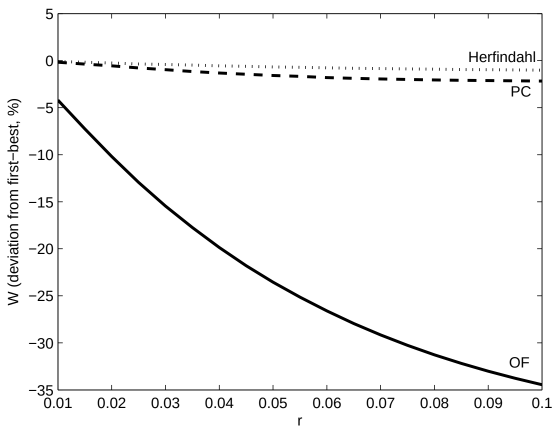
Panel (a) - Grey welfare



Panel (b) - Climate damage



Panel (c) - Social welfare



Notes: The figure shows percentage deviations of grey welfare (panel (a)), climate damage (panel (b)), and social welfare (panel (c)) from the first-best for various values of the interest rate. The solid (dashed) curves correspond to the oligopoly-fringe, OF (perfectly competitive, PC) equilibrium. The dotted line represents the Herfindahl scenario. Parameters are set at their benchmark values, as shown in Table 1.

when n is increased further, damages decline as the weakening of the sequence effect becomes dominant: by increasing competition, relatively cheap and clean OPEC oil crowds out relatively expensive and dirty fringe oil during the early years. Panel (b) depicts how climate damage depends on the emission factor of the fringe compared to that of the cartel. The figure shows the deviation of climate damage from the first-best, in percentage terms. When the relative emission factor equals unity, the OL-OFE coincides with the Herfindahl scenario, as the sequence effect becomes immaterial to climate change. Due to the conservation effect, climate damage is lower than under perfect competition, and even lower than in the first-best. However, by increasing the relative emission factor above 1.2, climate damage becomes higher than in the first-best, and eventually (above 1.45) higher than under perfect competition.

Figure 5 compares the levels of grey welfare (panel (a)), climate damage (panel (b)), and social welfare (panel (c)) between the different scenarios for various values of the interest rate, which is a crucial determinant of the welfare consequences of changes in the sequence of extraction[12] Comparison of the OL-OFE (solid line) and the Herfindahl scenario (dotted line) in the three panels learns that the difference in welfare and climate damage is mainly driven by the sequence effect. In our benchmark scenario with $r = 0.028$, the grey welfare loss in the OL-OFE, compared to the first-best (as depicted in panel (a)), is 10.4 percent, of which only 1.3 percentage points remain in the Herfindahl scenario: 87.5 percent of the grey welfare loss is driven by the sequence effect. Furthermore, at $r = 0.028$ climate damage (panel (b)) is 5.2 percent higher in the OL-OFE equilibrium than in the first-best, while the Herfindahl scenario would give a 4.8 percent *lower* climate damage than in the first-best. Panel (c) shows that social welfare at $r = 0.028$ is 14.5 percent lower in the OL-OFE than in the first-best, of which only 0.4 percentage points remain in the Herfindahl scenario: 97 percent of the loss in social welfare is due to the sequence effect. Panel (c) also shows that the difference between the OL-OFE and the Herfindahl line is increasing in the rate of interest. Intuitively, the higher the rate of interest, the more important timing becomes, and the larger will be the loss in welfare due to the violation of the Herfindahl rule in the OL-OFE.

[12]Throughout the paper, we offset changes in the interest rate by changes in ψ in order to leave the $SCC = \psi/r$ unaffected.

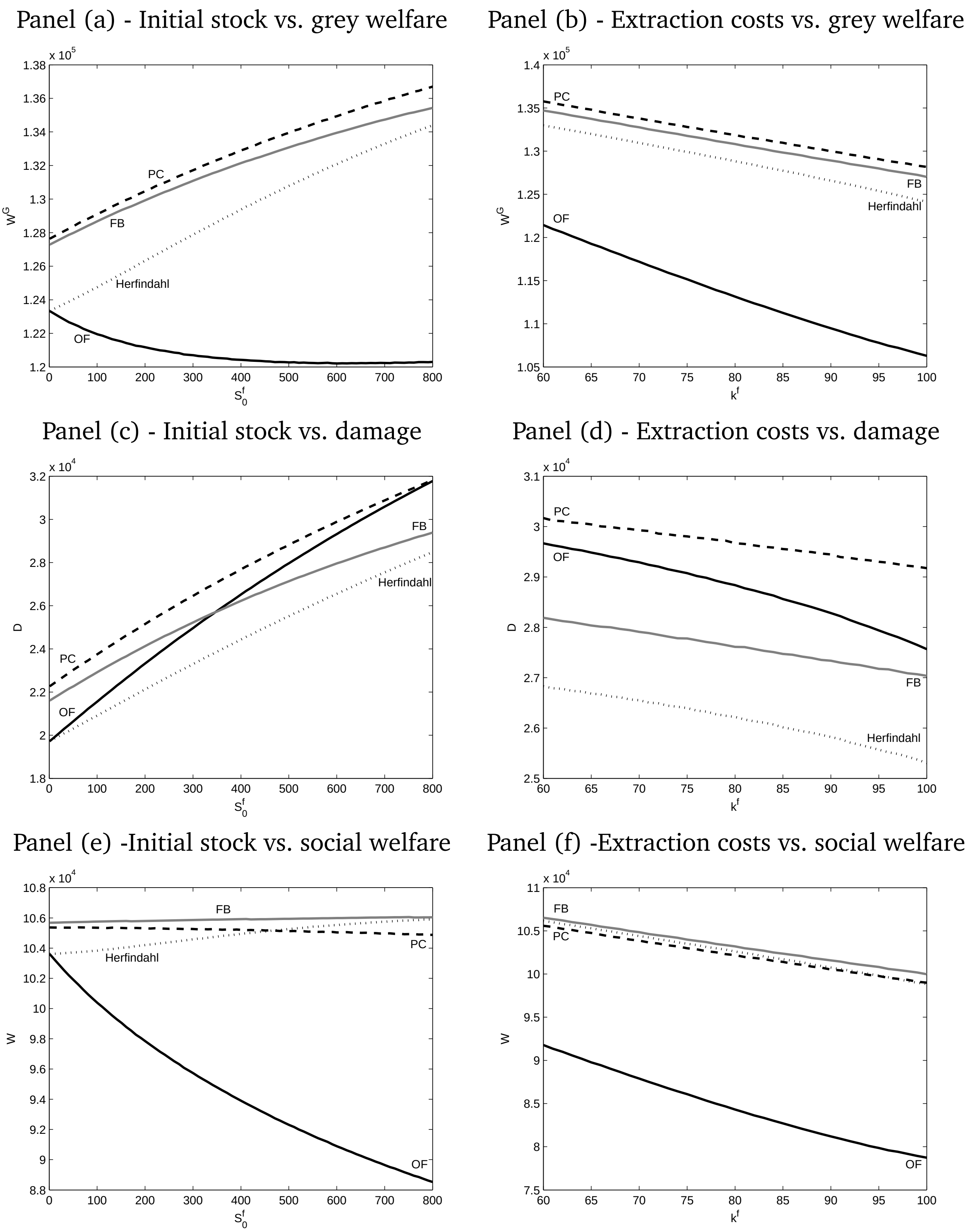
4.3 Shale oil revolution

Figure 6 represents the welfare and climate effects of the recent shale oil revolution, characterized by an increase in the proven reserves (left panels) and a decrease in marginal extraction costs (right panels). The shale oil revolution has increased the reserves of the rest of the world (i.e., the fringe) from 438 to 619 billion barrels EIA (2013), whereas the marginal extraction costs of shale oil have declined from over 100 to about 62.5 US$/bbl (Rystad Energy, 2014; Fischer and Salant, 2017). Panel (a) shows that the increase in resource reserves would have led to higher grey welfare under perfect competition, in the first-best, and in the Herfindahl scenario. However, in the OL-OFE, grey welfare goes down due to the sequence effect. Panel (b) shows that the increase in climate damage due to the increase in shale oil reserves is larger in the OL-OFE than in the other scenarios. It can be noted from panel (c) that the shale glut has decreased social welfare, although it would have increased social welfare in the first-best and the Herfindahl scenario. Panels (b), (d), and (f) show that the decrease in shale oil extraction costs has increased climate damage, but that grey welfare and social welfare nevertheless have increased: given the emissions factors and unit extraction costs considered, the sequence effect is not strong enough to offset the beneficial impact of the fringe's lower extraction costs.

