Leadership and Commitment in Oil Markets: Market Power Meets Climate Policy*

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Abstract

We examine how leadership and commitment in oil markets affect climate damages, welfare, and the effectiveness of climate policy. Using a cartel–fringe model with renewables and climate damages, we compare Nash–Cournot, open-loop von Stackelberg, and feedback von Stackelberg equilibria. Our results show that leadership changes extraction patterns: when the cartel acts as a von Stackelberg leader, relatively more polluting extraction by the fringe is postponed, reducing climate damages relative to Nash–Cournot. However, the absence of commitment in feedback equilibria limits these gains and can even increase damages with respect to Nash-Cournot. We quantify these welfare losses and decompose them into a conservation and sequence effect. We show both for carbon taxes and renewable subsidies that small policy changes can trigger abrupt shifts in extraction regimes, causing large jumps in welfare and climate damages. Marginal changes in climate policies can have qualitatively different impacts on climate damages than non-marginal changes. These findings highlight that a von Stackelberg type of leadership can either amplify or reduce climate damages, and that policy design must account for discontinuous responses.

JEL codes: Q01, Q30, Q38, Q42

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1 Introduction

The interaction between market power in fossil fuel markets and climate change has attracted growing attention in recent years. A long-standing intuition holds that monopolists are "the conservationist's best friend," because higher prices reduce extraction and emissions. Yet, this intuition is challenged in dynamic settings where multiple producers differ in extraction costs, carbon intensities, and strategic behavior. Understanding these interactions is crucial for designing climate policy and anticipating the welfare consequences of imperfect competition.

Recent empirical work has quantified the climate implications of market power in oil markets. Asker et al. (2019) document substantial welfare losses from misallocation in global oil extraction, estimating costs of $744 billion between 1970 and 2014, with 14–22% attributable to market power. Extending this analysis, Asker et al. (2024) show that OPEC's market power may have reduced cumulative emissions by 67 $GtCO_2$—about 18% of the carbon budget for the 1.5 °C Paris target—suggesting that the conservation effect can dominate. Conversely, Coulomb et al. (2025) document that inefficient sequencing—"carbon misallocation"—added at least 10 $GtCO_2$ between 1992 and 2008, causing damages of USD 2 trillion. These findings reveal a tension: market power can slow extraction but also distort extraction order, accelerating the use of carbon-intensive resources.

The theoretical literature provides a framework for interpreting these effects. Building on the seminal work of Hotelling (1931), dynamic models of exhaustible resources have evolved to incorporate strategic interactions. Early contributions such as Salant (1976); Lewis and Schmalensee (1980a,b); Ulph and Folie (1980); Newbery (1981); Ulph (1982) and Salant (1982) introduced cartel-fringe and oligopoly models, later refined by Groot et al. (2000, 2003). An overview can be found in Withagen (2013).

More recently, Benchekroun et al. (2020) introduce a dynamic cartel–fringe model with heterogeneous carbon intensities and show that market power indeed generates the two opposing forces found in the empirical literature, namely a *conservation effect* (lower total extraction) and a *sequence effect* (earlier extraction of dirtier oil). In their Nash–Cournot setting, the sequence effect dominates, raising climate damages by 5.3% relative to the social optimum. Kellogg (2024) uses a cartel-fringe model with investment in exploration to revisit the effects of expected future fossil fuel demand.

He finds that the 'disinvestment effect' (less investment in fossil infrastructure) dominates the 'green paradox effect' (acceleration of fossil fuel extraction) under realistic conditions.

Despite these advances, two gaps remain. First, most theoretical work assumes that the cartel and the fringe make their decisions simultaneously, whereas real-world cartels often act as leaders anticipating fringe responses. Second, existing cartel-fringe models of the oil market rarely incorporate renewable backstop technologies or climate damages explicitly. Our paper addresses both gaps by analyzing a dynamic game where the cartel is a von Stackelberg leader and the fringe is a follower, under the presence of renewables and climate damages. We compare three equilibrium concepts—Nash–Cournot, open-loop von Stackelberg, and feedback von Stackelberg—and contrast them with the social optimum and perfect competition.

This paper builds upon our previous work (Benchekroun et al., 2020, 2025) and on the accompanying study Elgersma et al. (2025). In Elgersma et al. (2025), we formally characterize the different equilibria and address the associated technical challenges. In this paper, we make four contributions. First, we explicitly show how leadership and the presence or absence of commitment shape extraction patterns in dynamic cartel–fringe games. While open-loop von Stackelberg leadership allows the cartel to dominate early supply due to the presence of commitment, Nash-Cournot and feedback von Stackelberg equilibria feature simultaneous extraction in the initial phase. Second, we quantify welfare losses and climate damages under alternative market structures and decompose them into conservation and sequence effects, highlighting how leadership and commitment alter these components. Third, we demonstrate that imperfect competition is not always good for the climate: leadership can mitigate the sequence effect, but time-consistency constraints may offset these gains. Fourth, we analyze climate policies—carbon taxes and renewable subsidies—and show that small policy changes can trigger abrupt shifts in extraction regimes, causing jumps in welfare and climate damages.

The remainder of the paper is organized as follows. Section 2 presents the model and equilibrium concepts. Section 3 calibrates the model to the global oil market and quantifies the effects of leadership and commitment. Section 4 shows the effect of cost reductions in resource extraction and renewables production, due to technical change. Section 5 discusses the effects of climate policies. Section 6 concludes.

2 The model

2.1 Set-up

We analyze an energy market. Energy can be generated from a non-renewable resource and a renewable backstop technology. The cartel owns a stock of exhaustible resources denoted by $S^c(t)$ at time t, with initial stock S^c_0. The competitive fringe consists of many identical price-taking firms whose combined stock is $S^f(t)$, with initial level S^f_0.[1]

Marginal extraction costs are constant: k^c for the cartel, k^f for the fringe, and b for the backstop. Production rates at time t are $q^c(t)$ for the cartel, $q^f(t)$ for the fringe, and $q^r(t)$ for renewables. The inverse residual demand function for energy is:

$$p(t) = \min\{b, \alpha - \beta(q^c(t) + q^f(t) + q^r(t))\}, \tag{1}$$

where $\alpha > 0$ and $\beta > 0$. We allow for the existence of renewable substitutes that cannot fully meet market demand. Our demand function should be interpreted as the *residual* demand for energy after subtracting the supply of these renewable substitutes (cf. Andrade de Sá and Daubanes, 2016). Throughout the paper, our use of the term *renewables* refers to the substitute produced by the backstop technology, which can supply unlimited energy at the constant unit cost b.

We impose the following parameter restrictions:

$$k^c < k^f < \tfrac{1}{2}(\alpha + k^c) < \alpha, \qquad k^f < b < \alpha.$$

These assumptions imply that cartel extraction is cheaper than fringe extraction and that the backstop cost lies in between the cartel's unit extraction cost and the choke price In the absence of resource scarcity and government policies, the backstop is too costly to be ever used. The term $\frac{1}{2}(\alpha + k^c)$ will later appear as the unconstrained

[1] In our numerical analysis in Section 3, we leave out coal and gas. Hence, our energy market there should be interpreted as energy used for transportation (where oil is the primary energy source and coal and gas only play a minor role).

monopoly price when the cartel's stock is large. Resource extraction generates carbon emissions at rate ω^c for the cartel and ω^f for the fringe. We assume $\omega^c < \omega^f$. The cost of carbon is constant and external to the firms.

The equilibrium must satisfy the resource constraint

$$\int_0^\infty q^c(t)\,dt = S_0^c, \qquad \int_0^\infty q^f(t)\,dt = S_0^f.$$

Furthermore $q^r(t) > 0$ can happen only if $p(t) = b$. The fringe is a price-taker. Its discounted profit is given by

$$\Pi^f = \int_0^\infty e^{-rt}[p(t) - k^f]q^f(t)\,dt.$$

If active along an interval of time, the fringe follows Hotelling's rule:

$$\frac{d(p(t) - k^f)}{dt} = r(p(t) - k^f) \text{ if } q^f(t) > 0,$$

where r is the constant interest rate, assumed identical for all producers. The cartel's discounted profit is:

$$\Pi^c = \int_0^\infty e^{-rt}[\alpha - \beta(q^c(t) + q^f(t)) - k^c]q^c(t)\,dt,$$

where renewable supply is omitted because it occurs only after depletion of both non-renewable stocks.

2.2 Supply regimes

Different sequences of supply regimes can occur in equilibrium. We denote these regimes as follows:

- C: cartel supplies at the competitive price, which satisfies Hotelling's rule:

  $$p(t) = k^c + e^{rt}\lambda^c,$$

  where λ^c is the endogenously determined shadow price of the cartel's stock.

- C^f: cartel supplies at the fringe's competitive price, which satisfies Hotelling's rule:

$$p(t) = k^f + e^{rt}\lambda^f \equiv P^f(t),$$

where λ^f is the endogenously determined shadow price of the fringe's stock.

- C^m: cartel charges the unrestricted monopoly price:

$$p(t) = \frac{1}{2}(\alpha + k^c) + \frac{1}{2}e^{rt}\lambda^c \equiv P^m(t),$$

- F: fringe supplies alone.
- S: cartel and fringe supply simultaneously, with $p(t) = P^f(t) < b$.
- L: cartel sets a limit price equal to or slightly below b, keeping renewables from the market.
- R: only renewables supply.

