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# When OPEC Leads and the Fringe Follows: A Climate Story

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**Abstract**

We study how market power, leadership, and commitment affect oil extraction and climate outcomes in a cartel–fringe model with renewables and a backstop technology. Comparing competitive, Nash–Cournot, open-loop, and feedback von Stackelberg equilibria, we show that market power and leadership can either increase or reduce climate damages, depending on commitment, cost and emission factor heterogeneity, and relative resource stocks. In a benchmark with a social cost of carbon of 250 USD/tC, market power without leadership lowers climate damages by 3.9 trillion USD relative to perfect competition. With leadership, these gains fall to 3.1 trillion USD when the leader can commit and to 2.6 trillion USD without commitment. Small changes in resource stocks, cost parameters, or climate policy can trigger regime shifts with discontinuous welfare and climate effects. Carbon taxes and backstop subsidies can remove sequencing distortions but may weaken the conservation effect of market power. When the cartel cannot commit, the second-best carbon tax lies well below the Pigouvian level yet often delivers near–first-best welfare. Finally, we show that market power and leadership may reduce cartel profits.

**JEL codes**: Q30, Q38, Q42, Q54, C72

**Keywords**: cartel-fringe, climate policy, renewables, dynamic game, von Stackelberg equilibrium

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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. In such environments, market power can either mitigate or exacerbate climate damages, depending on how it reshapes extraction timing and the composition of supply. The aim of this paper is to show how leadership and commitment fundamentally shape these conservation and sequencing effects, and thereby determine the impact of market power on climate outcomes.

A closely related empirical literature studies how misallocation and market structure shape the environmental and welfare consequences of global oil extraction. Coulomb et al. (2026) show that historical extraction patterns have generated substantial "carbon misallocation" by drawing too heavily on high–carbon-intensity deposits. Using detailed field-level data on extraction costs, carbon intensities, and geological constraints, they document that optimal deposit-level reallocation could have avoided more than 11 $GtCO_2$-eq since 1992, even when aggregate oil demand is held fixed. Their focus is entirely on the heterogeneity of deposits, taking market structure as exogenous. By contrast, Asker et al. (2019) quantify large productive inefficiencies in global oil extraction—arising from within- and across-country deviations from least-cost supply—and attribute a nontrivial share of these inefficiencies to OPEC's market power. Their analysis emphasizes how market power distorts the spatial allocation of production but abstracts from environmental externalities. Complementing this, Asker et al. (2024) show that OPEC's market power has had important environmental consequences: by suppressing global output, the cartel has reduced cumulative $CO_2$ emissions by an estimated 67 Gt, although this volume effect coexists with a countervailing sequencing effect whereby withholding low-cost (and relatively clean) OPEC barrels induces production from dirtier fringe fields.

Our paper connects and extends these lines of research by examining how *strategic interaction, leadership, and commitment* shape extraction dynamics, welfare, and climate damages in a dynamic cartel–fringe model with heterogeneous extraction costs and emission factors. Rather than taking misallocation or market power as exogenous, we endogenize the sequencing of extraction under different equilibrium concepts (Nash–Cournot, open-loop von Stackelberg, and feedback von Stackelberg). This allows us to disentangle two channels emphasized implicitly across the above studies: a *conservation effect*, through which market power slows aggregate depletion, and a *sequencing effect*, through which strategic behavior changes the order in which cleaner and dirtier resources are extracted. Whereas Coulomb et al. (2026) highlight the importance of deposit selection and Asker et al. (2019, 2024) emphasize productive and environmental distortions induced by market power, our contribution is to show how these distortions depend critically on the *equilibrium structure* and on whether the leader can commit. In doing so, we provide a unified framework that explains when market power reduces climate damages, when it raises them, and how climate policy interacts with the strategic environment.

The theoretical literature provides a natural foundation for this analysis. Building on the seminal work of Hotelling (1931), dynamic models of exhaustible resources have incorporated strategic interaction and imperfect competition. Early contributions such as Salant (1976); Lewis and Schmalensee (1980a,b); Ulph and Folie (1980); Newbery (1981); Ulph (1982); Salant (1982) and later refinements by Groot et al. (2000, 2003) characterize equilibrium behavior in cartel–fringe and oligopoly settings. A useful overview is provided by Withagen (2013). More recent work links these strategic considerations directly to climate policy. Benchekroun et al. (2020) study a cartel–fringe model with heterogeneous carbon intensities and show that market power indeed generates counteracting conservation and sequencing effects, with the latter dominating in their calibrated Nash–Cournot equilbrium. Building on Anderson et al. (2018), Kellogg (2024) embeds endogenous capacity investment in a cartel–fringe framework to study how an anticipated decline in future oil demand affects current supply behavior. He identifies two opposing forces—a "disinvestment effect" (slower extraction) and a countervailing "Green Paradox effect" (faster extraction)—and shows that, under empirically plausible parameterizations, the disinvestment effect dominates.[1] As a result, expectations of declining future demand are likely to reduce, rather than accelerate, short-run extraction. In a similar setting but

[1]A Green Paradox is said to occur if fossil fuel owners front-load their extraction due to expected future demand reductions, for example because of announced future climate policies (cf. Sinn, 2008).

exploiting detailed micro-level cost data, De Cannière (2025) analyzes the interaction between market power and climate policy and finds that the second-best carbon tax path differs from the first-best benchmark: the initial tax should lie below the social cost of carbon due to pre-existing market power, but should increase more steeply over time in order to induce an efficient reallocation of production from high-cost fringe producers to lower-cost cartel producers.