The magnitude of the effects of the shale revolution on climate change, depend obviously on the SCC. Furthermore, the sequence effect in the OL-OFE is crucially affected by the rate of interest: the higher the rate of interest, the more important the timing of extraction becomes for welfare. Therefore, panel (a) of Figure 7 shows combinations of the SCC and the rate of interest for which the increase in the fringe's oil reserves (from 438 to 619.5 billion barrels) lead to an increase (grey area) and a decrease (white area) in social welfare. Similarly, panel (b) shows for which combinations of the SCC and the interest rate the fall in shale oil unit extraction costs (from 82.5 to 62.5) has increased social welfare. Both panels clearly show that for high values of the SCC and the rate of interest (i.e., in the upper-right corners), the shale oil revolution causes a decline in social welfare.

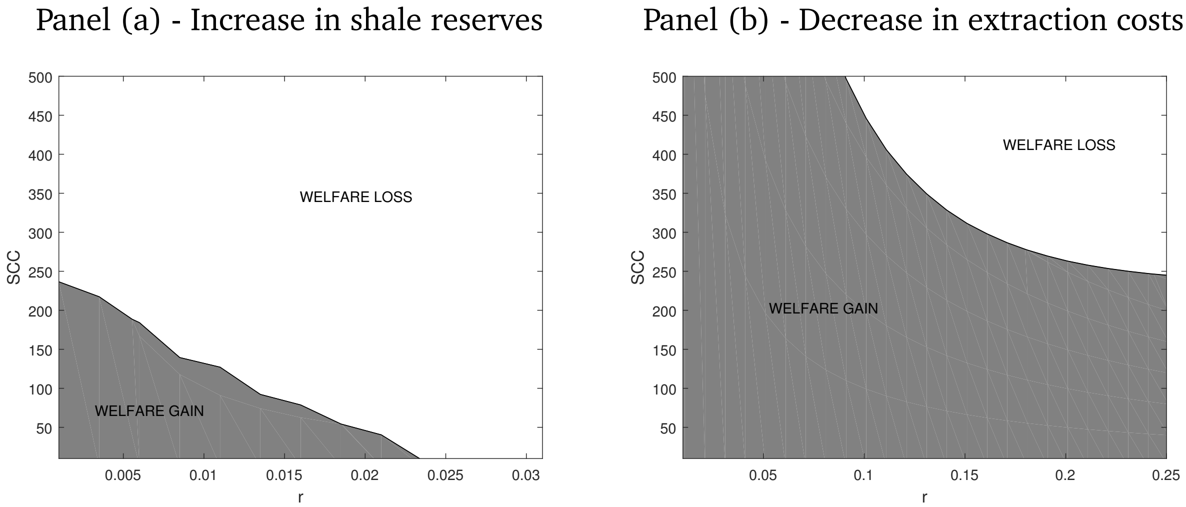
The main conclusion of our analysis is that 97 percent of the loss in social welfare under the oligopoly-fringe framework relative to the first-best is due to the inefficient order of use the resources. Moreover, although the pure conservation effect of imperfect

Figure 6: Welfare effects of the 'shale revolution'



Notes: The figure shows grey welfare (panels (a) and (b)), climate damage (panels (c) and (d)) and social welfare (panels (e) and (f)) for various values of the fringe's initial resource stock and marginal extraction costs. The solid curves correspond to the oligopoly-fringe, OF equilibrium. The dashed black (solid grey) curves indicate the perfectly competitive equilibrium, PC (first-best outcome, FB). The dotted curves represent the Herfindahl scenario. Parameters are set at their benchmark values, as shown in Table 1.

Figure 7: Welfare effects of the 'shale oil revolution'



Notes: The figure shows combinations of r and SCC for which the 'shale oil revolution' has been beneficial for welfare (grey) or detrimental to welfare (white). Panel (a) shows the results for an increase in S_0^f from 438 to 619.5. Panel (b) depicts the outcomes for a decrease of k^f from 82.5 to 62.5. Parameters are set at their benchmark values, as shown in Table 1.

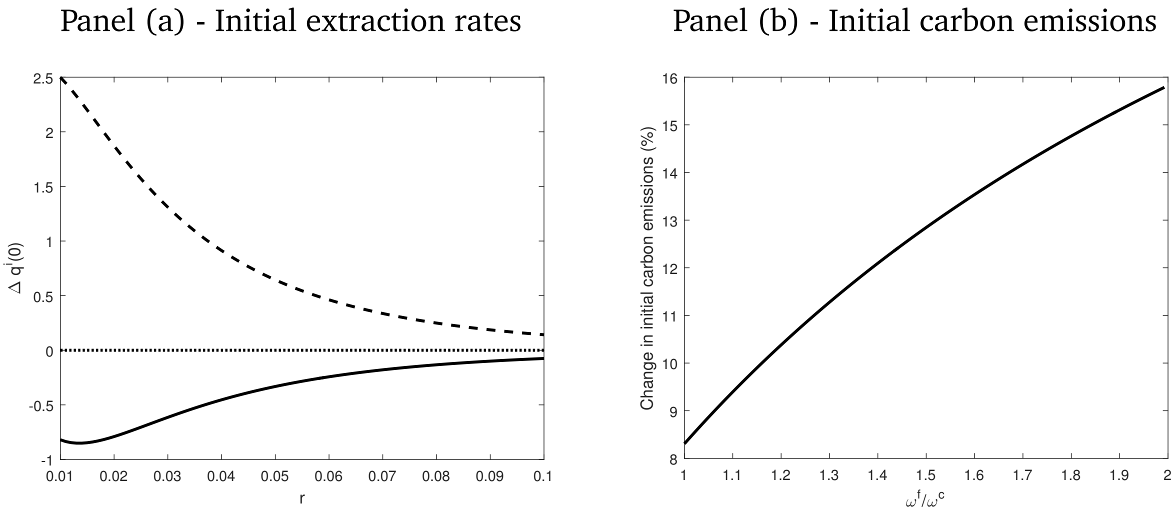
competition would imply 4.8 percent lower climate damages in the OL-OFE than in the first-best, by taking this sequence effect into account, climate damages are actually 5.2 percent *larger* than in the first-best. A lot of attention in the literature and the policy debate on how to address climate change evolves around ways to reduce the use of polluting resources. The merit of the policy options should be evaluated while having this important feature of the climate change problem in mind.

Below we discuss environmental policy options while taking into account their impact on the order of use of the polluting resources.

4.4 Green Paradox and welfare effects of environmental policy

In this section, we first examine the effect of a renewables subsidy on the initial extraction and emission levels. Subsequently, we analyze the welfare and climate effects of renewables subsidies and carbon taxes. Panel (a) of Figure 8 shows that, over a range of different interest rates, a renewables subsidy equal to 10 percent of the renewables unit production cost (i.e., $\sigma = 10.25$) increases initial output of the fringe (dashed line)—in line with the literature on the Green Paradox (Sinn, 2008, 2012)—but decreases output of the cartel (solid line). The decrease in the cartel's initial output is in line with the 'Green *Orthodox*' response of a monopolist to a renewables subsidy (Van der Meijden et al., 2015; Van der Meijden and Withagen, 2016). Panel (b) shows how the increase in initial extraction depends on the relative emission factor for the fringe. If the fringe is as polluting as the cartel, initial emissions would go up by 8.3 percent, whereas they would increase by almost 16 percent if the fringe were twice as polluting as the cartel. In the benchmark scenario with $r = 0.028$, initial emissions go up with 12 percent.