2.3 Equilibrium concepts

We use three equilibrium concepts: Nash-Cournot, open-loop von Stackelberg, and feedback von Stackelberg. These equilibria are derived in detail in Benchekroun et al. (2020), Benchekroun et al. (2025) and Elgersma et al. (2025), respectively. Here, we will focus on the essentials.

We will also compare these three equilibria to the social optimum and the perfectly competitive outcome. In the perfectly competitive outcome, the unique equilibrium sequence is $C \to F$, which satisfies the Herfindahl rule since cheap reserves are depleted before more expensive reserves are exploited (recall the unit extraction costs satisfy $k^c < k^f$). The social optimum is also characterized by the sequence $C \to F$, but accounts for the social cost of carbon, which implies that extraction is slowed down compared to the perfectly competitive case under *laissez-faire* (recall that the emission factors satisfy $\omega_c < \omega_f$).

Nash-Cournot In this equilibrium, the cartel maximizes its profits at time zero by choosing a supply *path* taking the supply path of the fringe as given, while the fringe simultaneously maximizes its profits by choosing a supply path taking the price path as given.[2] Producers of renewable energy serve residual demand if the price is equal to their unit cost (including the scarcity rent). The equilibrium satisfies resource constraints, and the energy market clears at each instant of time. As shown by Benchekroun et al. (2019), under our parameter restrictions, for a given initial stock of the fringe, the three possible equilibrium sequences are:

(i) $S \rightarrow F \rightarrow R$ (if the cartel's initial stock is small);

(ii) $S \rightarrow L \rightarrow R$ (for intermediate values of the cartel's initial stock);

(iii) $S \rightarrow C^m \rightarrow L \rightarrow R$ (if the cartel's initial stock is large).

As long as both the cartel and the fringe start with a strictly positive stock, the equilibrium thus begins with a phase of simultaneous supply, denoted by S. This follows from our parameter assumptions: sole supply by the fringe (F) cannot occur before the cartel's stock is depleted, because otherwise the cartel would undercut the fringe. Similarly, the cartel cannot supply alone—whether at the fringe's competitive price (C^f), the monopoly price (C^m), or the limit price (L)—before the fringe's stock is exhausted, since the fringe would undercut the cartel.

After the initial S-phase, the sequence depends on the cartel's initial stock. If the cartel's stock is relatively small, the sequence continues with $F \rightarrow R$. If the cartel's stock is somewhat larger, the next phases are $L \rightarrow R$. Finally, if the cartel's stock is sufficiently large, the simultaneous supply phase is followed by $C^m \rightarrow L \rightarrow R$. The region with $S \rightarrow C^m \rightarrow L \rightarrow R$ disappears when $b < \frac{1}{2}(\alpha + k^c)$, because in that case the cartel cannot set the unrestricted monopoly price P^m.

Importantly, the existence of an initial S-phase implies a violation of the Herfindahl rule, since cheap and expensive oil are supplied simultaneously from the outset.

Open-loop von Stackelberg In the open-loop von Stackelberg equilibrium with a price-taking fringe, the leader (i.e., the cartel) announces and commits to a price *path* at time zero. The follower (i.e., the fringe) then takes this price path as given and chooses its extraction path, also at time zero. In equilibrium, both players' discounted

[2] We formulated the Nash-Cournot equilibrium here as the outcome of an open-loop game (à la Salant (1976)). However, in this setting the open-loop cartel-fringe equilibrium coincides with the feedback cartel-fringe equilibrium (cf. Benchekroun and Withagen, 2012; Kellogg, 2024).

profits are maximized, the resource constraints are satisfied, and the energy market clears at each instant of time.

This situation is equivalent to allowing the cartel, at time zero, to select a price path and simultaneously determine the fringe's supply path, subject to the condition that the fringe is indifferent between extracting at different points in time (and subject to the resource constraints and market clearance).

Because the cartel effectively controls the fringe's supply path, leadership enables the cartel to choose C^f (serving the entire market at the fringe's competitive price P^f), or to choose C^m (serving the entire market at the monopoly price P^m) already before the fringe's stock is depleted. This is not possible under Nash-Cournot. Nevertheless, similar to Nash-Cournot, the cartel can still opt for limit pricing L (serving the entire market at the backstop price) once the fringe's stock is exhausted.

As shown by Benchekroun et al. (2025), under our parameter assumptions, increasing the cartel's initial stock while keeping the fringe's stock fixed leads to the following equilibrium sequences as we gradually increase the cartel's stock:

(i) $C^f \to F \to R$ (for small S_0^c);

(ii) $C^f \to F \to L \to R$;

(iii) $C^f \to F \to C^m \to L \to R$;

(iv) $C^f \to C^m \to F \to C^m \to L \to R$ (for large S_0^c).

This outcome is intuitive. When the cartel's initial stock is small, it will be exhausted while the fringe is still active (case (i)). With a larger initial stock, the cartel still has a positive stock left when the fringe's stock is depleted; in this situation, it opts for limit pricing if the remaining stock is relatively small or if the backstop cost is relatively low (case (ii)). If the remaining stock is substantial and the backstop cost is sufficiently large, it becomes profitable to set the monopoly price immediately after the fringe exits the market (case (iii)). For an even larger initial stock, it is advantageous to adopt the monopoly price already before the fringe enters (case (iv)). By varying the unit cost of the backstop technology instead of the initial stock of the cartel, the equilibrium can also move between the different sequences: a lower backstop cost decreases market power which can make the equilibrium sequence change from case (iv), with two unrestricted monopoly pricing phases to sequences with only one (case (iii)) or no unrestricted monopoly pricing phase at all (case (ii)), as shown by Benchekroun et al. (2025).

Unlike the Nash–Cournot equilibrium, there is no simultaneous supply under open-loop von Stackelberg: at price P^f, the cartel either supplies the entire market itself or leaves the market entirely to the fringe. Moreover, every equilibrium sequence begins with C^f. This implies that all sequences except (i) are time-inconsistent: once C^f ends, the cartel, upon recalculating its optimum, would prefer to continue with another C^f-phase (also in case (i), but there its stock is depleted). A marginal increase in the length of C^f-phase shortens the following $F-$phase, which increases the discounted sum of profits of the cartel (Elgersma et al. (2025), appendix ...). Moreover, at phase transitions between F and C^m the market price jumps (Benchekroun et al., 2025). Time inconsistency and (anticipated) discontinuities in energy prices are undesirable characteristics of the open-loop von Stackelberg equilibrium. We therefore turn to the final equilibrium concept that will be employed in our analysis.

Feedback von Stackelberg **SE: change this section and footnote 3?** The feedback (or: Markov perfect) von Stackelberg equilibrium removes time-inconsistency by requiring that extraction decisions of the cartel and the fringe are optimal at each point in time for any combination of stocks, rather than letting both players choose and commit to a time path $q^c(t)$ and $q^f(t)$ at time zero. Without commitment, time-inconsistent strategies are not credible and hence cannot be used by the leader: the follower anticipates that the leader will ex post deviate from its announced strategy (cf. Dockner et al., 2000; Groot et al., 2003). Because of the leader-follower structure of the equilibrium concept, at any point in time and given the resource stocks at that point, the leader (i.e., the cartel) first determines its extraction rate. Given this extraction rate, the follower (i.e., the fringe) chooses its extraction rate simultaneously.[3] Acting as a von Stackelberg leader, the cartel takes the instantaneous best-response by the fringe into account. Hence, to find the cartel's policy rule $q^c(t, S^c, S^f)$, we first determine the reaction of the fringe. Since the fringe is modeled

[3]The instantaneous first mover advantage arises due to the limit of a sequence of time discretizations of the discrete time Stackelberg game. See section 7.6.2 of Başar and Olsder (1998) and Elgersma et al. (2025) for a thorough discussion.

as a price-taker, its reaction is similar to what it would be under open-loop von Stackelberg and is thus given by the Hotelling rule $p(t) \leq P^f(t)$, with equality if $q^f(t) > 0$ (Groot et al., 2003). Hence, the fringe only supplies at $p(t) = P^f(t)$ and only if residual demand (i.e., after subtracting the cartel's supply from total market demand) is positive.

Profit maximization of the cartel implies that, given the reaction function of the fringe, the following Hamilton-Jacobi-Bellman (HJB) equation should be satisfied:

$$\frac{\partial V^c}{\partial t} + \max_{q^c} \left[e^{-rt}(p - k^c)q^c - \frac{\partial V^c}{\partial S^c} q^c - \frac{\partial V^c}{\partial S^f} q^f \right] = 0,$$

where V^c denotes the cartel's value function and p is given by (1). Due to a possible phase of simultaneous supply, it is difficult to find a solution to the HJB equation. Elgersma et al. (2025) show that, under our parameter restrictions, the equilibrium is characterized by one of the following three equilibrium sequences:

(i) $C^f \to F \to R$ (if the cartel's initial stock is small);

(ii) $S \to L \to R$ (for intermediate values of the cartel's initial stock);

(iii) $S \to C^m \to L \to R$ (if the cartel's initial stock is large).