Despite these advances, two important gaps remain. First, most theoretical work assumes simultaneous decision-making, even though real-world cartels frequently behave as leaders anticipating the reactions of competitive fringe producers. Second, existing cartel–fringe models rarely incorporate renewable backstop technologies and climate damages explicitly, despite their centrality for long-run market structure and welfare. This paper addresses both gaps by analyzing a dynamic game in which the cartel acts as a von Stackelberg leader facing a competitive fringe, in a setting with renewables, a backstop technology and climate damages. We compare Nash–Cournot, open-loop von Stackelberg, and feedback von Stackelberg equilibria, and contrast them with the social optimum and the perfectly competitive outcome.

This paper builds upon our previous work (Benchekroun et al., 2020, 2025) and the accompanying study by Elgersma et al. (2026). In Elgersma et al. (2026), we formally characterize the equilibrium outcomes and address the technical challenges the feedback von Stackelberg equilibrium entails. The present paper makes four contributions. First, we show how leadership and commitment shape extraction patterns in dynamic cartel–fringe games: whereas open-loop leadership enables the cartel to dominate *early* supply, the Nash–Cournot equilibrium features simultaneous initial extraction, and the feedback von Stackelberg equilibrium does so as well when the cartel's initial stock is sufficiently large relative to that of the fringe.

Second, we quantify profits, welfare, and climate damages across alternative market structures to isolate the roles of market power, leadership, and commitment. We show that market power without leadership, and leadership without commitment, can both reduce cartel profits. In particular, the cartel may be worse off in an open-loop Nash–Cournot equilibrium than under perfect competition—a result first highlighted by Ulph and Folie (1978) and discussed in Ulph (1982). Furthermore, the finding that a leader's profits can fall below those in a simultaneous-move game bears similarities with recent results by Bizzotto et al. (2026). They study a setting with limited commitment in which the leader cannot commit to a single action, but instead commits to a subset of actions from which the final choice is made. The Cournot and von Stackelberg benchmarks arise as limiting cases, corresponding to no commitment and full commitment, respectively. Their main insight is that the form of commitment is crucial. When the commitment structure is "simple"—that is, when it partitions the leader's action space into intervals—the leader's payoff is bounded between the Cournot and Stackelberg payoffs. However, with more general (non-simple) commitment structures, this ordering can break down, and the leader may obtain a payoff below the Cournot benchmark. In our model, the leader's 'action set' is a set of price paths, and limited commitment corresponds to the possibility of revising the price path at some future date. As in Bizzotto et al. (2026), restrictions on commitment can undermine the leader's advantage and reduce equilibrium profits.

Third, we demonstrate that imperfect competition is not inherently beneficial for the climate: leadership may mitigate sequencing distortions, but time-consistency constraints can erode these gains. Fourth, we study climate policies—carbon taxes, backstop subsidies and subsidies for renewable energy—and show that even small policy changes can trigger abrupt shifts in extraction regimes, producing jumps in welfare and climate damages.

Our policy analysis shows that climate instruments interact strongly with market power, giving rise to non-monotonic and regime-dependent welfare effects. In particular, a carbon tax can yield large welfare gains at moderate levels by triggering discrete changes in extraction behavior. In the benchmark scenario, welfare under the feedback von Stackelberg equilibrium (FBSE) responds little to taxation until the tax reaches roughly 150 USD/tC, at which point a regime shift in the extraction sequence raises welfare abruptly to 99.98 percent of the social optimum. The welfare-maximizing (second-best) tax lies about 100 USD/tC below the Pigouvian level, with further tax increases reducing welfare due to the conservation effect. Across alternative cartel structures and emissions profiles, we consistently find that welfare-maximizing carbon taxes fall below the social cost of carbon and that market power does not necessarily reduce welfare. We also show that larger cartels do not necessarily reduce welfare: for example, at a tax of 150 USD/tC, welfare is higher when all OPEC members coordinate than when market power is limited to a core subset (cf. Kellogg, 2024).

We also examine the effects of subsidies for the backstop technology and for renewable energy. A backstop subsidy of around 32 USD/BOE—close to current EU renewable support levels—eliminates sequencing inefficiencies and maximizes welfare. Still, the backstop subsidy increases climate damages through a Green Paradox effect. By contrast, a renewables subsidy consistently lowers emissions, yet reduces welfare in the presence of market power by reinforcing the conservation effect, while under perfect competition the optimal subsidy is modest, around 10 USD/BOE. Overall, the results imply that second-best climate policies can deliver near-optimal welfare by inducing regime shifts in strategic extraction behavior.

The remainder of the paper is organized as follows. Section 2 presents the model and the equilibrium concepts. Section 3 calibrates the model to the global oil market and quantifies the effects of leadership and commitment. Section 4 examines the effects of climate policies. Section 5 analyzes the impact of cost reducing techncical change in fossil extraction and the backstop technology. Section 6 concludes.