Figure 8: Renewables subsidy and the Green Paradox



Notes: The figure shows the effect of an increase in σ from 0 to 10.25 on the initial extraction rates for various values of the interest rate (panel (a)) and on initial emissions for various values of the relative emission factor ω^f/ω^c (panel (b)). In panel (a), the solid line represents extraction of the oligopolist and the dashed line represents extraction of the fringe. Parameters are set at their benchmark values, as shown in Table 1.

Figure 9 shows the effects of a renewables subsidy (panel (a)) and a carbon tax (panel (b)) on the percentage deviation of social welfare from the first-best. Panel (a) shows that a subsidy would lower welfare under perfect competition, because it speeds up resource depletion and therefore increases climate damage. In the OL-OFE, however, a subsidy may increase social welfare, as long as the subsidy rate is not too high. The reason is that, by counteracting the conservation effect, a small renewables subsidy increases grey welfare. Panel (b) shows that a carbon tax would increase welfare under perfect competition,[13] by slowing down extraction and lowering climate change. In the

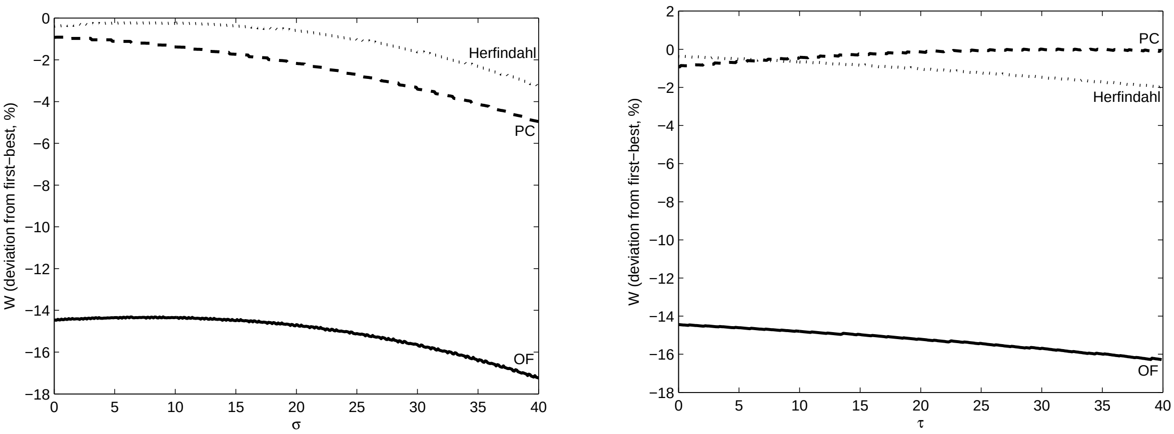
[13]Because extraction by the cartel and by the fringe are taxed at the same rate (so, strictly speaking, τ denotes a *resource* tax instead of a *carbon* tax), the perfectly competitive equilibrium only coincides with the first-best if emission factors of the cartel/oligopolists and the fringe are the same and the tax rate equals the SCC multiplied by the common emission factor. With differing emission factors, the first-best cannot be reached by imposing a resource tax. In the calibrated model, the second-best resource tax rate (i.e., the top of the dashed curve in panel (b) of Figure 9) lies between 27 and 38 US$/ bbl, the SCC of a unit of extraction by the cartel and fringe, respectively).

OL-OFE, however, extraction is already relatively slow and the carbon tax is welfare reducing, although it reduces climate damage.

Figure 9: Welfare effects of climate policies (percentage deviations from first-best)

Panel (a) - Renewables subsidy

Panel (b) - Carbon tax



Notes: The figure shows percentage deviations of social welfare from the first-best for various values of the renewables subsidy (panel (a)) and the carbon tax rate (panel (b)). The solid (dashed) curves correspond to the oligopoly-fringe, OF (perfectly competitive, PC) equilibrium. The dotted curves represent to the Herfindahl scenario. Parameters are set at their benchmark values, as shown in Table 1.

5 Conclusion

The analysis in this paper highlighted the importance of the order of use of different reserves of fossil fuels. A calibrated version of our model revealed that the distortions coming from the inefficient order of use of the different reserves can be of first order. These distortions which are rarely explicitly discussed during climate negotiations could play a major role in a solution to the climate change problem. Our results were established within a model where energy needs are met by fossil fuels (owned by a number of oligopolists and a fringe) and by renewables that are perfect substitutes for fossil fuels and that can be produced in unlimited amounts by using backstop technologies.

Our analysis delivered several important new insights. First, by establishing the existence of and by fully characterizing a Nash-Cournot equilibrium on the energy market, we were able to show that—in line with the current real-world situation—the oligopolists and the fringe start out supplying simultaneously to the market, despite their differing unit extraction costs. If the relative initial stock of the fringe is large, the phase with simultaneous supply will be followed by a phase during which only the fringe is extracting. However, if the initial stock of the cartel is relatively large, the phase with simultaneous supply will be followed by a period during which only the oligopolists are active. During this period, depending on their remaining resource stock and on the marginal profits at the limit price, the oligopolists either choose to price strictly below the price of renewables, or to perform a limit-pricing strategy of just undercutting the renewables price.

Second, by decomposing the welfare and global warming consequences of imperfect competition into a *conservation* and a *sequence* effect, we demonstrated that although the monopolist may be the conservationist's friend, they will certainly not become best friends. On the one hand, the conservation effect indeed slows down climate change by increasing the initial oil price. On the other hand, imperfect competition causes front-loading in time of relatively dirty shale oil, which aggravates global warming. In our calibrated model, imperfect competition reduces social welfare by 14.5 percent compared to the first-best, 97 percent of which is due to the sequence effect. Furthermore, although the conservation effect lowers climate damages by 4.8 percent, by taking the sequence effect into account we find that imperfect competition on balance *increases* climate damages by 5.2 percent.

Third, the analysis of climate policies delivered relevant new insights. In our benchmark scenario a subsidy for renewable energy reduces current OPEC supply, but increases shale oil production. Hence, the average carbon content of current oil supply increases. This provides an additional channel through which announced future climate policies increase current carbon emissions. In our calibrated model, a renewables subsidy equal to 10 percent of the unit production cost of renewable energy, increases current emission by 12 percent.

Fourth, we have shown that the break-down of OPEC has an ambiguous effect on climate damages. On the one hand, climate change is accelerated as extraction becomes less conservative. On the other hand, extraction of the fringe is back-loaded, which slows down climate change as the fringe's resource is relatively dirty. Oil from tar sands in Canada that may soon be transported by the Keystone XL pipeline to refineries in the US might qualify for an even dirtier resource supplied by the fringe, aggravating climate damage from the sequence effect.

Fifth, our results also show that the recent shale oil revolution not only increases climate damage, but also can lower grey welfare as it crowds out relatively cheap OPEC oil. If the interest rate and the social cost of carbon are large enough, the shale oil revolution causes a reduction in social welfare.

Admittedly, our results were derived within a stylized model and under a number of assumptions made for tractability or ease of exposition. For example, alternative models to investigate include the feedback Nash-Cournot and the Stackelberg framework.[14] The analysis of more sophisticated dynamic climate policies would be a natural extension of the analysis. However, we think that addressing the order of use of fossil fuels should be given more careful attention when evaluating different climate change mitigation options. Introducing explicitly the interests of different fossil owners in the research on self-enforcing international environmental agreements is also a fruitful direction for future research. While there is a successful and growing literature on strategic interactions between resource users and resource owners (e.g., Liski and Tahvonen, 2004; Harstad, 2012; Kagan et al., 2015) there is none that tackles the interactions between different resource owners and resource users. Such triangular interactions may well turn out to be key in reaching a sustainable solution to curbing carbon emissions. For example, inspired by Harstad (2012) a possible solution for the problem of inefficient order of use of resources is to allow for the possibility that resource users and owners of the 'cleaner' resource buy out the 'dirtier' reserves or compensate their owners to induce them to halt their extraction. This is obviously not a simple task, however, it is definitely worth further investigation.

[14]Benchekroun and Withagen (2012) show that in a cartel-fringe game (i.e., with the number of oligopolists equal to unity) the feedback and the open-loop Nash-Cournot equilibria coincide. However, this result may not extend to the case with multiple oligopolists.