Elgersma et al. (2025) then succeed in deriving a partial differential equation for cases (ii) and (iii) from which the cartel's value function can be solved. For case (i), the derivation is slightly less cumbersome, as the $S-$phase is absent. At first glance, the feedback von Stackelberg equilibrium may appear similar to the Nash–Cournot equilibrium. However, the threshold values of initial stocks that trigger regime shifts differ between the two. Moreover, in cases (ii) and (iii), the extraction paths generally diverge even when both equilibria are of the same type. Intuitively, while the Nash–Cournot equilibrium is (weakly) time-consistent in a game where the cartel and the fringe move simultaneously, this property does not necessarily hold when the cartel moves first. In cases (ii) and (iii), once time has progressed during S, the cartel can have an incentive to revise its strategy and increase its own extraction rate at the expense of the fringe.

For a similar reason, types (ii)–(iv) of the open-loop von Stackelberg equilibrium cannot constitute a feedback equilibrium: at $t > 0$, the cartel would prefer to lower the price path $P^f(t)$ that it committed to at $t = 0$. By contrast, the equilibrium of type (i) is time-consistent, as the cartel serves the entire market until its stock is depleted.

Finally, note that unless the equilibrium is of type (i), the Herfindahl rule is violated in both the open-loop and feedback von Stackelberg equilibria. The quantitative implications of this violation for welfare and climate damage will be examined in the next section.

3 The oil market

In this section, we calibrate our model to the oil market. We characterize the equilibrium of the calibrated model under Nash-Cournot, open-loop von Stackelberg and feedback von Stackelberg. Furthermore, we also derive the perfectly competitive outcome and the social optimum. This allows us to discuss the effects of imperfect competition, leadership and commitment on profits, climate damage, and welfare.

3.1 Calibration

To facilitate comparison with previous results from the literature, we closely follow Benchekroun et al. (2020) in calibrating the model. This implies the following benchmark parameters: $\alpha = 225.5$, $\beta = 4.3$, $b = 102.5$, $k^c = 18$ (all in USD per barrel of oil), $S_0^c = 1212$, $S_0^f = 619.5$ (both in billion barrels of oil), and $r = 0.028$. However, for the extraction cost of the fringe, k^f, we allow for two scenarios. Recent data from Rystad Energy shows that the average break-even price for different types of non-OPEC oil varies from 37 USD per barrel for offshore shelf to 57 USD per barrel for oil sands (Busby, 2024). To cover this range, we focus on two scenarios: a low-cost and a high-cost scenario. We set $k^f = 40$ in the low-cost scenario and $k^f = 62.5$ (equal to the value in Benchekroun et al. (2020)) in the high-cost scenario. Note that with these parameter values we have $b < \frac{1}{2}(\alpha + k^c)$, implying that the cartel can never set the unrestricted monopoly price. Hence, the phase C^m does not exist in the calibrated model.

We also include climate damages from oil combustion. Following Benchekroun et al. (2020) once more, we use 250 USD per tC for the Social Cost of Carbon (SCC) and emission factors $\omega^c = 0.11083$ and $\omega^f = 0.1525$ (both in tC/bbl), implying that oil extraction by the fringe (mainly from offshore shelf, offshore deepwater, shale oil, oil sands) generates more carbon emissions than the cartel (mainly from onshore conventional oil).[4]

3.2 Resource stocks and equilibrium sequences

Figure 1 characterizes equilibrium sequences under our three definitions (Nash-Cournot, open-loop von Stackelberg, and feedback von Stackelberg), for various combinations of initial resource stocks. We have marked the calibrated stocks with x. The solid black curve divides the space into two regions. Above this locus, the feedback von Stackelberg equilibrium is of the type $C^f \rightarrow F \rightarrow R$; below, it is $S \rightarrow L \rightarrow R$. This confirms that the cartel exerts more monopoly power when the fringe holds a small initial stock.

The dotted curve marks the dividing locus for the Nash-Cournot equilibrium. Below this curve, the sequence is $S \rightarrow L \rightarrow R$; above, $S \rightarrow F \rightarrow R$. Hence, Nash-Cournot does not always predict the feedback von Stackelberg type (cf. Karp and Newbery, 1993). Moreover, even if both equilibria are of the type $S \rightarrow L \rightarrow R$, extraction paths generally differ.

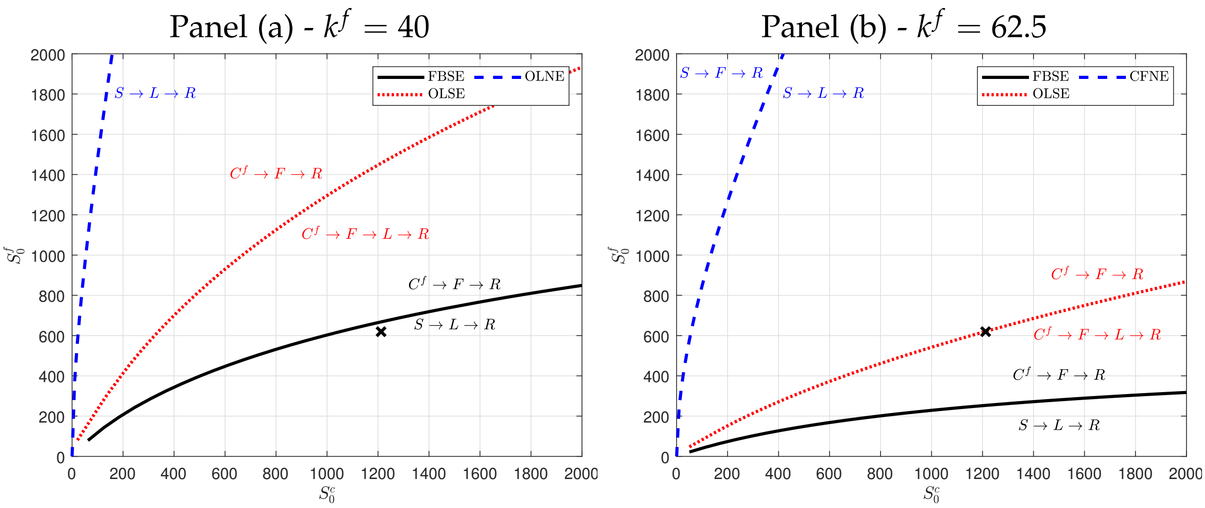
The dotted curve corresponds to the open-loop von Stackelberg equilibrium, where simultaneous supply phases are excluded. Below this locus, the sequence is $C^f \rightarrow F \rightarrow L \rightarrow R$ (time-inconsistent); above, it is $C^f \rightarrow F \rightarrow R$, implying coincidence with the feedback von Stackelberg equilibrium in that region.

3.3 The effects of leadership and commitment

Table 1 reports welfare and its components for our three equilibrium concepts—FBSE, OLSE, and CFNE—alongside the perfectly competitive outcome (PC) and the social optimum (SO). Panel (a) shows the results for the low-cost scenario ($k^f = 40$) whereas panel (b) depicts the high-cost scenario ($k^f = 62.5$). The equilibrium sequences in these two scenarios correspond to those marked by the crosses in panel (a) and panel (b) of Figure 1, respectively.

[4]See https://oci.carnegieendowment.org/#total-emissions for detailed data on carbon emission factors (per region and oil category).

Figure 1: Characterization of equilibria in stock-space



Notes: The solid curve separates feedback von Stackelberg (FBSE) types: above it $C^f \to F \to R$, below $S \to L \to R$. The dashed curve separates equilibrium types under Nash-Cournot (CFNE): above $S \to F \to R$, below $S \to L \to R$. The dotted curve divides open-loop von Stackelberg (OLSE): below $C^f \to F \to L \to R$, above $C^f \to F \to R$. The cross marks the calibrated initial stocks.

Using the perfectly competitive outcome as a benchmark, the impact of introducing market power without leadership is captured by the difference between columns PC and CFNE. In the low-cost scenario (panel (a)), market power reduces welfare, consumer surplus, and climate damage, while increasing profits for both the cartel and the fringe.

The effect of leadership with commitment is shown by the difference between CFNE and OLSE. In this case, welfare, consumer surplus, and the cartel's profit rise, whereas the fringe's profit and climate damage decline. When leadership lacks commitment (compare FBSE with CFNE), welfare and consumer surplus still increase, and fringe profits fall. However, cartel profits now decrease, and climate damage rises.

Hence, despite its leadership position, the cartel may earn *less* under feedback von Stackelberg than under Nash–Cournot. To see why, note that both Nash–Cournot and feedback von Stackelberg equilibria are of type $S \to L \to R$, as the point marked by the cross in panel (a) of Figure 1 lies below the solid and dashed curves. If cartel profits at the cross were smaller than under feedback von Stackelberg starting from the cross, this would contradict the fact that the cartel could always adopt Stackelberg extraction rates and earn more. Hence, leadership does not guarantee higher profits.