# 2 The model

## 2.1 Set-up

We analyze an energy market. Time is continuous. Energy can be generated from a non-renewable resource, from renewable resources and from a backstop technology. The cartel owns a stock of non-renewable resources denoted by $S^c(t)$ at time $t$, with initial stock $S_0^c$. The competitive fringe can be represented as a single representative price-taking firm whose stock is $S^f(t)$, with initial level $S_0^f$.

Production rates at time $t$ are $q^c(t)$ for the cartel, $q^f(t)$ for the fringe, $q^b(t)$ for the backstop and $q^r(t)$ for renewables. Marginal extraction costs of the fringe and the cartel are denoted by $k^c$ and $k^f$, respectively. The backstop can be produced at marginal cost $b$. Renewables production (e.g., biofuels, solar, wind) is subject to decreasing returns to scale. The key difference between the backstop technology and renewables is that the former features high marginal production costs that are independent of scale, whereas the latter exhibits low marginal costs at small scales but increasingly high marginal costs at large scales, for instance if renewables were to supply the entire energy demand (cf. Andrade de Sá and Daubanes, 2016; Van den Bijgaart and Rodriguez, 2023; Fischer and Salant, 2017). To capture this, we impose that marginal production costs of renewables are linear in the production rate and given by $\zeta + \eta \cdot q^r(t)$.

In our numerical analysis in Section 3, we leave out coal and gas. Hence, our energy market should be interpreted as energy used for transportation (where oil is the primary energy source and coal and gas only play a minor role). The inverse demand function for energy is given by

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

where $\tilde{\alpha} > 0$ and $\tilde{\beta} > 0$. We assume that the cartel and the fringe take the supply functions of the backstop and renewable producers as given. The inverse residual demand function faced by the non-renewable resource owners then reads

$$p(t) = \begin{cases} \min\{b, \alpha - \beta(q^c(t) + q^f(t))\}, & \text{if } p(t) > \zeta, \\ \min\{b, \tilde{\alpha} - \tilde{\beta}(q^c(t) + q^f(t))\}, & \text{if } p(t) \leq \zeta. \end{cases} \tag{2}$$

where $\alpha = (\tilde{\alpha}\eta + \tilde{\beta}\zeta)/(\eta + \tilde{\beta})$ and $\beta = \tilde{\beta}\eta/(\eta + \tilde{\beta})$. Throughout, we assume that $p(t) > \zeta$ for all $t$, so that the supply of renewables is positive at each instant of time (i.e., the first row of (2) applies).

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

The equilibrium must satisfy the resource constraints

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

Furthermore, $q^b(t) > 0$ 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 backstop 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.[2] 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 $\lambda^c$ 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

[2]For notational brevity, we omit renewable supply, which is positive throughout due to the assumption that $p(t) > \zeta$ for all $t$.

rule:

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

where $\lambda^f$ is the endogenously determined shadow price of the fringe's stock.

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

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

- $F$: 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 marginally below $b$, keeping the backstop from the market.
- $R$: only backstop 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. (2026), respectively. Here, we will focus on the essentials. We will also compare these three equilibria to the social optimum and the perfectly competitive outcome.

**Perfect competition and social optimum** In the perfectly competitive outcome, the unique equilibrium sequence is $C \rightarrow F \rightarrow R$, which satisfies the Herfindahl rule (Herfindahl, 1967) since cheap reserves are depleted before more expensive reserves are exploited (recall that the unit extraction costs satisfy $k^c < k^f$). The social optimum is also characterized by the sequence $C \rightarrow F \rightarrow R$, but does account 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 price *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.[3] Producers of the backstop 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) $S \to F \to R$ (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).

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 monopoly price ($C^m$) or the limit price ($L$)—before the fringe's stock is exhausted, since the fringe would undercut the cartel. Furthermore, it is not willing to supply alone at the competitive price or the fringe's competitive price ($C$ or $C^f$) during a non-degenerate interval of time.

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 $F \to R$. If the cartel's stock is somewhat larger, the next phases are $L \to R$. Finally, if the cartel's stock is sufficiently large, the simultaneous supply phase is followed by $C^m \to L \to R$. The region with $S \to C^m \to L \to R$ 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.

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

**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 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, 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 $S_0^c$).

The intuition is as follows. 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., 2026). 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 subsequent analysis.

**Feedback von Stackelberg** 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). The feedback von Stackelberg equilibrium is conceptually very similar to the open-loop von Stackelberg equilibrium, but with the additional requirement of subgame-perfectness. In Appendix A, we formalize this notion. Intuitively, at $t = 0$ the cartel first announces a feedback rule, taking the global best-response correspondence of the fringe into account. After the announcement of the cartel, the fringe announces its feedback rule. 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 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). But, the Hotelling rule is now also an implicit function of the resource stock of the fringe, captured by the shadow value. 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 correspondence 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 (2). Due to a possible phase of simultaneous supply, it is difficult to find a solution to the HJB equation. Elgersma et al. (2026) show that, under our parameter restrictions, for a given initial stock of the fringe, the equilibrium is characterized by one of the following three equilibrium sequences:

(i) $C^f \rightarrow F \rightarrow R$ (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).

Elgersma et al. (2026) then derive 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 less cumbersome, as the $S-$phase is absent. At first glance, the feedback von Stackelberg equilibrium may appear similar to the Nash–Cournot equilibrium (cf. Newbery, 1981). 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.