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Appendix

Throughout this Appendix, we will refer to the stock sizes S^c_{0S}, $\hat{S}^c_0$ and $\hat{S}_L$, and extraction durations T_S, $\hat{T}_S$ and $\hat{\Delta}$, which are defined in the main text and are, for convenience, restated here:

- For each S^f_0 there exists a unique S^c_{0S} such that the equilibrium reads S. The unique duration of this S-phase is denoted by T_S (see Lemma 4).
- For each S^f_0, there exists a unique $\hat{S}^c_0$ such that the equilibrium reads $S \to \hat{L}$. The duration of the S-phase is denoted by $\hat{T}_S$, the duration limit pricing is $\hat{\Delta}$, and the cumulative extraction during limit pricing is $\hat{S}_L$ (see Lemma 7).

A Preliminary results on equilibrium sequences

Lemma A.1 *Suppose the equilibrium reads $S \to F$ with transition at T_S and final time T_F. Then*

$$\begin{aligned} r\beta S^f_0 = & -n(k^f - k^c)(rT_S - 1 + e^{-rT_S}) + (\hat{b} - k^f)(rT_F - 1 + e^{-rT_F}) \\ & + (\alpha - \tau - \hat{b})rT_F, \end{aligned} \tag{A.1}$$

$$r\beta S^c_0 = n(k^f - k^c)(rT_S - 1 + e^{-rT_S}). \tag{A.2}$$

Proof. Along S we have (21) and (22). Along F we have (18). Furthermore $\lambda^f = (\hat{b} - k^f)e^{-rT_F}$. Also $\lambda^c = (k^f - k^c)e^{-rT_S} + \lambda^f = (k^f - k^c)e^{-rT_S} + (\hat{b} - k^f)e^{-rT_F}$. Then taking the time integrals of q^f and q^c yields the result. □

Lemma A.2 *Suppose the equilibrium reads $S \to \tilde{L}$ with transition at $\tilde{T}_S$ and final time $\tilde{T}_L$. Then*

$$\begin{aligned} r\beta S^f_0 = & \left(\alpha - \tau + nk^c - (n+1)k^f\right) r\tilde{T}_S - n(\hat{b} - k^c)e^{-r\tilde{T}_L}(1 - e^{r\tilde{T}_S}) \\ & - (n+1)(\hat{b} - k^f)(1 - e^{-r\tilde{T}_S}), \end{aligned} \tag{A.3}$$

$$\begin{aligned} r\beta S^c_0 = & n(k^f - k^c)r\tilde{T}_S + n(\hat{b} - k^f)(1 - e^{-r\tilde{T}_S}) + n(\hat{b} - k^c)e^{-r\tilde{T}_L}(1 - e^{r\tilde{T}_S}) \\ & + (\alpha - \tau - \hat{b})r(\tilde{T}_L - \tilde{T}_S). \end{aligned} \tag{A.4}$$

Proof. Along S we have (21) and (22). Along the $\tilde{L}$-phase we have (27). It follows from (15) that $\lambda^c = (\hat{b} - k^c)e^{-r\tilde{T}_L}$. It follows from (19) together with price continuity that $\lambda^f = (\hat{b} - k^f)e^{-r\tilde{T}_S}$. Then taking the time integrals of q^f and q^c yields the result. □

Note that the Hamiltonian is discontinuous at $\tilde{T}_S$ if the initial stocks differ from those in Lemma 6: q^c and μ jumps upward $\tilde{T}_S$, while q^f jumps downward.

Lemma A.3 *Suppose the equilibrium reads $S \to C \to \hat{L}$ with transitions at $\bar{T}_S$ and $\bar{T}_C$ and final time $\bar{T}_L$. Then*

$$r\beta S_0^f = \left(\alpha - \tau + nk^c - (n+1)k^f\right)(r\bar{T}_S - 1 + e^{-r\bar{T}_S}), \tag{A.5}$$

$$\begin{aligned} r\beta S_0^c = &\frac{n}{n+1}\left((n+1)k^f - nk^c - (\alpha - \tau)\right)(r\bar{T}_S - 1 + e^{-r\bar{T}_S}) \\ &+ \frac{n}{n+1}\left(\frac{n+1}{n}\hat{b} - k^c - \frac{\alpha - \tau}{n}\right)(r\bar{T}_C - 1 + e^{-r\bar{T}_C}) \\ &+ (\alpha - \tau - \hat{b})r\bar{T}_L, \end{aligned} \tag{A.6}$$

$$(\hat{b} - k^c)e^{-r\bar{T}_L} = \left[\left(1 + \frac{1}{n}\right)\hat{b} - \frac{\alpha - \tau}{n} - k^c\right]e^{-r\bar{T}_C}. \tag{A.7}$$

Proof. Along S we have (21) and (22). Along the C-phase we have (25). Along the $\hat{L}$-phase we have (27). Moreover, we have $\lambda^c = (\hat{b} - k^c)e^{-r\bar{T}_L}$. The price is continuous at $\bar{T}_S$ so that

$$k^f + \lambda^f e^{r\bar{T}_S} = \frac{1}{n+1}\left(\alpha - \tau + n(k^c + \lambda^c e^{r\bar{T}_S})\right). \tag{A.8}$$

Condition (A.7) is obtained by combining (12) and (15) and using price continuity at $t = \bar{T}_C$. Then taking the time integrals of q^f and q^c yields the result. □

B Proofs of Lemmata 2-3 and 5-10 and Propositions 2-3

B.1 Proof of Lemma 2.

Part (i). Given our definition of C and F a transition can only take place at a moment T where the price is below b. Indeed, in an equilibrium the price is increasing in both phases and must therefore be smaller than b. The price is continuous at T:

$$\begin{aligned} p(T) &= \alpha - \beta(q^f(T) + q^c(T)) = k^f + \lambda^f e^{rT} \\ &= \frac{1}{n+1}(\alpha - \tau + n(k^c + \lambda^c e^{rT})). \end{aligned}$$

If we have $F \to C$ then it follows from (16) and (17) that $k^f + \lambda^f e^{rT} \leq k^c + \lambda^c e^{rT}$. Hence $\left[(n+1)(k^f + \lambda^f e^{rT}) - (\alpha - \tau)\right] \frac{1}{n} \geq k^f + \lambda^f e^{rT}$, implying $p(T) \geq \alpha - \tau$, a contradiction. The proof for $C \to F$ is similar.

Part (ii). Suppose it is optimal to have $F \to \hat{L}$ or $F \to \tilde{L}$ and assume the transition takes place at T. Then for $0 \leq t \leq T$ we have

$$q^f(t) = \frac{\alpha - \tau - k^f - \lambda^f e^{rt}}{\beta}, q^f(T) = \frac{\alpha - \tau - \hat{b}}{\beta} \tag{A.9}$$

because of price continuity. Hence:

$$\begin{aligned} \hat{b} - k^f &= \lambda^f e^{rT}, \\ q^f(t) &= \frac{\alpha - \tau - k^f - (\hat{b} - k^f)e^{rt - rT}}{\beta}. \end{aligned}$$

The oligopolists should not want to supply before T so that for $0 \leq t \leq T$ we have

$$\alpha - \tau - \beta\left[\frac{\alpha - \tau - k^f - (\hat{b} - k^f)e^{r(t-T)}}{\beta}\right] \leq k^c + \lambda^c e^{rt} = k^c + (\hat{b} - k^c)e^{r(t-T^c)}, \tag{A.10}$$

from (15), or $k^f(1 - e^{r(t-T)}) - k^c(1 - e^{r(t-T^c)}) \leq \hat{b}e^{rt - rT^c}(1 - e^{r(T^c - T)})$. Take the limit for t approaching T. Then the condition boils down to $(\hat{b} - k^c)(1 - e^{r(T-T^c)}) \leq 0$, a contradiction.

Part (iii). Along F we have $k^f + \lambda^f e^{rt} \leq k^c + \lambda^c e^{rt}$, which implies $k^f - k^c \leq (\lambda^c - \lambda^f)e^{rt}$. At the transition from F to S at say T we have from the continuity of the price $k^f - k^c = (\lambda^c - \lambda^f)e^{rt}$. Because we have assumed $k^f > k^c$, the left-hand sides of the latter two expressions are positive. Hence, the right-hand side of these expressions is growing over time. However, since F precedes S, $(\lambda^c - \lambda^f)e^{rt}$ is larger than $k^f - k^c$ before T and equal to $k^f - k^c$ at T. Hence, the right-hand sides must be declining, which yields a contradiction.