Table 1: Comparison of equilibria for two cost scenarios

(a) $k^f = 40$ (USD/bbl)

Metric	FBSE	OLSE	CFNE	PC	SO
Welfare	103.710	105.090	99.995	108.915	109.825
Consumer surplus	85.259	81.396	75.370	100.106	114.034
Profit cartel	36.381	38.733	36.566	29.872	21.259
Profit fringe	12.757	14.637	18.327	9.516	3.228
Climate damage	30.690	29.672	30.269	30.579	28.696

(b) $k^f = 62.5$ (USD/bbl)

Metric	FBSE	OLSE	CFNE	PC	SO
Welfare	105.714	105.714	90.637	104.929	105.883
Consumer surplus	83.752	83.752	72.162	95.730	108.927
Profit cartel	45.063	45.063	37.335	33.470	24.820
Profit fringe	5.317	5.317	10.717	5.801	0.233
Climate damage	28.418	28.418	29.577	30.071	28.097

Intuitively, moving from Nash-Cournot to feedback von Stackelberg offers a leadership benefit—the profit increase when moving from CFNE to OLSE in panel (a) of Table 1—but also imposes a cost: the requirement of time consistency when commitment is not possible. This cost is reflected in the profit decrease when moving from OLSE to FBSE, which can be more restrictive for a von Stackelberg leader than for a Nash-Cournot player.[5] After all, an open-loop Nash-Cournot equilibrium is weakly time-consistent, whereas an open-loop von Stackelberg equilibrium is not—except when it is of type $C^f \to F \to R$, because the cartel's stock then is depleted once the fringe becomes active.

In Panel (b), the open-loop von Stackelberg equilibrium is of the $C^f \to F \to R-$type and is thus time-consistent. As a result, the numbers in the FBSE and OLSE columns are identical. In this case, the requirement of time-consistency in the absence of commitment has no effect. Hence, leadership is beneficial for the cartel, as shown by comparing FBSE (or OLSE) with CFNE. Furthermore, leadership now decreases climate damages.

[5]Formally, this follows from the equilibrium definitions in the appendix.

4 Technical change

In this section we examine the impact of technical change. We consider two types of technical change: one that reduces the fringe's unit extraction cost, and one that decreases the unit cost of the backstop technology. In our discussion of the effects of technical change, we make two welfare decompositions in order to clarify the effects of market power, leadership, and commitment.

First, following Benchekroun et al. (2020), we decompose the welfare loss from imperfect competition into two components: a *conservation effect* and a *sequence effect*. To construct this decomposition, we start from a market equilibrium and modify it by imposing that total extraction at each point in time remains unchanged, while applying the Herfindahl rule. This rule ensures that, at any instant, the cheapest resource is extracted first. Thus, in the Herfindahl scenario, supply comes from the cartel until its stock is exhausted; then from the fringe; and finally, when both stocks are depleted, from renewables.

This adjustment removes one source of inefficiency—depleting expensive resources before cheaper ones are depleted—which we capture as the *sequence effect*. This adjustment also removes a related source of inefficiency–that the emission intensity of the cartel is smaller than that of the fringe. However, it does not eliminate the inefficiency caused by reduced extraction under imperfect competition, which we call the *conservation effect*. Consequently, the difference between the first-best outcome and the market equilibrium can be decomposed into these two effects: the sequence effect and the conservation effect.

Second, we decompose the gap between the feedback von Stackelberg equilibrium and the perfectly competitive outcome into three components: (i) the *market power effect*, defined as the difference between Nash-Cournot and perfect competition; (ii) the *leadership effect*, given by the difference between open-loop von Stackelberg and Nash-Cournot; and (iii) the *commitment effect*, which is the difference between feedback von Stackelberg and open-loop von Stackelberg.

We now turn to a welfare analysis to examine the impact of technical change and climate policies. We consider two types of technical change: one that reduces the fringe's unit extraction cost, and one that decreases the unit cost of the backstop technology. For climate policy, we focus on two instruments: a carbon tax and a subsidy for the backstop.

4.1 A decrease of the fringe's extraction cost

We illustrate the role of the fringe's extraction cost k^f, which equals 62.5 in the benchmark case but may change due to technical progress. For example, the weighted average break-even oil price for the Canadian oil sands sector has fallen 41% between 2015 and 2023 (Kaplan, 2023).

4.1.1 Welfare, profits and climate damage

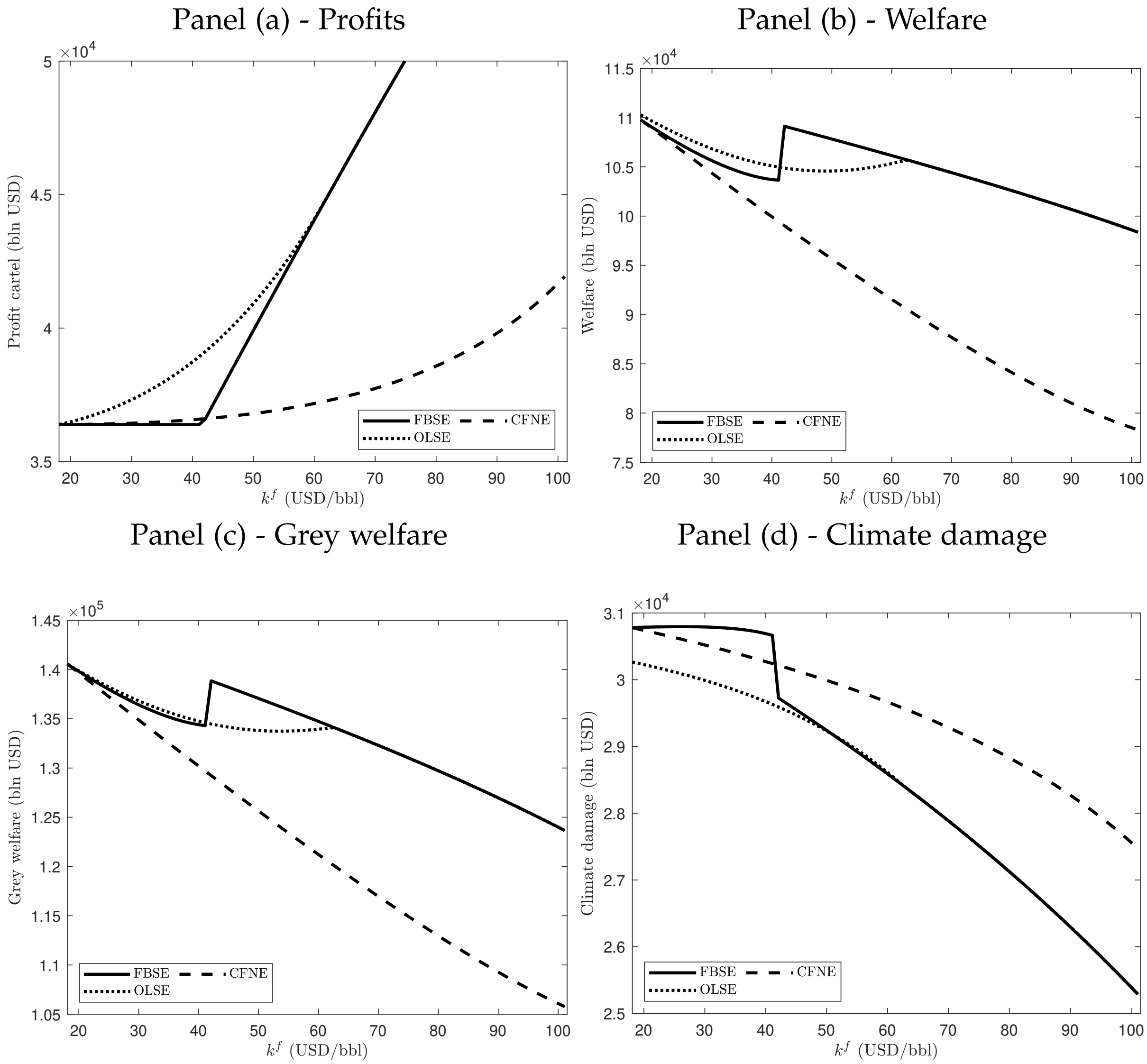
We compare the equilibrium outcomes for a range of values of the marginal extraction cost of the fringe.[6] In Figures 2–3, we vary k^f from 19 (slightly above k^c) to 102.5 (equal to b). Figure 2 reports cartel profits (panel a), total welfare (panel b), grey welfare excluding climate damages (panel c), and climate damages (panel d) under the three equilibrium concepts. Note that Nash-Cournot and feedback von Stackelberg coincide in the symmetric case $k^c = k^f = 18$. While the indusry's production path is unique, the market shares of the cartel and the fringe are not. Both players are indifferent between the exact moment they sell their oil. The open-loop von Stackelberg equilibrium is therefore not unique in this case, and the outcome of the Nash-Cournot equilibrium coincides with one of the infinitely many outcomes of the open-loop von Stackelberg equilibrium, namely with the outcome of the only time-consistent von Stackelberg equilibrium.

Several patterns emerge from panel (a). For relatively small values of k^f (up to 42), cartel profit is lower under feedback von Stackelberg than under Nash-Cournot (see Section 3.2). In this range, the profit-maximizing sequence is $S \rightarrow L \rightarrow R$, and cartel profits are independent of k^f. For larger k^f, the feedback equilibrium switches to $C^f \rightarrow F \rightarrow R$, and cartel profits increase with k^f. Beyond a certain threshold, cartel profit under feedback von Stackelberg exceeds that under Nash-Cournot. Profits under open-loop von Stackelberg are always weakly higher than in the other two equilibria.

Panel (b) highlights the role of k^f for welfare. Under Nash-Cournot and open-loop

[6] Instead of allowing for exogenously decreasing extraction costs over time (cf. André and Smulders, 2014), we compare scenarios with different constant marginal extraction costs.