Finally, note that, unless the equilibrium is of type (i), the Herfindahl rule (which, due to discounting, requires depletion of reserves with low marginal extraction costs before extraction from more costly reserves) is violated. 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 and characterize its equilibrium under Nash–Cournot competition, open-loop von Stackelberg leadership, and feedback von Stackelberg leadership. We also derive the perfectly competitive outcome and the social optimum. This framework allows us to analyze how imperfect competition, leadership, and commitment affect profits, climate damages, and overall welfare. Furthermore, we will examine the effects of climate policies (a carbon tax, a backstop subsidy and a subsidy for renewables) and technical change that lowers the fringe's marginal extraction cost and the marginal production cost of the backstop.

Welfare is defined as the present value of the sum of the consumer surplus, the profits of the cartel, the profits of the fringe and the producer surplus of the renewables producers, net of climate damage (which is also measured in present value terms). Grey welfare is defined as welfare plus climate damage.

To quantify climate damage, we impose a fixed Social Cost of Carbon (SCC). Estimates of the SCC vary widely in the literature (cf. Tol, 2025). We adopt a value of 250 USD per tC,[4] which lies near the upper-middle range of reported estimates.

## 3.1 Calibration

We calibrate the inverse oil demand function—its choke price, $\alpha$, and slope, $\beta$—such that at $p = 80$ USD and $q = 34$ billion barrels, values that approximate the average Europe Brent spot price (EIA, 2026) and global oil demand (IEA, 2025b) over the past five years, the implied price elasticity of oil demand equals $-0.55$, which is the

[4] Tol (2025) reports that, based on all published SCC estimates, there is a 61 percent probability that the SCC is below 250 USD/tC.

middle of the range of long-run demand elasticities reported by Uria Martinez et al. (2018) based on their meta analysis.

We compute the cartel's marginal extraction cost and emission factor as proven reserve-weighted averages across OPEC members. An analogous procedure is used for the fringe, relying on data for non-OPEC countries. Data on proven reserves are taken from the Energy Institute (2025). IMF (2015) provides operational cost estimates for 43 oil-producing countries, based on data from Rystad Energy. Total cost data, which cover fewer countries, are obtained from Statista (2015). To maximize country coverage, we calculate the reserve-weighted average ratio of total to operational costs and apply this ratio to each country's operational cost from IMF (2015) to obtain a consistent estimate of total extraction costs. With our 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 appear in the calibrated model.

Full-cycle emission factors are taken from CEIP (2026). Oil extraction by the fringe—drawing disproportionately on offshore shelf, offshore deepwater, shale oil, and oil sands resources—has a higher weighted-average emission factor than extraction by the cartel, whose production is concentrated in lower-emission onshore conventional fields (cf. Fischer and Salant, 2017).

Our calibration approach differs from the approach of Coulomb et al. (2026). Their analysis relies on the Rystad UCube dataset combined with detailed engineering-based estimates of upstream and midstream carbon intensities (OPGEE, PRELIM) to quantify field-level heterogeneity in both extraction costs and carbon intensities. In contrast, our model abstracts from deposit-level variation. Instead, we use freely available country-level data to compute reserve-weighted averages for marginal extraction costs and emission factors for the cartel and the fringe. This aggregation reflects our focus on strategic interaction rather than on granular geological differences. Nevertheless, the empirical patterns documented by Coulomb et al. (2026), the wide dispersion in carbon intensities across deposits, support the relevance of modeling asymmetric emission factors between producers.

For the interest rate, we use the average return on 5-year U.S. government bonds over the period 2018–2023 (U.S. Department of the Treasury, 2026). We then set the intercept of the renewables' marginal cost function, $\zeta$, to zero and calibrate the slope

| parameters | description | full OPEC | core OPEC | clean-dirty | unit |
|---|---|---|---|---|---|
| $\tilde{\alpha}$ | energy choke price | 248 | 248 | 248 | US$/BOE |
| $\tilde{\beta}$ | slope inverse energy demand function | 4.7 | 4.7 | 4.7 | US$/BOE |
| $\eta$ | slope renewables supply function | 47.1 | 47.1 | 47.1 | US$/BOE |
| $\zeta$ | intercept renewables supply function | 0 | 0 | 0 | US$/BOE |
| $b$ | backstop price | 102.5 | 102.5 | 102.5 | US$/BOE |
| $k^c$ | marginal extraction cost cartel | 16 | 11 | 16 | US$/bbl |
| $k^f$ | marginal extraction cost fringe | 39 | 28 | 39 | US$/bbl |
| $r$ | interest rate | 0.028 | 0.028 | 0.028 | per annum |
| $S_0^c$ | initial stock cartel | 1238 | 497 | 1238 | bln bbl |
| $S_0^f$ | initial stock fringe | 480 | 1221 | 480 | bln bbl |
| $\omega^c$ | emission factor cartel | 0.1496 | 0.1363 | 0.1421 | tC/bbl |
| $\omega^f$ | emission factor fringe | 0.1541 | 0.1569 | 0.1734 | tC/bbl |
| $SCC$ | social cost of carbon | 250 | 250 | 250 | US$/tC |
| $\alpha$ | oil choke price | 225.5 | 225.5 | 225.5 | US$/bbl |
| $\beta$ | slope inverse oil demand function | 4.3 | 4.3 | 4.3 | US$/bbl |

**Table 1:** Calibrated scenarios.

of this marginal cost function, $\eta$, and the backstop unit cost, $b$, such that the initial renewable energy share equals 3.6 percent—close to the 2022 global renewable share in transport of 3.4 percent reported by REN21 (2025)—and initial oil demand equals 37.5, consistent with recent global levels (IEA, 2025b). The choke price, $\tilde{\alpha}$, and the slope of aggregate energy demand function, $\tilde{\beta}$, follow directly from these calibrated parameters.