Part (iv). Suppose the initial regime is C. Then it follows from (23) and (24) that along C we have $\alpha - \tau + nk^c - (n+1)k^f \leq ((n+1)\lambda^f - n\lambda^c)e^{rT}$. There is no transition possible to F. Hence there must be a transition to S, say at T. So $\alpha - \tau + nk^c - (n+1)k^f = ((n+1)\lambda^f - n\lambda^c)e^{rT}$. Since $\alpha - \tau + nk^c - (n+1)k^f > 0$ by assumption and C starts at time 0, we have $(n+1)\lambda^f - n\lambda^c > 0$, so that $((n+1)\lambda^f - n\lambda^c)e^{rt}$ is increasing over time, yielding a contradiction. □

B.2 Proof of Lemma 3.

Along S we have (21) and (22). Moreover, $\lambda^c = (\hat{b} - k^c)e^{-rT_S}$ and $p(T_S) = \alpha - \beta(q^f(T_S) + q^c(T_S)) = \hat{b}$ so that $\lambda^f = (\hat{b} - k^f)e^{-rT_S}$. Then taking the time integrals of q^f and q^c yields the result. □

B.3 Proof of Lemma 5.

First rewrite the system (A.1) and (A.2) as

$$\begin{aligned} \mathbf{F}(T_S, T_F) &= 0 \\ \mathbf{G}(T_S, T_F) &= 0 \end{aligned}$$

where

$$\begin{aligned} \mathbf{F}(T_S, T_F) \equiv & -n(k^f - k^c)(rT_S - 1 + e^{-rT_S}) + (\hat{b} - k^f)(rT_F - 1 + e^{-rT}) \\ & + (\alpha - \tau - \hat{b})rT_F - r\beta S_0^f \\ \mathbf{G}(T_S, T_F) \equiv & \, n(k^f - k^c)(rT_S - 1 + e^{-rT_S}) - r\beta S_0^c \end{aligned}$$

Given S_0^c, if the equilibrium reads $S \to F$ then the transition time T_S denotes the duration of the equilibrium the equilibrium that reads S.

Now given T_S, is there a solution $T_F \geq T_S$ that solves $\mathbf{F}(T_S, T_F) = 0$? When $S_0^f = S_{0S}^f$ we have $\mathbf{F}(T_S, T_S) = 0$, so when $S_0^f > S_{0S}^f$ we get $\mathbf{F}(T_S, T_S) < 0$. We derive

$$\begin{aligned} \mathbf{F}_T &= r\left((\hat{b} - k^f)(1 - e^{-rT_F}) + (\alpha - \tau - \hat{b})\right) > 0, \\ \mathbf{F}_{TT} &= r^2(\hat{b} - k^f)e^{-rT_F} > 0. \end{aligned}$$

Hence, $\mathbf{F}$ is monotonically increasing and strictly convex in T_F. As a result, there exists at most one T_F that solves $\mathbf{F}(T_S, T_F) = 0$ with $T_F > T_S$. Such a solution exists if

$$\lim_{T\to\infty} \mathbf{F}(T_S, T_F) > 0.$$

We have $\lim_{T\to\infty} \mathbf{F}(T_S, T_F) = \lim_{T_F\to\infty} \left(\hat{b} - k^f + \alpha - \tau - b\right) rT_F = \infty$. □

B.4 Proof of Lemma 6.

Along S we have (21) and (22). Along the $\hat{L}$-phase we have (27). It follows from (19) that $\lambda^f = (\hat{b} - k^f)e^{-r\hat{T}_S}$. It follows from (20) and continuity of the price and the Hamiltonian of the cartel that $\lambda^c = \left[\left(1 + \frac{1}{n}\right)\hat{b} - \frac{\alpha-\tau}{n} - k^c\right] e^{-r\hat{T}_S}$. Condition (35) is obtained by combining (12) and (15). Then taking the time integrals of q^f and q^c yields the result. □

B.5 Proof of Lemma 7.

Given S_0^f there exists a unique T denoted $\hat{T}_S$ that satisfies

$$r\beta S_0^f = (\alpha - \tau + nk^c - (n+1)k^f)(rT - 1 + e^{-rT}).$$

Next, we establish that $\hat{T}_S > T_S$. Note from (31)-(32) that T_S is the solution to

$$\begin{aligned} r\beta S_0^f &= (\hat{b} + nk^c - (n+1)k^f)(rT_S - 1 + e^{-rT_S}) + (\alpha - \tau - \hat{b})rT_S \\ &= (\alpha - \tau + nk^c - (n+1)k^f)(rT_S - 1 + e^{-rT_S}) + (\alpha - \tau - \hat{b})\left(1 - e^{-rT_S}\right). \end{aligned}$$

Let $\mathbf{f}(T) \equiv (\alpha - \tau + nk^c - (n+1)k^f)(rT - 1 + e^{-rT})$. We have $\mathbf{f}' > 0$ and $\mathbf{f}\left(\hat{T}_S\right) = \mathbf{f}(T_S) + (\alpha - \tau - \hat{b})\left(1 - e^{-rT_S}\right) > \mathbf{f}(T_S)$, implying $\hat{T}_S > T_S$.

We now argue that there exist $\hat{T}^L = \hat{T}_S + \hat{\Delta}$ and $\hat{S}_0^c > S_{0S}^c + \hat{S}_L$ which satisfy (34) and (35):

$$\begin{aligned} r\beta\hat{S}_0^c &= (\hat{b} - (\alpha - \tau) + n(k^f - k^c))(r\hat{T}_S - 1 + e^{-r\hat{T}_S}) \\ &\quad + (\alpha - \tau - \hat{b})r\left(\hat{T}_S + \hat{\Delta}\right), \qquad \text{(A.11)} \\ (\hat{b} - k^c)e^{-r\hat{\Delta}} &= (1 + \frac{1}{n})\hat{b} - \frac{\alpha - \tau}{n} - k^c). \qquad \text{(A.12)} \end{aligned}$$

Condition (35) is satisfied by definition of $\hat{Delta}$.

The rest of the proof consists of showing that the stock given by (A.11), $\hat{S}_0^c$, is larger than $S_{0S} + \hat{S}_L$. Using the definition of $\hat{S}_L$, (A.11) becomes

$$r\beta\left(\hat{S}_0^c - \hat{S}_L\right) = (\hat{b} - (\alpha - \tau) + n(k^f - k^c))(r\hat{T}_S - 1 + e^{-r\hat{T}_S}) + (\alpha - \tau - \hat{b})r\hat{T}_S. \quad \text{(A.13)}$$

Summing (33) with $T = \hat{T}_S$ and (A.13) yields

$$\begin{aligned} r\beta\left(\hat{S}_0^c - \hat{S}_L + S_0^f\right) &= (\alpha - \tau + nk^c - (n+1)k^f)(r\hat{T}_S - 1 + e^{-r\hat{T}_S}) \\ &\quad + (\hat{b} - (\alpha - \tau) + n(k^f - k^c))(r\hat{T}_S - 1 + e^{-r\hat{T}_S}) \\ &\quad + (\alpha - \tau - \hat{b})r\hat{T}_S, \\ &= (\hat{b} - k^f)(r\hat{T}_S - 1 + e^{-r\hat{T}_S}) + (\alpha - \tau - \hat{b})r\hat{T}_S, \\ &= (\hat{b} - k^f)\mathbf{g}\left(\hat{T}_S\right) + (\alpha - \tau - \hat{b})r\hat{T}_S, \end{aligned} \quad \text{(A.14)}$$

where $\mathbf{g}(T) \equiv rT - 1 + e^{-rT}$. By definition of S_{0S}^c we have

$$r\beta S_0^f = (\hat{b} + nk^c - (n+1)k^f)(rT_S - 1 + e^{-rT_S}) + (\alpha - \tau - \hat{b})rT_S, \quad \text{(A.15)}$$

$$r\beta S_{0S}^c = n(k^f - k^c)(rT_S - 1 + e^{-rT_S}). \quad \text{(A.16)}$$

Summing (A.15) and (A.16) gives

$$r\beta\left(S_{0S}^c + S_0^f\right) = (\hat{b} - k^f)(rT_S - 1 + e^{-rT_S}) + (\alpha - \tau - \hat{b})rT_S, \quad \text{(A.17)}$$

$$= (\hat{b} - k^f)\; g\left(T_S\right) + (\alpha - \tau - \hat{b})rT_S. \quad \text{(A.18)}$$

Since $\mathbf{g}\left(T\right) + (\alpha - b)rT$ is increasing in T and since $\hat{T}_S > T_S$, we have from (A.14) and (A.18) $r\beta\left(S_{0S}^c + S_0^f\right) < r\beta\left(\hat{S}_0^c - \hat{S}_L + S_0^f\right)$, implying $\hat{S}_0^c > S_{0S}^c + \hat{S}_L$. $\square$

B.6 Proof of Lemma 8.