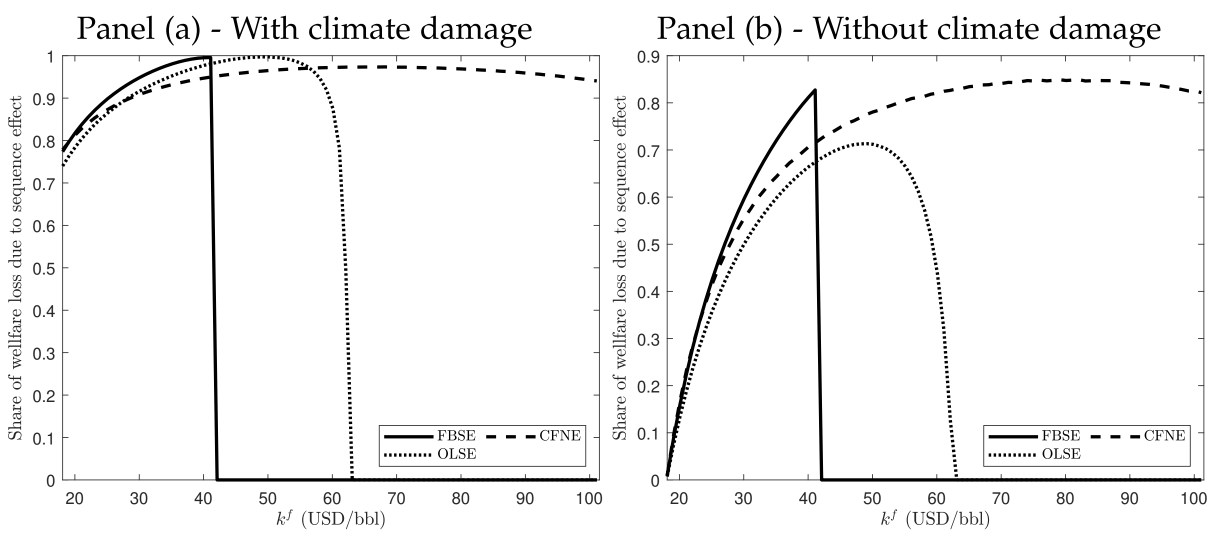
Figure 2: Welfare comparison between different equilibrium concepts



Notes: The figure illustrates how varying the fringe's extraction cost k^f affects outcomes under three equilibrium concepts. In all panels, the solid curve represents the Nash-Cournot equilibrium, the dashed curve represents the open-loop von Stackelberg equilibrium, and the dotted curve represents the feedback von Stackelberg equilibrium.

von Stackelberg, welfare varies continuously with k^f, though the relationship may be non-monotonic (as in open-loop von Stackelberg) because higher k^f can reduce the sequence effect (see below). Most notably, welfare under feedback von Stackelberg jumps at $k^f = 42$, reflecting a regime change from $S \rightarrow L \rightarrow R$ to $C^f \rightarrow F \rightarrow R$. This transition brings the equilibrium closer to the competitive outcome, increasing welfare because the cheaper resource is extracted first, consistent with the Herfindahl rule. In other words, the sequence effect disappears when the equilibrium switches from $S \rightarrow L \rightarrow R$ to $C^f \rightarrow F \rightarrow R$. Grey welfare and climate damages (panels c and d) exhibit similar jumps: grey welfare rises and climate damages fall when the sequence effect vanishes.

Figure 3: Importance of the sequence effect



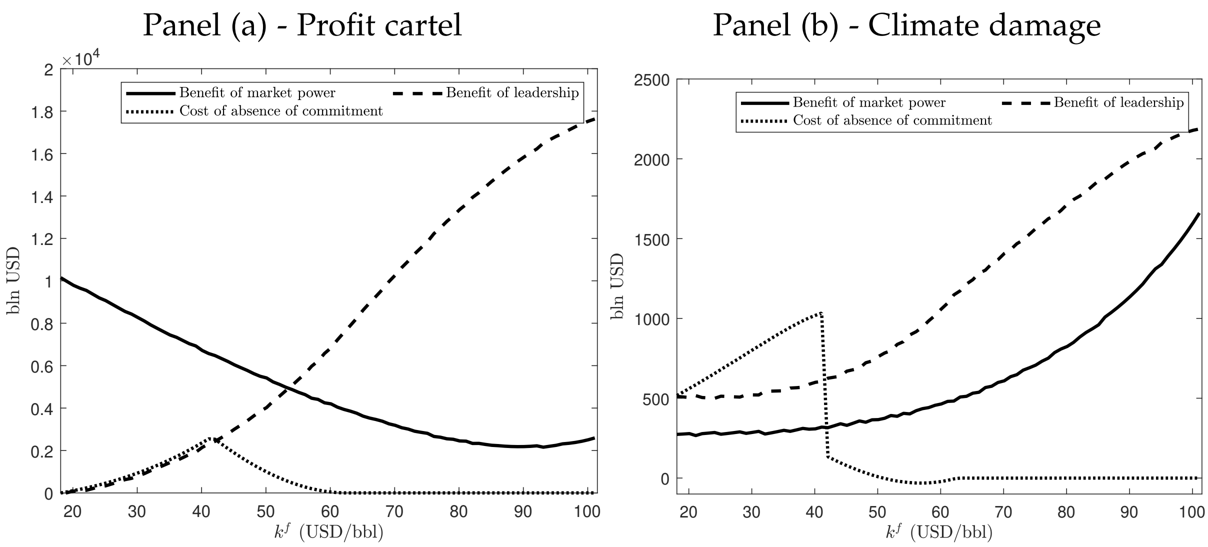
Notes: The figure shows the importance of the sequence effect as a share of the welfare loss relative to the social optimum. Panel (a) includes climate damages, while panel (b) excludes them. In both panels, the solid curve represents the Nash-Cournot equilibrium, the dashed curve represents the open-loop von Stackelberg equilibrium, and the dotted curve represents the feedback von Stackelberg equilibrium.

4.1.2 Sequence effect

Figure 3 shows the importance of the sequence effect as a share of the welfare loss relative to the social optimum. Panel (a) includes climate damages; panel (b) excludes them. In both cases, the sequence effect depends non-monotonically on k^f: higher fringe extraction costs make deviations from the Herfindahl rule more costly, but also delay fringe extraction, bringing the sequence closer to the social optimum. Under Nash-Cournot, the sequence effect remains high throughout. Under open-loop von

Stackelberg, the sequence effect declines smoothly and vanishes when the equilibrium changes from $C^f \to F \to L \to R$ to $C^f \to F \to R$. Under feedback von Stackelberg, it disappears abruptly when the equilibrium switches from $S \to L \to R$ to $C^f \to F \to R$. In the case without climate damages (panel b), the sequence effect vanishes when cartel and fringe extraction costs converge to $k^f = k^c = 18$, since the extraction order then no longer affects welfare. However, if the fringe's emission factor exceeds that of the cartel, the sequence effect may remain significant even when costs are similar (see panel a).

Figure 4: Effects of market power, leadership and commitment



Notes: Panel (a) shows three curves: the solid curve represents the benefit of market power, measured as the profit difference between Nash-Cournot and perfect competition; the dashed curve represents the benefit of leadership, measured as the profit difference between open-loop von Stackelberg and Nash-Cournot; and the dotted curve represents the cost of the absence of commitment, given by the profit difference between open-loop von Stackelberg and feedback von Stackelberg. Panel (b) shows the corresponding effects on climate damage: the solid curve represents the reduction in climate damage due to market power, the dashed curve represents the reduction due to leadership, and the dotted curve represents the increase in climate damage due to commitment.

4.1.3 Market power, leadership, and commitment

Figure 4 illustrates the effects of market power, leadership, and commitment on cartel profit (panel a) and climate damage (panel b). For the cartel, the benefit of market power equals the profit difference between Nash-Cournot and perfect competition; the benefit of leadership with commitment equals the difference between open-loop von Stackelberg and Nash-Cournot; and the cost of time-consistency (which is required in the absence of commitment) equals the difference between open-loop von Stackelberg and feedback von Stackelberg. In panel (a), the solid curve shows that market power always raises cartel profit; the dashed curve shows that leadership increases profit; and the dotted curve shows that the cost of commitment exceeds leadership benefits for $k^f \leq 43$. In panel (b), the solid curve shows that market power reduces climate damage by \$266–1,661 billion USD, and leadership adds a reduction of \$500–2,187 billion USD. The absence of commitment, however, can increase climate damage by up to \$1,034 billion USD (at $k^f = 42$) or decrease it by up to \$31 billion USD (at $k^f = 57$).