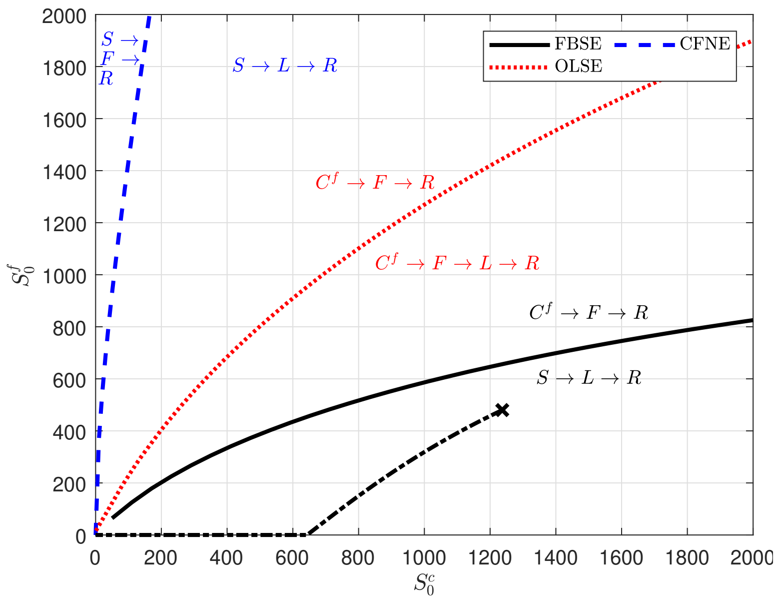
Table 1 summarizes all parameter values. The column "full OPEC" presents the benchmark case in which the cartel includes all OPEC members. We also examine two alternative market-structure scenarios. Following Kellogg (2024), the "core OPEC" scenario restricts the cartel to Kuwait, Saudi Arabia, and the United Arab Emirates, with the remaining OPEC members together with the non-OPEC countries treated as a competitive fringe. The "clean-dirty" scenario mirrors the "full OPEC" benchmark but imposes a larger disparity in emission factors between the cartel and the fringe. Specifically, we reduce the cartel's emission factor by 6.5 percent and adjust the fringe's emission factor upward so that the total carbon content of initial reserves remains unchanged. This calibration yields a fringe emission factor that is 28 percent higher than that of the cartel, approximately matching the percentage difference observed between Canada and Saudi Arabia.

## 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 a cross. The solid black curve divides the space into two regions. Above this locus, the feedback von Stackelberg equilibrium is of the type $C^f \to F \to R$; below, it is $S \to L \to R$. This confirms that the cartel exerts more monopoly power when the fringe holds a small initial stock.

The dashed blue curve marks the dividing locus for the Nash–Cournot equilibrium. Below this curve, the sequence is $S \to L \to R$; above, $S \to F \to R$. Hence, the Nash–Cournot equilibrium does not always predict the feedback von Stackelberg equilibrium well (cf. Newbery, 1981; Karp and Newbery, 1993). Moreover, even if both equilibria are of the type $S \to L \to R$, extraction paths generally differ.

**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 blue curve separates equilibrium types under Nash–Cournot (CFNE): above $S \to F \to R$, below $S \to L \to R$. The dotted red 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, and the dashed-dotted curve reflects the state trajectory under the FBSE.

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

### 3.3 Market equilibria in three scenarios

**Table 2:** Comparison of equilibria

**(a)** Benchmark: OPEC (cartel) vs. non-OPEC (fringe) [$S \to L \to R$]

| Metric (tln USD) | FBSE | FBSE-H | OLSE | CFNE | PC | SO |
|---|---|---|---|---|---|---|
| Welfare | 120.2 | 124.6 | 121.1 | 118.2 | 123.6 | 124.7 |
| Profit cartel | 41.8 | 50.0 | 43.6 | 41.9 | 32.8 | 18.1 |
| Profit fringe | 12.5 | 8.5 | 13.7 | 16.4 | 8.2 | 2.8 |
| Climate damage | 34.8 | 34.6 | 34.3 | 33.5 | 37.4 | 35.0 |

**(b)** Core-OPEC (cartel) vs. Rest of OPEC and non-OPEC [$C^f \to F \to R$]

| Metric (tln USD) | FBSE | FBSE-H | OLSE | CFNE | PC | SO |
|---|---|---|---|---|---|---|
| Welfare | 123.4 | 123.4 | 123.4 | 119.1 | 123.2 | 124.4 |
| Profit cartel | 17.1 | 17.1 | 17.1 | 14.6 | 16.0 | 11.5 |
| Profit fringe | 24.3 | 24.3 | 24.3 | 29.9 | 24.5 | 10.0 |
| Climate damage | 36.6 | 36.6 | 36.6 | 36.8 | 36.7 | 34.2 |