The proof consists of showing that there exist $\bar{T}_S$ and $\bar{T}_C$ such that the system (A.5)-(A.7) holds, where $\bar{T}_L = \bar{T}_C + \hat{T}_{LM}$. Note that given S_0^f the solution to $r\beta S_0^f = (\alpha - \tau + nk^c - (n+1)k^f)(rT - 1 + e^{-rT})$ is unique and therefore $\bar{T}_S$ is the same as the duration of the S phase when $S_0^c = S_{0S}^c + \hat{S}_L$ that is when the regime reads $S \to \hat{L}$. Hence, $\bar{T}_S = \hat{T}_S$.

The proof now consists of showing that there exists $\bar{T}_C$ that solves

$$\begin{aligned}\mathbf{Y}(\bar{T}_C) \equiv & -r\beta S_0^c + \frac{n}{n+1}\Big((n+1)k^f - nk^c - (\alpha-\tau)\Big)(r\bar{T}_S - 1 + e^{-r\bar{T}_S}) \\ & + \frac{n}{n+1}\left(\frac{n+1}{n}\hat{b} - k^c - \frac{\alpha-\tau}{n}\right)(r\bar{T}_C - 1 + e^{-r\bar{T}_C}) \\ & + (\alpha-\tau-\hat{b})r\bar{T}_L = 0.\end{aligned}$$

We know that $\mathbf{Y}\left(\bar{T}_S\right) < 0$ for $S_0^c > \hat{S}_0^c$ since $\mathbf{Y}\left(\bar{T}_S\right) = 0$ when $S_0^c = \hat{S}_0^c$. Moreover, we have $\lim_{\bar{T}_C\to\infty}\mathbf{Y}\left(\bar{T}_C\right) = \infty$ and $\mathbf{Y}' > 0$, which implies the existence and unicity of $\bar{T}_C$ that solves $\mathbf{Y}\left(\bar{T}_C\right) = 0$. $\square$

B.7 Proof of Lemma 9.

To prove Lemma 9 it will be useful to make the following two remarks.

Remark 1 *Given S_0^f, when S_0^c approaches S_{0S}^c from above, $\tilde{T}_L$ and $\tilde{T}_S$ approach T_S: the $\tilde{L}$ collapses. Indeed simple substitution of S_0^c by S_{0S}^c, $\tilde{T}_S$ by T_S and $\tilde{T}_L$ by T_S shows that the system* (A.3)-(A.4) *becomes after simplification*

$$r\beta S_0^f = (\hat{b} + nk^c - (n+1)k^f)(rT_S - 1 + e^{-rT_S}) + (\alpha-\tau-\hat{b})rT_S, \tag{A.19}$$

$$r\beta S_{0S}^c = n(k^f - k^c)(rT_S - 1 + e^{-rT_S}), \tag{A.20}$$

which holds by definition of T_S and S_{0S}^c (see Lemma 3).

Remark 2 *Given S_0^f, when $S_0^c = \hat{S}_0^c$ we have $\tilde{T}_S = \hat{T}_S$ and $\tilde{T}_L = \hat{T}_S + \hat{\Delta}$: the length of $\tilde{L}$ equals the length of $\hat{L}$. Indeed simple substitution of these three equalities in* (A.3)-(A.4) *and using* (35) *gives*

$$r\beta S_0^f = (\alpha - \tau + nk^c - (n+1)k^f)(r\hat{T}_S - 1 + e^{-r\hat{T}_S}), \tag{A.21}$$

$$\begin{aligned}r\beta\hat{S}_0^c = & (\hat{b} - (\alpha-\tau) + n(k^f - k^c))(r\hat{T}_S - 1 + e^{-r\hat{T}_S}) \\ & + (\alpha-\tau-\hat{b})r(\hat{T}_S + \hat{\Delta}),\end{aligned} \tag{A.22}$$

$$(\hat{b} - k^c)e^{-r(\hat{T}_S+\hat{\Delta})} = \left[\left(1+\frac{1}{n}\right)\hat{b} - \frac{\alpha-\tau}{n} - k^c\right]e^{-r\hat{T}_S}. \tag{A.23}$$

which holds by definition of $\hat{T}_S$, $\hat{\Delta}$, and $\hat{S}_0^c$ (see Lemma 6 and Lemma 7).

The proof of Lemma 9 makes use of the remarks above. It consists of showing that for any S_0^f and for any $S_0^c \in \left[S_{0S}^c, \hat{S}_0^c\right]$ there exists $\tilde{T}_S$ and $\tilde{T}_L \geq \tilde{T}_S$ such that (A.3) and (A.4) are satisfied. The sum of (A.3) and (A.4) reads

$$r\beta\left(S_0^f + S_0^c - \frac{\alpha-\tau-\hat{b}}{\beta}(\tilde{T}_L - \tilde{T}_S)\right) = (\alpha-\tau-k^f)r\tilde{T}_S - (\hat{b}-k^f)(1-e^{-r\tilde{T}_S}). \quad \text{(A.24)}$$

Condition (A.24) defines a unique relationship between the duration of limit pricing $\tilde{T}_L - \tilde{T}_S$ and the time of transition (or duration of the S phase); we rewrite this condition as

$$\tilde{T}_L - \tilde{T}_S = \mathbf{H}\left(\tilde{T}_S, S_0^f, S_0^c\right) \equiv \frac{r\beta\left(S_0^f + S_0^c\right) - (\alpha-\tau-k^f)r\tilde{T}_S + (\hat{b}-k^f)(1-e^{-r\tilde{T}_S})}{(\alpha-\tau-\hat{b})r}. \quad \text{(A.25)}$$

Manipulations allow to rewrite (A.3) as $e^{r\left(\tilde{T}_L - \tilde{T}_S\right)} = \mathbf{Z}\left(\tilde{T}_S, S_0^f\right)$, with

$$\mathbf{Z}\left(\tilde{T}_S, S_0^f\right) \equiv \frac{n(\hat{b}-k^c)(1-e^{-r\tilde{T}_S})}{r\beta S_0^f + (n+1)(\hat{b}-k^f)(1-e^{-r\tilde{T}_S}) - (\alpha-\tau+nk^c-(n+1)k^f)r\tilde{T}_S}. \quad \text{(A.26)}$$

Substituting $\tilde{T}_L - \tilde{T}_S = \mathbf{H}\left(\tilde{T}_S, S_0^f, S_0^c\right)$ allows us to characterize $\tilde{T}_S$ as the solution to

$$\mathbf{W}\left(\tilde{T}_S, S_0^f, S_0^c\right) = 0, \text{ with } \mathbf{W}\left(\tilde{T}_S, S_0^f, S_0^c\right) \equiv e^{\mathbf{H}\left(\tilde{T}_S, S_0^f, S_0^c\right)} - \mathbf{Z}\left(\tilde{T}_S, S_0^f\right). \quad \text{(A.27)}$$

We argue that, given S_0^f, for any $S_0^c \in \left[S_{0S}^c, \hat{S}_{0S}^c\right]$ there exists a solution $\tilde{T}_S$ to (A.27). From Remark 1 and Remark 2 above we get

$$\mathbf{W}\left(T_S, S_0^f, S_{0S}^c\right) = 0 = \mathbf{W}\left(\hat{T}_S, S_0^f, \hat{S}_{0S}^c\right).$$