4.2 The role of the backstop cost

In this subsection, we investigate the role of the renewables cost. We examine the effect of cost reductions, which could be driven by technical change. For example, Way et al. (2022, p. 2057) report that "for several decades the costs of solar photovoltaics (PV), wind, and batteries have dropped (roughly) exponentially at a rate near 10% per year".[7]

4.2.1 Welfare, profits and climate damage

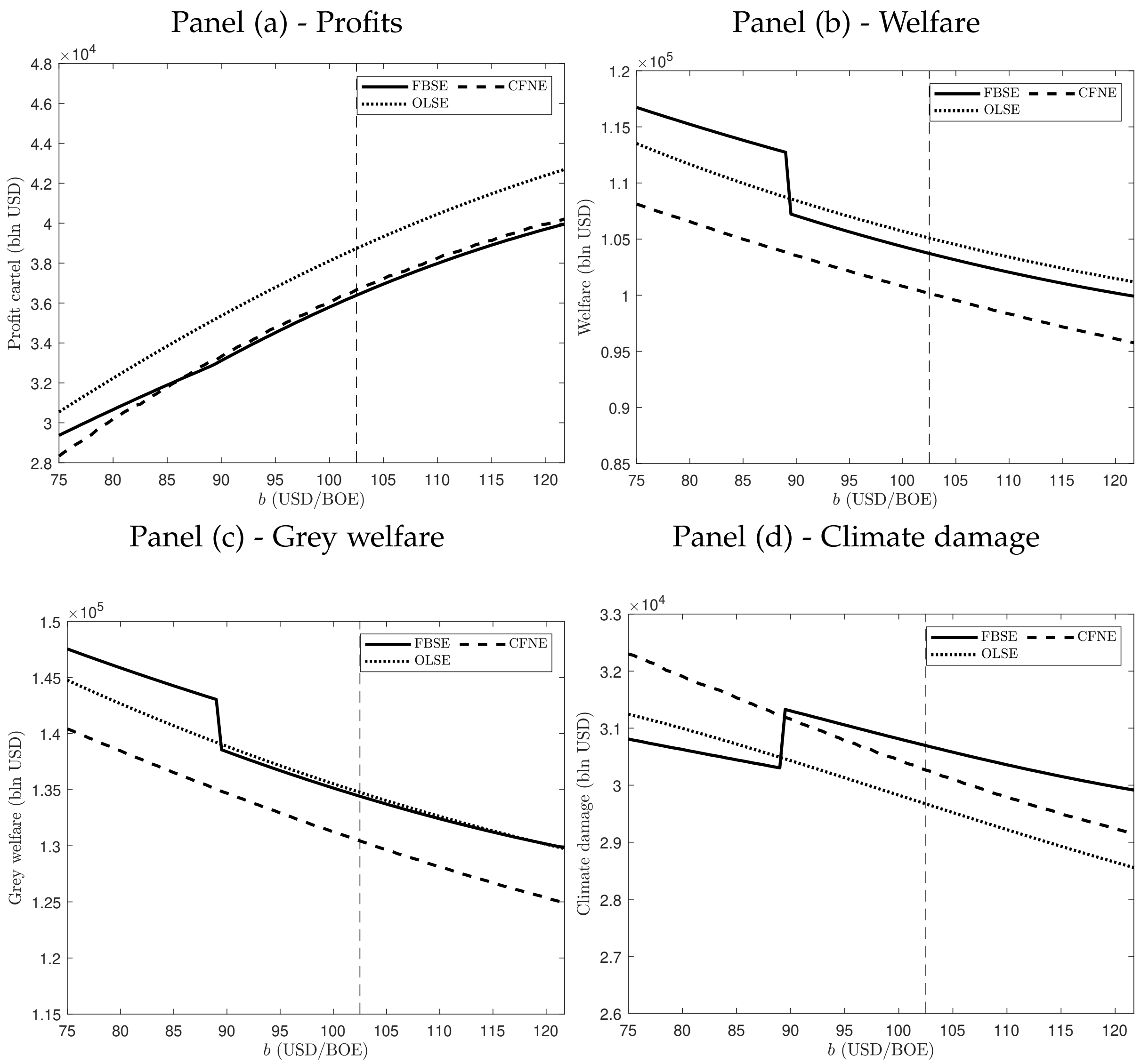
Figure 5 illustrates how the backstop cost b affects outcomes when $k^f = 40$. The vertical dashed line marks the benchmark value $b = 102.5$. For low values of b, the equilibrium sequence is $C^f \to F \to R$; for $b > 90$, it switches to $S \to L \to R$.

Panel (a) shows that cartel profit increases monotonically with b. Panels (b) and (c) reveal that welfare and grey welfare (excluding climate damages) decline as b rises. In the feedback von Stackelberg equilibrium, (grey) welfare exhibits a jump at the point where the sequence changes from $C^f \to F \to R$ to $S \to L \to R$, reflecting the disappearance of the sequence effect.

Panel (d) highlights climate policy implications. Starting from the benchmark $b = 102.5$, a decrease in b initially increases climate damage due to a Green Paradox effect: fossil fuel suppliers accelerate extraction when a cheaper clean substitute reduces

[7]Instead of allowing for exogenously decreasing unit costs of the backstop technology over time (cf. Fischer and Salant, 2017), we compare scenarios with different constant unit costs of the backstop technology.

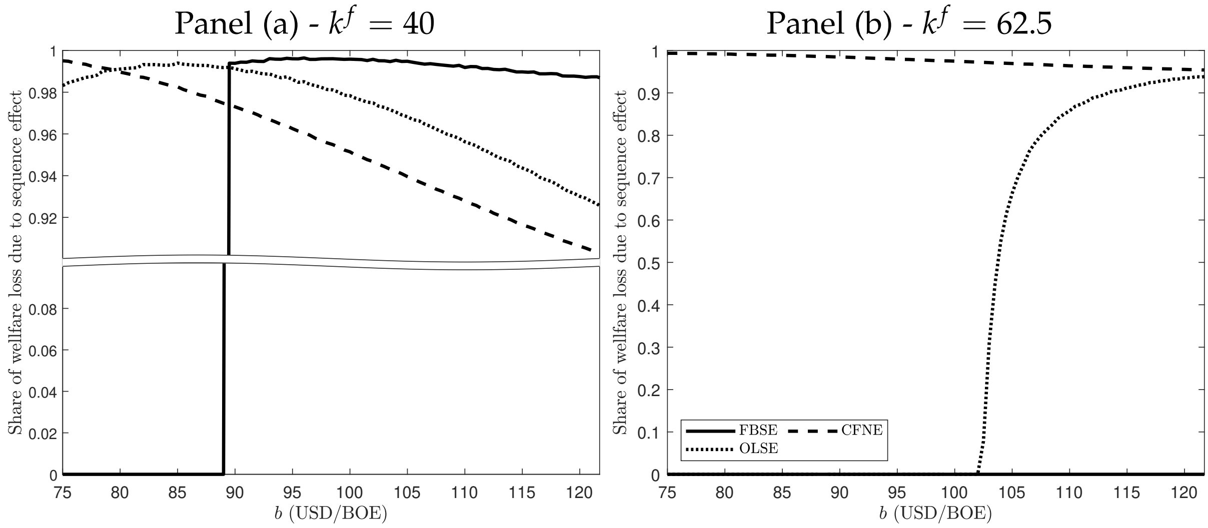
Figure 5: Welfare effects of cheaper renewables ($k^f = 40$)



Notes: The figure shows how the backstop cost b affects outcomes when $k^f = 40$. The vertical dashed line marks the benchmark $b = 102.5$. Panel (a) reports cartel profit, panel (b) total welfare, panel (c) grey welfare (excluding climate damages), and panel (d) climate damages. In all panels, the solid curve represents the Nash-Cournot equilibrium, the dashed curve the open-loop von Stackelberg equilibrium, and the dotted curve the feedback von Stackelberg equilibrium.

scarcity rents. However, if b falls below 90, the equilibrium switches to $C^f \to F \to R$, eliminating the sequence effect, delaying dirty fringe extraction, and causing climate damage to drop sharply. Thus, small changes in backstop cost can have large, non-marginal effects on climate outcomes.

Figure 6: Importance of the sequence effect



Notes: The figure shows how the sequence effect depends on the backstop cost b for $k^f = 40$ (panel a) and $k^f = 62.5$ (panel b). In both panels, the solid curve represents the Nash-Cournot equilibrium, the dashed curve represents the open-loop von Stackelberg equilibrium, and the dotted curve represents the feedback von Stackelberg equilibrium. There is an axis break in panel (a) to improve visibility.

4.2.2 Sequence effect

Figure 6 shows how the sequence effect depends on b for $k^f = 40$ (panel a) and $k^f = 62.5$ (panel b). Under Nash-Cournot, the sequence effect declines with b. Under von Stackelberg, the relationship can be non-monotonic: in the open-loop case, the dependence is smooth, while in the feedback case the sequence effect drops abruptly from nearly 100% to zero when $b < 90$ (panel a). In panel (b), the sequence effect under feedback von Stackelberg is zero throughout because the equilibrium remains $C^f \to F \to R$ over the entire interval. Under open-loop von Stackelberg, the sequence effect is zero for $b < 102$ and converges to the Nash-Cournot level for higher b.