**(c)** Cleaner cartel and dirtier fringe [$S \to L \to R$]

| Metric (tln USD) | FBSE | FBSE-H | OLSE | CFNE | PC | SO |
|---|---|---|---|---|---|---|
| Welfare | 119.7 | 125.7 | 121.0 | 117.2 | 124.6 | 125.8 |
| Profit cartel | 41.8 | 50.0 | 43.6 | 41.9 | 32.8 | 20.1 |
| Profit fringe | 12.5 | 8.5 | 13.7 | 16.4 | 8.2 | 2.1 |
| Climate damage | 35.3 | 33.5 | 34.4 | 34.6 | 36.4 | 33.9 |

*Notes:* FBSE-H reports the outcome for the Herfindahl scenario, in which aggregate extraction follows the FBSE path, but the extraction sequence is fixed to $C^f \to F \to R$ to satisfy the Herfindahl rule, thereby eliminating the sequencing effect. PC represents perfect competition and SO the social optimum. Panel (a) presents the benchmark case where the cartel comprises all OPEC members. Panel (b) considers a cartel limited to the core OPEC countries: Kuwait, Saudi Arabia, and the United Arab Emirates. Panel (c) examines a setting that mirrors the "full OPEC" benchmark but imposes a larger disparity in emission factors between the cartel and the fringe in such a way that the total carbon content of the initial reserves remains unchanged. For each panel, the equilibrium sequence for the FBSE is indicated between brackets.

Table 2 reports welfare, profits, and climate damages across equilibrium concepts and market-structure scenarios. In addition to the FBSE, OLSE, and CFNE equilibria, it includes the perfectly competitive equlibrium (PC) and the social optimum (SO). The column FBSE-H corresponds to the "Herfindahl scenario," which retains the aggregate extraction path from the FBSE but imposes the efficient depletion sequence—exclusive extraction by the cartel until its reserves are exhausted, followed by exclusive extraction by the fringe. FBSE-H is therefore not an equilibrium outcome but a theoretical construct that removes the sequencing effect generated by market power. After removing the sequencing effect, the "conservation effect" remains: the cartel marks up the price, which slows down the depletion of oil reserves.

**Market power without leadership (CFNE vs. PC).** Relative to the perfectly competitive benchmark, introducing market power through Nash–Cournot behavior reduces welfare and raises profits for the fringe in all scenarios. Interestingly, in the "core-OPEC" case (panel (b)), the cartel's profit falls when moving from perfect competition to the CFNE. According to Ulph (1982) this possibility was shown in Ulph and Folie (1978).

In panels (a) and (c), climate damages are lower under CFNE than under perfect competition, consistent with the conservation effect dominating. In the "core-OPEC" case shown in panel (b), however, the cartel controls a smaller share of reserves and the emission factor differential between the cartel and the fringe is larger, so the sequencing effect dominates, resulting in slightly higher climate damages under CFNE than under perfect competition.

**Leadership with commitment (OLSE vs. CFNE).** Introducing von Stackelberg leadership with commitment raises welfare and cartel profits in every scenario, while reducing fringe profits.

Climate effects of leadership differ across scenarios. Leadership increases climate damages in panel (a), but reduces them in panels (b) and (c). When emission factors differ strongly, leadership mitigates the sequencing effect by shifting extraction toward the cleaner cartel, improving climate outcomes despite weakening the conservation effect.

**Leadership without commitment (FBSE vs. CFNE).** Comparing FBSE directly with CFNE isolates the effect of leadership in the absence of commitment. Across scenarios, welfare is higher under FBSE and fringe profits are lower. Note that the cartel can earn *less* under FBSE than under CFNE despite holding a leadership role. This occurs in panels (a) and, (c). The key mechanism is the time-consistency constraint: while the cartel could in principle mimic CFNE extraction rates, doing so would be dynamically inconsistent when it acts as a von Stackelberg leader. Hence, the value of leadership is partially or fully eroded unless 'full-commitment' is available (cf. Bizzotto et al., 2026).

Leadership reduces climate damage only in panel (b), where it eliminates the sequencing distortion. In panels (a) and (c), the reduction of the conservation effect outweighs improvements in sequencing, raising climate damages.

**Commitment vs. no commitment (FBSE vs. OLSE).** In panels (a) and (c), removing commitment lowers welfare, reduces both cartel and fringe profits, and increases climate damages. This pattern does not arise in panel (b), where the OLSE is time-consistent and therefore coincides with the FBSE.

**Eliminating the sequencing effect (FBSE-H vs. FBSE).** The Herfindahl scenario (FBSE-H) removes distortions in extraction timing. Front-loading cleaner cartel production improves welfare and reduces climate damages in panels (a) and (c), while increasing cartel profits and reducing fringe profits. Panel (b) is again the exception: since its equilibrium sequence already satisfies $C^f \to F \to R$, FBSE-H coincides with FBSE.

# 4 Climate policies

We now exploit the characterization of the different equilibria and the calibration to analyze the effects of three climate policy instruments—a carbon tax, a subsidy for the backstop technology, and a subsidy for renewable energy. We begin by separately examining all three instruments in the benchmark scenario (i.e., the cartel consists of all OPEC members). For the alternative two scenarios, our analysis focuses on the carbon tax, as it is the most direct and widely used policy instrument and provides the most informative comparison across scenarios.