As $\mathbf{W}\left(\tilde{T}_S, S_0^f, S_0^c\right)$ is an increasing function of S_0^c, we have for any $S_0^c \in \left(S_{0S}^c, \hat{S}_{0S}^c\right)$

$$\mathbf{W}\left(T_S, S_0^f, S_0^c\right) > \mathbf{W}\left(T_S, S_0^f, S_{0S}^c\right) = 0,$$
$$\mathbf{W}\left(\hat{T}_S, S_0^f, S_0^c\right) < \mathbf{W}\left(\hat{T}_S, S_0^f, \hat{S}_{0S}^c\right) = 0.$$

Since $\mathbf{W}\left(\tilde{T}_S, S_0^f, S_0^c\right)$ is a continuous function of $\tilde{T}_S$ we can therefore state that for any $S_0^c \in \left[S_{0S}^c, \hat{S}_{0S}^c\right]$ there exists a solution $\tilde{T}_S \in \left[T_S, \hat{T}_S\right]$ to $\mathbf{W}\left(\tilde{T}_S, S_0^f, S_0^c\right) = 0$.

We still need to check that for any $S_0^c \in \left(S_{0S}^c, \hat{S}_{0S}^c\right)$ we have $\mathbf{H}\left(\tilde{T}_S, S_0^f, S_0^c\right) > 0$ where $\tilde{T}_S \in \left[T_S, \hat{T}_S\right]$ is solution to $\mathbf{W}\left(\tilde{T}_S, S_0^f, S_0^c\right) = 0$, that is $e^{\mathbf{H}\left(\tilde{T}_S, S_0^f, S_0^c\right)} = \mathbf{Z}\left(\tilde{T}_S, S_0^f\right) > 1$. This last inequality holds indeed since (i) $\mathbf{Z}\left(T_S, S_0^f\right) = e^{\mathbf{H}\left(T_S, S_0^f, S_{0S}^c\right)} = 1$ (see Remark 1) and (ii) $\frac{\partial \mathbf{Z}}{\partial \tilde{T}_S} > 0$ and therefore $\mathbf{Z}\left(\tilde{T}_S, S_0^f\right) > \mathbf{Z}\left(T_S, S_0^f\right) > 1$ for all $\tilde{T}_S > T_S$. Indeed one can check that $\frac{\partial \mathbf{Z}}{\partial \tilde{T}_S} > 0$: rewrite (A.26) as

$$\mathbf{Z}\left(\tilde{T}_S, S_0^f\right) = \frac{n(\hat{b} - k^c)}{\frac{r\beta S_0^f}{1-e^{-r\tilde{T}_S}} + (n+1)(\hat{b} - k^f) + (\alpha - \tau + nk^c - (n+1)k^f)\frac{-r\tilde{T}_S}{1-e^{-r\tilde{T}_S}}}. \tag{A.28}$$

The denominator is an decreasing function of $\tilde{T}_S$ since both $\frac{r\beta S_0^f}{1-e^{-r\tilde{T}_S}}$ and $\frac{-r\tilde{T}_S}{1-e^{-r\tilde{T}_S}}$ are decreasing functions of $\tilde{T}_S$ and the term $(\alpha - \tau + nk^c - (n+1)k^f) > 0$ from Assumption 2. This implies that $\frac{\partial \mathbf{Z}}{\partial \tilde{T}_S} > 0$. □

B.8 Proof of Lemma 10.

If $\hat{\pi} \leq 0$, once the stock of the fringe is depleted (which occurs before depletion of the oligopolists' stocks if $S_0^c > S_{0S}^c$) the equilibrium is $\tilde{L}$ until exhaustion (from (28)). Moreover, Lemma 2 implies that the initial regime is S. Finally, a transition from F to $\tilde{L}$ is ruled out. We rule out as well a transition from S to F because $S_0^c > S_{0S}^c$.

Indeed, suppose that, given S_0^f, we have for $S_0^c > S_{0S}^c$ a sequence $S \to F$, i.e., from Lemma A.1, there exist T_S and T_F with $T_S < T_F$ that solve

$$\begin{aligned} r\beta S_0^f = & -n(k^f - k^c)(rT_S - 1 + e^{-rT_S}) + (\hat{b} - k^f)(rT_F - 1 + e^{-rT_F}) \\ & + (\alpha - \tau - \hat{b})rT_F, \end{aligned} \tag{A.29}$$

$$r\beta S_0^c = n(k^f - k^c)(rT_S - 1 + e^{-rT_S}). \tag{A.30}$$

The value of T_S is uniquely determined by S_0^c, moreover the value of T_F and hence of the duration of the F phase is a strictly increasing function of S_0^f. Now, given $S_0^c > S_{0S}^c$, consider the stock $\tilde{S}_0^f$ such that when the fringe owns a stock $\tilde{S}_0^f = \Phi^{-1}\left(S_0^c\right)$ (the function Φ^{-1} defined immediately after Lemma 3) and the oligopolists own a stock S_0^c we have the equilibrium consisting only of an S phase: the duration of the F phase is nil. However we know that since $S_0^c > S_{0S}^c$ we have $\tilde{S}_0^f = \Phi^{-1}(S_0^c) > S_0^f = \Phi^{-1}(S_{0S}^c)$ (since the function Φ^{-1} is strictly increasing) and therefore if the duration of the F phase is positive under the stocks S_0^c and S_0^f it should be longer and therefore also positive, when the stock of the oligopolists is S_0^c and the stock of the fringe $\tilde{S}_0^f > S_0^f$. Hence a contradiction of the fact that the duration of the phase is nil under the stocks S_0^c and $\tilde{S}_0^f$, by definition of $\tilde{S}_0^f$.

This rules out a sequence $S \to F$ when $S_0^c > S_{0S}^c$ and only leaves $S \to \tilde{L}$ as equilibrium sequence if $\hat{\pi} \leq 0$ and $S_0^c > S_{0S}^c$. □

B.9 Proof of Proposition 2.

To prove part (i), note from (A.2) that $\frac{dT_S}{d\sigma} = 0$, from (22) that $\frac{dq^c(0)}{d\sigma} = \frac{n}{\beta}d\left(\lambda^f - \lambda^c\right)$, and from (16), (20) and price continuity that $\lambda^c - \lambda^f = (k^f - k^c)e^{-rT_S}$. Combining these expressions yields $\frac{dq^c(0)}{d\sigma} = 0$. To prove the increase in $q^f(0)$ upon a marginal increase in σ, we totally differentiate (A.1)-(A.2) and use $p(t) = k^f + (\hat{b} - k^f)e^{-r(T_F - t)}$ to obtain

$$\frac{dp(0)}{d\sigma} = \frac{[\alpha - (b - \sigma)]e^{-rT_F}}{(\hat{b} - k^f)e^{-rT_F} - (\alpha - \tau - k^f)} < 0, \tag{A.31}$$

where the inequality follows from Assumption 2. As $\frac{dq^c(0)}{d\sigma} = 0$, $\frac{dp(0)}{d\sigma} < 0$ implies $\frac{dq^f(0)}{d\sigma} = 0 > 0$.