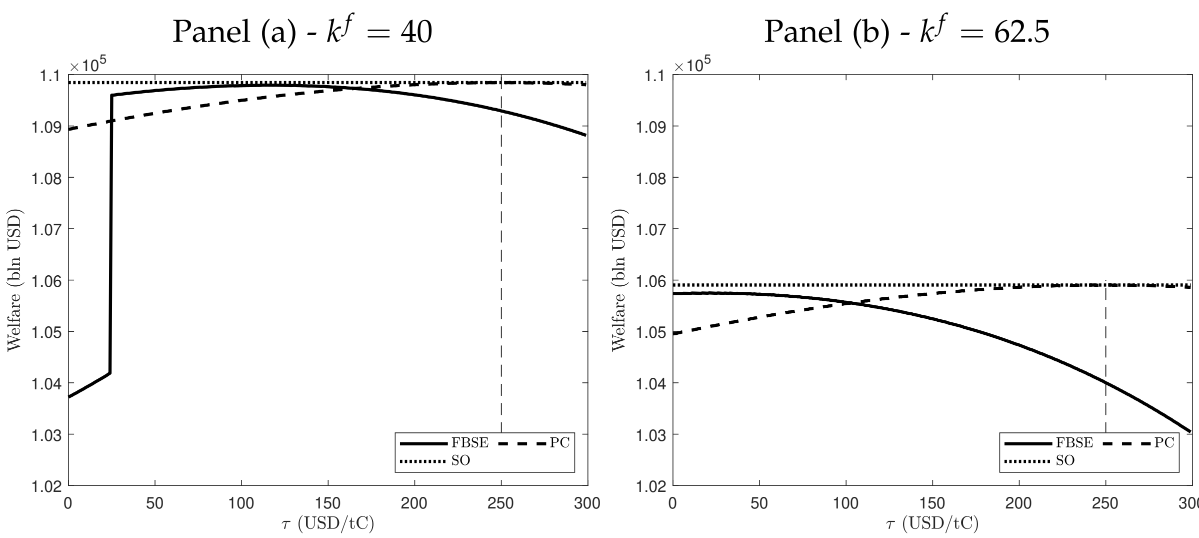
5 Climate policies

In this section, we examine the effect of climate policies. We focus on the feedback von Stackelberg equilibrium and leave out open-loop von Stackelberg and Nash-Cournot results.

5.1 Carbon tax

We first consider the effect of introducing a tax on carbon emissions from the fringe and the cartel, taking into account that the emission factor of the fringe exceeds that of the cartel.

Figure 7: Carbon tax: welfare effects



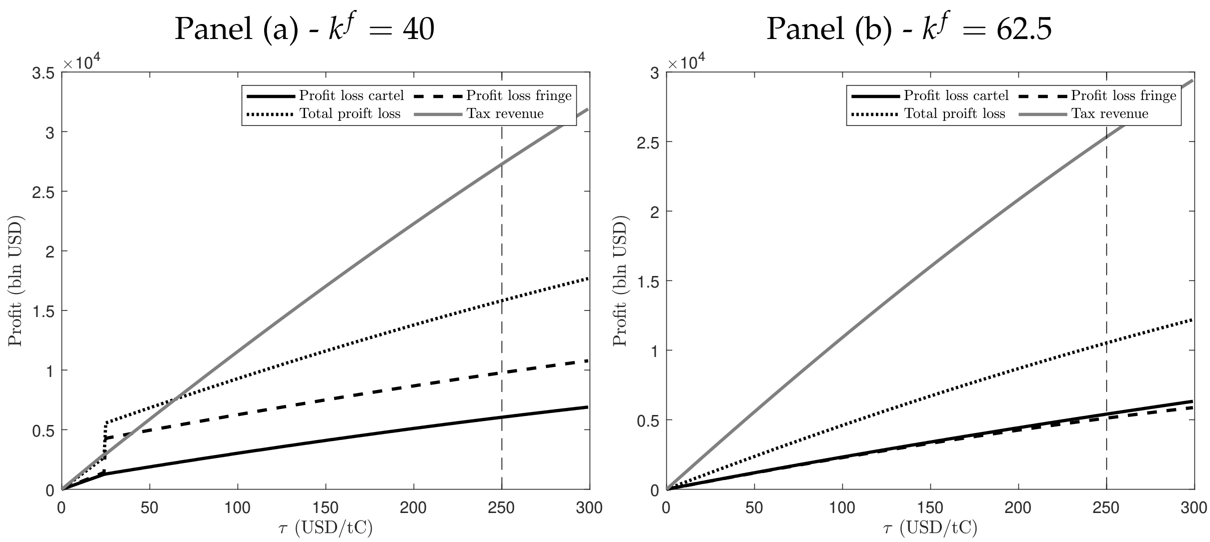
Notes: The figure shows the effect of a carbon tax on welfare. It compares the social optimum (dotted line), the perfectly competitive outcome (dashed curve), and the feedback von Stackelberg equilibrium (solid curve). Panel (a) shows the case with $k^f = 40$, and panel (b) the case with $k^f = 62.5$.

Figure 7 compares the social optimum (dotted line), the perfectly competitive outcome (dashed curve), and the feedback von Stackelberg equilibrium (solid curve). Panel (a) shows the low-cost case with $k^f = 40$, while panel (b) shows $k^f = 62.5$. Two key insights emerge. First, in the feedback von Stackelberg equilibrium the second-best carbon tax (of $\tau = 113$ USD/tC in panel (a) and $\tau = 22$ USD/tC in panel (b)) is lower than the Pigouvian tax of 250 USD/tC because of the conservation effect of market power. Second, in the low-cost scenario (panel a), a carbon tax can induce the cartel to switch from $S \to L \to R$ to $C^f \to F \to R$, eliminating the sequence effect.

As a result, two tax levels that are relatively close, 24 and 25 USD/tC, can result in rather different outcomes. While a tax of 24 increases with respect to laissez-faire by 0.5%, a tax of 25 USD/tC results in an increase of 5.7% and brings welfare to 99.8% of the level in the social optimum. In the presence of a Stackelberg leader that is not able to commit, a carbon tax can have a double dividend of fignig an incentive to reduce emissions and beyond a certain threshold can make the equilibrium order of extraction obey the Herfindahl rule and thus eliminate an important source of inefficiency.

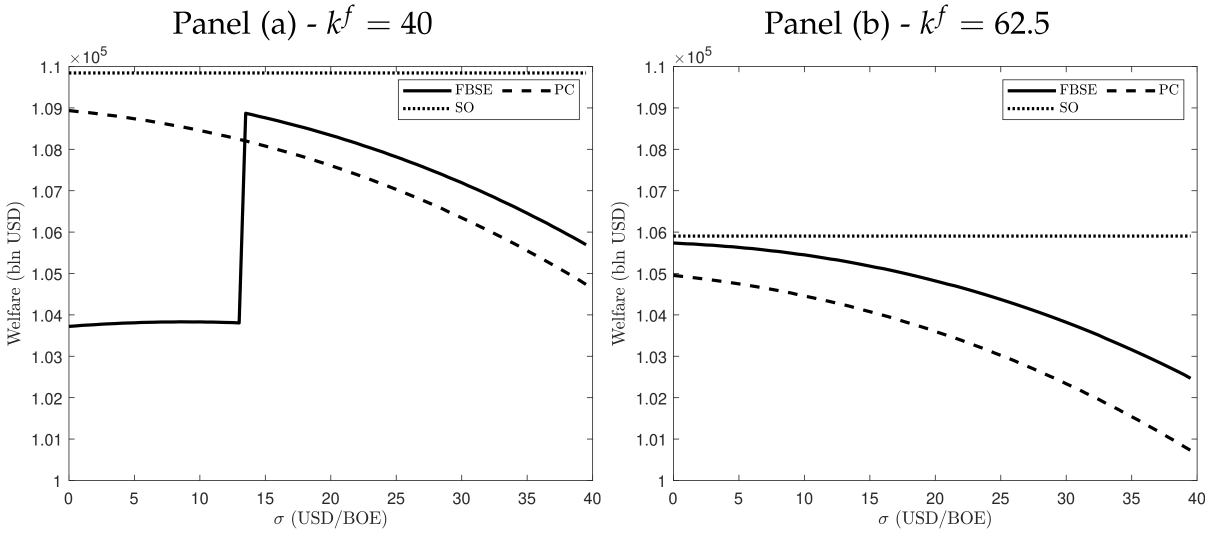
Figure 8 shows the profit losses of the cartel and the fringe due to the carbon tax. Both the cartel (solid curves) and the fringe (dashed curves) lose profits, although panel (a) shows that the fringe is the one who suffers from the tax-induced regime shift. The figure also shows total profit losses (dotted curves) and total tax revenues (solid grey curves). Panel (b) shows that tax revenues in the high-cost case are always large enough to compensate the producers for the losses. In the low-cost scenario (see panel (a)), this is only possible for tax rates up to 24. For tax rates between 24 and 65, profit losses exceed tax revenues. For higher tax rates, tax revenues are again large enough to compensate both producers.

Figure 8: Carbon tax: profit losses and tax revenues



Notes: The figure shows the profits loss of the cartel (solid black curves), the fringe (dashed curves), and total profits (dotted curves). Total tax revenues are depicted by the solid grey curves. Panel (a) shows the case with $k^f = 40$, and panel (b) the case with $k^f = 62.5$.

Figure 9: Backstop subsidy: welfare effects



Notes: The figure shows the effect of a backstop subsidy on welfare for $k^f = 40$ (panel a) and $k^f = 62.5$ (panel b). In both panels, the dashed curve represents the perfectly competitive outcome and the solid curve represents the feedback von Stackelberg equilibrium.