Technically, the carbon tax, at rate $\tau$ per tC emitted, is incorporated into the model by redefining the marginal extraction costs as

$$\hat{k}^c = k^c + \tau \cdot \omega^c,$$
$$\hat{k}^f = k^f + \tau \cdot \omega^f.$$

Similarly, a backstop subsidy of $\sigma$ per barrel of oil equivalent (BOE) implies an after-subsidy unit cost

$$\hat{b} = b - \sigma,$$

and a renewables subsidy of $\nu$ per BOE implies

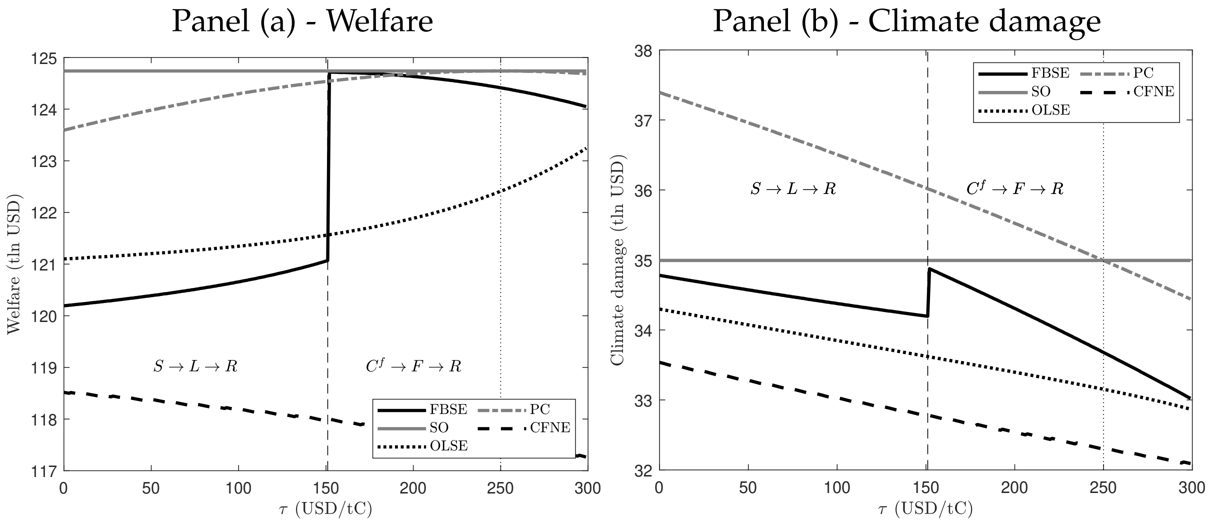
$$\hat{\zeta} = \zeta - \nu.$$

Lump-sum transfers are used both to rebate tax revenues and to finance subsidy payments. Hence, when determining market equilibria, we use the after-tax-and-subsidy cost parameters (those with hats), whereas the welfare calculations rely on the pre-tax-and-subsidy parameters. The social optimum is obtained by imposing the perfectly competitive outcome with $\tau = SCC$.

## 4.1 Carbon tax

We first consider the effect of introducing a tax on carbon emissions from the fringe and the cartel in the benchmark scenario. Although a uniform global carbon tax will be hard to implement in practice, its consequences for welfare and climate damage in the current setting are interesting.

**Figure 2:** Carbon tax: welfare effects




*Notes:* The figure shows the effect of a carbon tax on welfare (panel (a)) and climate damages (panel (b)). It compares the cartel fringe equilibria with the social optimum (solid grey lines) and the perfectly competitive outcome (dash-dotted grey curves).

Figure 2 illustrates how a carbon tax affects welfare (panel (a)) and climate damages (panel (b)). Both panels compare the FBSE (solid black line) with the perfectly competitive outcome (dash–dotted grey line), the social optimum (flat solid grey line), the CFNE (dashed black line), and the OLSE (dotted black line). The vertical dashed line marks the tax rate at which the FBSE switches from the $S \to L \to R$ regime to the $C^f \to F \to R$ regime. The vertical dotted line indicates the Pigouvian carbon tax (at $\tau = SCC$), which maximizes welfare under perfect competition.

A striking pattern emerges in panel (a). A carbon tax has two conceptually distinct effects in our setting. First, because the fringe is more carbon intensive than the cartel ($\omega_f > \omega_c$), the tax raises the fringe's effective marginal extraction cost by more than that of the cartel. In that sense, the tax acts not only as a standard corrective instrument that discourages fossil-fuel use, but also as a device that tends to improve the extraction order by shifting production toward the relatively cleaner cartel. This works against the *sequencing effect*, i.e. the inefficiency that arises when a relatively expensive and dirty producer supplies too early. Second, the tax strengthens the *conservation effect*: by increasing the cost of fossil extraction, it delays depletion. Since market power already tends to slow extraction relative to the social optimum, an additional tax may push the economy toward excessive conservation. The welfare effect of the carbon tax therefore depends on which of these two effects dominates.