To prove part (ii), note from (A.5) that $\frac{d\bar{T}_S}{d\sigma} = 0$. Furthermore, by integrating (21) and imposing the fringe's resource constraint, we obtain

$$S_0^f = \int_0^{\bar{T}_S} q^f(t)dt = \frac{1}{\beta}\left(\alpha - \tau - (n+1)k^f + nk^c\right)\bar{T}_S + \frac{n\lambda^c - (n+1)\lambda^f}{r\beta}\left(e^{r\bar{T}_S} - 1\right).$$

Combining these two results yields

$$n\frac{d\lambda^c}{d\sigma} = (n+1)\frac{d\lambda^f}{d\sigma}. \tag{A.32}$$

Evaluating (21) at $t = 0$, taking the derivative with respect to σ and imposing (A.32), we find $\frac{dq^f(0)}{d\sigma} = 0$. To prove the decrease in $q^c(0)$ upon a marginal increase in σ if $n = 1$

we totally differentiate (A.5)-(A.8) to find

$$\frac{dp(0)}{d\sigma} = \frac{n[\alpha - (b-\sigma) - r(\bar{T}_L - \bar{T}_C)(\hat{b} - k^c)]e^{-r\bar{T}_C}}{(1+n)e^{r(\bar{T}_L - \bar{T}_C)}(b-\sigma-\alpha) - (1-e^{-r\bar{T}_C})n(\hat{b}-k^c)} > 0 \text{ if } n = 1, \quad \text{(A.33)}$$

where the inequality follows from noting that the denominator is negative due to Assumption 2, and by using (A.7) to rewrite the term between brackets in the numerator as

$$\frac{1 - r(\bar{T}_L - \bar{T}_C)}{e^{-r(\bar{T}_L - \bar{T}_C)}}\left[\left(1+\frac{1}{n}\right)\hat{b} - \frac{\alpha-\tau}{n} - k^c\right] - [2\hat{b} - \alpha + \tau - k^c], \quad \text{(A.34)}$$

which is negative for $n = 1$. As $\frac{dq^f(0)}{d\sigma} = 0$, $\frac{dp(0)}{d\sigma} > 0$ implies $\frac{dq^c(0)}{d\sigma} = 0 < 0$. □

B.10 Proof of Proposition 3.

For the equilibrium sequence $S \to F$, we totally differentiate (A.1)-(A.2) to get

$$\frac{dT_F}{d\sigma} = \frac{1 - e^{-rT_F}}{r[(\hat{b} - k^f)e^{-rT_F} - (\alpha - \tau - k^f)]} < 0, \quad \text{(A.35)}$$

$$\frac{dT_F}{d\tau} = -\frac{e^{-rT} - 1 + rT_F}{r[(\hat{b} - k^f)e^{-rT_F} - (\alpha - \tau - k^f)]} > 0, \quad \text{(A.36)}$$

where the inequalities follow from Assumption 2.

For the equilibrium sequence $S \to C \to \hat{L}$, we totally differentiate (A.5)-(A.7) to obtain

$$\frac{d\bar{T}_L}{d\sigma} = -\frac{(1-e^{-r\bar{T}_C})n + e^{r(\bar{T}_L - \bar{T}_C)}(1+n)r(\bar{T}_L - \bar{T}_C)}{e^{r(\bar{T}_L - \bar{T}_C)}(1+n)r[\alpha - (b-\sigma)] + (1-e^{-r\bar{T}_C})nr(\hat{b}-k^c)} < 0, \quad \text{(A.37)}$$

$$\frac{d\bar{T}_L}{d\tau} = -\frac{(1-e^{-r\bar{T}_C} - e^{r(\bar{T}_L - \bar{T}_C)}r\bar{T}_C)n}{e^{r(\bar{T}_L - \bar{T}_C)}(1+n)r[\alpha - (b-\sigma)] + (1-e^{-r\bar{T}_C})nr(\hat{b}-k^c)} > 0, \quad \text{(A.38)}$$

$$\frac{d(\bar{T}_L - \bar{T}_C)}{d\sigma} = \frac{n(\alpha - k^c - \tau)}{[\alpha - b(1+n) + \sigma + n(k^c + \sigma + \tau)]^2} > 0, \quad \text{(A.39)}$$

$$\frac{d(\bar{T}_L - \bar{T}_C)}{d\tau} = \frac{n[\alpha - (b-\sigma)]}{[\alpha - b(1+n) + \sigma + n(k^c + \sigma + \tau)]^2} > 0, \quad \text{(A.40)}$$

where the inequalities follow from Assumption 2. □

C Perfectly competitive equilibrium and first-best

In the perfectly competitive equilibrium, the oligopolists take the price path as given. Hence, the necessary conditions associated with each oligopolist i's problem is given by he Hamiltonian associated with the fringe's problem reads

$$\mathcal{H}_i^c = e^{-rt}(p(t) - k^c)q_i^c + \lambda^c[-q_i^c]. \tag{A.41}$$

The necessary conditions include

$$p(t) = \alpha - \tau - \beta(q^f(t) + q^c(t)) \leq k^c + \lambda^c e^{rt}, \tag{A.42}$$

$$[k^c + \lambda^c e^{rt} - (\alpha - \tau) + \beta(q^c(t) + q^c(t))]q_i^c(t) = 0, \tag{A.43}$$

$$\dot{\lambda}^c = 0. \tag{A.44}$$

Along C we have

$$p(t) = \alpha - \tau - \beta q^c(t) = k^f + \lambda^c e^{rt}, \tag{A.45}$$

$$p(t) = \alpha - \tau - \beta q^c(t) \leq k^c + \lambda^f e^{rt}, \tag{A.46}$$

$$q^c(t) = \frac{1}{\beta}(\alpha - \tau - k^c - \lambda^c e^{rt}). \tag{A.47}$$

Throughout a phase of simultaneous use, (7) and (A.42) must hold with equality, which is not possible because $k^f > k^c$. Hence, simultaneous use cannot occur in a perfectly competitive equilibrium. A limit-pricing phase requires a constant price, which contradicts (A.43). Furthermore, the equilibrium sequence $F \to C$ can be excluded, because, according to (8), during the initial regime the net price $p - k^f$ grows at the rate of intrest, implying that the net price $p - k^c$ would grow at a rate lower than the rate of interest (because $k^f > k^c$). Hence, the oligopolists prefer current extraction over future extraction and will undercut the fringe's price. Therefore, the unique equilibrium sequence under perfect competition reads $C \to F$. Thus, by integrating (18) and (A.47) over time, denoting the transition time by T_1 and the depletion time by T_2, using the terminal condition $\lambda^f = (\hat{b} - k^f)e^{-rT_2}$, the price continuity condition $k^c + \lambda^c e^{rT_1} = k^f + \lambda^f e^{rT_1}$, and the resource constraints of the oligopolists and the fringe, we find that the perfectly competitive equilibrium is described by

$$r\beta S_0^f = (\hat{b} - k^f)\left(r(T_2 - T_1) - 1 + e^{-r(T_2 - T_1)}\right) + (\alpha - \tau - \hat{b})r(T_2 - T_1), \tag{A.48}$$

$$r\beta S_0^c = -(k^f - k^c)\left(1 - e^{-rT_1}\right) - (\hat{b} - k^f)\left(e^{-r(T_2 - T_1)} - e^{-rT_2}\right) + (\alpha - \tau - k^c)rT_1. \tag{A.49}$$

In the perfectly competitive equilibrium described by (A.48)-(A.49) the only remaining market failure is the climate externality. Hence, the competitive equilibrium coincides with the first-best if carbon is priced at a rate equal to the SCC. This requires $\tau = \frac{\omega^c \psi}{r}$ during C and $\tau = \frac{\omega^f \psi}{r}$ during F. By imposing these optimal tax rates together with $\sigma = 0$, by integrating (18) and (A.47) over time, denoting the first-best transition time by T_1^* and the first-best depletion time by T_2^*, using the terminal condition $\lambda^f = (b - \frac{\omega^f \psi}{r} - k^f)e^{-rT_2}$, the social cost continuity condition $k^c + \lambda^c e^{rT_1^*} + \frac{\omega^c \psi}{r} = k^f + \lambda^f e^{rT_1^*} + \frac{\omega^f \psi}{r}$, and the resource constraints of the oligopolists and the fringe, we find that the first-best is described by

$$r\beta S_0^f = \left(b - \frac{\psi\omega^f}{r} - k^f\right)\left(r(T_2^* - T_1^*) - 1 + e^{-r(T_2^* - T_1^*)}\right) + (\alpha - b)r(T_2^* - T_1^*),$$

$$r\beta S_0^c = -\left(k^f - k^c + \frac{\psi(\omega^f - \omega^c)}{r}\right)\left(1 - e^{-rT_1^*}\right) + (\alpha - \frac{\psi\omega^c}{r} - k^c)rT_1^* - \left(b - \frac{\psi\omega^f}{r} - k^f\right)\left(e^{-r(T_2^* - T_1^*)} - e^{-rT_2^*}\right).$$