5.2 Subsidy for renewables

Next, we examine the effects of a backstop production subsidy. Figure 9 shows results for $k^f = 40$ (panel a) and $k^f = 62.5$ (panel b) for subsidy rates ranging fom 0 to 40 USD/BOE. To get a crude number for existing renewables subsidies, we take total renewable energy subsidies in the EU of 61 billion euro in 2023 (European Commission, 2025). By using a conversion factor of 6.98 barrels per ton of oil equivalent (EIA, 2025; IEA, 2025), total primary energy use in the EU in 2023 was 1208.5 million tonnes of oil equivalent = 8.44 billion BOE (EEA, 2025a). A renewable share of 24.6 percent (EEA, 2025b) then yields a renewable energy consumption of 2.08 BOE. This implies an average renewables subsidy rate of 29.4 euro per BOE (around 32 USD per BOE). At the global level, this number is much lower.[8]

Under perfect competition (dashed curves), welfare declines as the subsidy increases because the subsidy accelerates oil extraction through a Green Paradox effect; and oil was already extracted too quickly in the absence of carbon pricing. In the feedback von Stackelberg equilibrium (solid curves), welfare responds non-monotonically to the subsidy. The reason is that a backstop subsidy speeds up oil depletion (and

[8]With a global primary energy consumption of 15 billion tonnes of oil equivalent and global renewables subsidies of 168 billion USD, using the same conversion factors we get a subsidy rate of 14.5 USD/BOE.

thus counteracts the conservation effect), but also affects the sequence effect, which completely vanishes at a subsidy of 14 USD/BOE. The minimum subsidy cost of imposing $\sigma = 14$ USD/BOE amount to 4 trillion USD.

Similar to a carbon tax, in the presence of a von Stackelberg leader, two relatively close subsidy rates of 13 and 14 USD/BOE can have a drastically different impact on the market outcomes in the low-cost case (panel (a)). When the subsidy rate exceeds a certain threshold (which happens to be around the current global average renewables subsidy rate), the subsidy policy has a double dividend of affecting the supply at the extensive margin. It allows the leader to credibly supply oil at levels that push the fringe out of the market which makes the order of extraction follow the Herfindahl rule and eliminate the sequence effect of market power.

Panel (b) shows that in the high extraction cost case with $k^f = 62.5$ the subsidy is welfare-reducing throughout. The reason is that the sequence effect is not present in this scenario.

6 Conclusion

This paper has examined the interaction between market power, resource heterogeneity, and climate policy in a dynamic cartel-fringe setting with exhaustible resources and a renewable backstop. By comparing Nash-Cournot, open-loop von Stackelberg, and feedback von Stackelberg equilibria to the social optimum and perfect competition, we have highlighted how leadership and commitment shape extraction paths, welfare outcomes, and climate damages.

Three main insights emerge. First, imperfect competition is not necessarily good for the climate. While market power slows down total extraction—the conservation effect—it also distorts extraction order—the sequence effect—by accelerating the use of carbon-intensive resources. Our analysis shows that leadership can mitigate the sequence effect, particularly when the cartel commits to a price path under open-loop von Stackelberg. However, the requirement of using credible and thus time-consistent strategies in feedback von Stackelberg equilibria may offset these gains, sometimes leading to higher climate damages and lower cartel profits than under Nash-Cournot. This underscores that leadership is not always advantageous for the leader or for the climate: the requirement of time consistency in the absence of commitment imposes a cost that can outweigh the benefits of leadership.

Second, the welfare decomposition clarifies the relative importance of conservation and sequence effects. Across most scenarios, the sequence effect dominates, accounting for more than 90% of welfare losses under Nash-Cournot. Under feedback von Stackelberg, the sequence effect can vanish abruptly when equilibrium regimes switch from simultaneous supply to sequential extraction, consistent with the Herfindahl rule. These regime shifts occur at critical thresholds of fringe extraction cost or backstop cost, producing discontinuous jumps in welfare and climate damages. Such non-marginal responses imply that small technological or policy changes can have disproportionately large effects on climate outcomes.

Third, climate policy interacts strongly with market structure. A carbon tax below the Pigouvian level can improve welfare by counteracting the conservation effect and, in some cases, eliminating the sequence effect. For example, in the low-cost fringe scenario, a modest tax of 25 USD/tC induces a regime change that brings the decentralized outcome close to the social optimum. Similarly, a backstop subsidy can reduce welfare losses when it removes the sequence effect, but excessive subsidies trigger a Green Paradox, accelerating extraction and increasing climate damages. These findings highlight the importance of designing second-best policies that account for strategic behavior in the presence of differences in costs and emission factors between producers, rather than relying solely on first-best Pigouvian principles.

From a broader perspective, our results suggest that the climate implications of market power depend critically on the interplay between leadership, commitment, and technological change. Future research could extend the current framework in several directions. First, incorporating endogenous technical change and learning in extraction and fossil fuel production would enrich the analysis. Second, modeling endogenous investment in exploration and renewables could capture the interplay between market power, technical change and cumulative fossil fuel use during the energy transition. Third, a more granular calibration using detailed, micro-level data on extraction costs and emissions could refine welfare estimates and improve policy relevance. Finally, it would be interesting to allow for more sophisticated strategic behavior by exploring multi-cartel settings or strategic interactions across fuels.

Appendix

In this appendix, we formally define the three equilibrium concepts used in the main text.

Nash-Cournot

At time 0 the cartel chooses a price path, and the fringe chooses an extraction path. A Nash-Cournot equilibrium is a couple of paths $\left(p^{NC}\left(.\right), q^{f,NC}\left(.\right)\right)$ such that

$$\int_0^\infty p^{NC}\left(t\right) q^{f,NC}(t) e^{-rt} dt \geq \int_0^\infty p^{NC}\left(t\right) q^{f}(t) e^{-rt} dt \text{ for all } q^f \in \Sigma_F\left(S_0^f\right), \tag{A.1}$$

where $\Sigma_F\left(S_0^f\right) = \left\{q^f\left(.\right) : \int_0^\infty q^f(t) dt = S_0^f\right\}$ and

$$\begin{aligned}&\int_0^\infty p^{NC}\left(t\right)\left(D\left(p^{NC}\left(t\right)\right) - q^{f,NC}(t)\right) e^{-rt} dt \\ &\geq \int_0^\infty p\left(t\right)\left(D\left(p\left(t\right)\right) - q^{f,NC}(t)\right) e^{-rt} dt \text{ for all } \Sigma_C\left(S_0^c, q^{f,NC}\right),\end{aligned} \tag{A.2}$$

where $\Sigma_C\left(S_0^c, q^f\right) = \left\{p\left(.\right) : \int_0^\infty \left(D\left(p\left(.\right)\right) - q^f\left(.\right)\right) dt = S_0^c\right\}$.

A necessary condition for (A.1) is that for $q^f\left(t\right) > 0$ during an interval we must have $\frac{\dot{p}}{\left(p - k^f\right)} = r$.

Von Stackelberg

A von Stackelberg equilibrium is a couple of paths $\left(p^S, q^{f,S}\right)$ such that

$$\int_0^\infty p^S\left(t\right) q^{f,S}(t) e^{-rt} dt \geq \int_0^\infty p^S\left(t\right) q^f(t) e^{-rt} dt \text{ for all } q^f \in \Sigma_F\left(S_0^f\right).$$

Moreover, in an OLSE it must hold that

$$\begin{aligned}&\int_0^\infty p^S\left(t\right)\left(D\left(p^S\left(t\right)\right) - q^{f,S}(t)\right) e^{-rt} dt \\ &\geq \int_0^\infty p\left(t\right)\left(D\left(p\left(t\right)\right) - q^{f,S}(t)\right) e^{-rt} dt \text{ for all } p \in \tilde{\Sigma}_C\left(S_0^c, q^{f,S}\right),\end{aligned} \tag{A.3}$$

where

$$\tilde{\Sigma}_C\big(S_0^c, q^{f,S}\big) = \Big\{p(\cdot) : \int_0^\infty \big(D\big(p(\cdot)\big) - q^{f,S}(\cdot)\big)\,dt = S_0^c$$
$$\text{with } \frac{\dot{p}}{p-k^f} = r \text{ during an interval where}$$
$$q^{c,S}(t) = D\big(p(t)\big) - q^{f,S}(t) < D\big(p(t)\big)\Big\}.$$

In a FBSE, instead of (A.3) it is required that

$$\int_z^\infty p^S(t)\left(D\left(p^S(t)\right) - q^{f,S}(t)\right)e^{-rt}dt$$
$$\geq \int_z^\infty p(t)\left(D(p(t)) - q^{f,S}(t)\right)e^{-rt}dt \text{ for all } p \in \tilde{\Sigma}_{C,z}\left(S_z^c, q^{f,S}\right)$$

for all $z > 0$ and where $S_z^c = S^c(z)$ and

$$\tilde{\Sigma}_{C,z}\big(S_z^c, q^{f,S}\big) = \Big\{p(\cdot) : \int_z^\infty \big(D\big(p(\cdot)\big) - q^{f,S}(\cdot)\big)\,dt = S_z^c$$
$$\text{with } \frac{\dot{p}}{p-k^f} = r \text{ during an interval where}$$
$$q^{c,S}(t) = D\big(p(t)\big) - q^{f,S}(t) < D\big(p(t)\big)\Big\}.$$

Note that while $p^{NC} \in \tilde{\Sigma}_C\left(S_0^c, q^{f,NC}\right)$ it is not necessarily true that $p^{NC} \in \tilde{\Sigma}_{C,z}\left(S_z^c, q^{f,NC}\right)$ for all $z > 0$ and where $S_z^c = S^c(z)$.

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