Under the FBSE, welfare responds only modestly to the carbon tax as long as the equilibrium remains of type $S \to L \to R$. In that region, the tax gradually weakens the fringe by increasing its effective extraction cost disproportionately, but not yet enough to overturn the underlying equilibrium structure. Once the tax reaches roughly 150 USD/tC, however, the economy crosses a regime boundary and the FBSE switches from $S \to L \to R$ to $C^f \to F \to R$. This discrete change eliminates the initial phase of simultaneous extraction and thereby removes the main sequencing distortion. As a result, welfare jumps upward to 99.98 percent of the first-best level. Beyond this threshold, further tax increases no longer generate an additional gain from correcting the extraction order, while they do reinforce the conservation effect. Consequently, welfare falls again as the tax approaches the Pigouvian benchmark. The second-best carbon tax is therefore well below the social cost of carbon, even though it delivers welfare very close to the social optimum.

The contrast with the CFNE is instructive. Although both the FBSE and the CFNE are of type $S \to L \to R$ over part of the tax interval, the effect of the carbon tax differs because the extraction paths within the initial $S$-phase are not the same. In the CFNE, a higher carbon tax mainly translates into a higher equilibrium price path and slower aggregate depletion, thereby reinforcing the conservation effect. In the FBSE, by contrast, the tax weakens the fringe disproportionately and thereby allows the cartel, as a time-consistent leader, to expand its own extraction at the expense of the fringe within the $S$-phase. Hence, under the FBSE the tax primarily improves the composition of supply — shifting production from the dirtier fringe to the cleaner cartel — whereas under the CFNE it primarily strengthens conservation. This difference in within-regime adjustment explains why welfare may increase with the tax in the FBSE even before the regime switch, while it decreases monotonically in the CFNE.

The OLSE illustrates most clearly how carbon taxation interacts with commitment. In the benchmark calibration, the OLSE is of type $C^f \to F \to L \to R$, so that simultaneous supply is absent from the outset. Because the fringe is more carbon intensive than the cartel, a higher carbon tax raises the fringe's effective extraction cost by more and thereby weakens the constraint that the fringe imposes on the cartel. Under open-loop commitment, the cartel can translate this immediately into a more favorable extraction pattern through its announced price path. The tax therefore shifts production away from the dirtier fringe and reduces the importance of the later limit-pricing phase, improving the extraction order without requiring a discrete regime switch. In that sense, under the OLSE the carbon tax primarily acts as a strategic re-ordering device rather than as a mere demand-suppression instrument, which explains why welfare rises with the tax over the relevant range.

Note that, in the absence of a carbon tax, the perfectly competitive equilibrium dominates the other equilibria in terms of welfare, and in particular dominates the FBSE for all tax levels up to 150 USD/tC, where the regime shift occurs and welfare is highest in the FBSE.

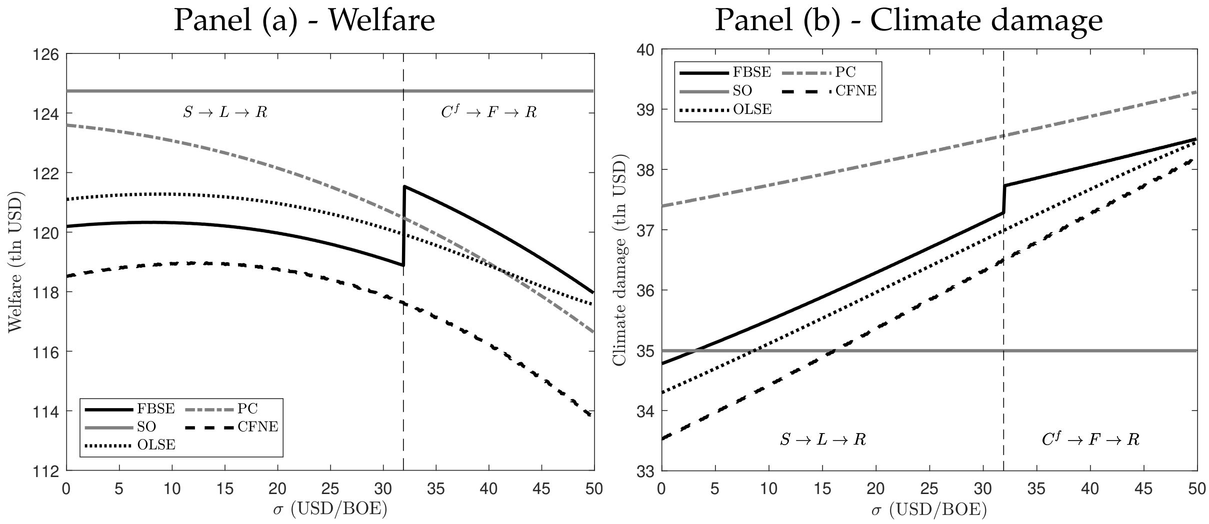
Panel (b) shows that climate damages also jump upward at the tax rate that produces the welfare jump in the FBSE. Although the shift from $S \to L \to R$ to $C^f \to F \to R$ removes the sequencing effect and would, in isolation, reduce climate damages, it also weakens the conservation effect: at the regime shift the cartel must expand its own supply sharply in order to keep the fringe out of the market at the fringe's competitive price. Relative to the preceding $S$-phase, this discrete increase in cartel output weakens the conservation effect substantially. In the benchmark calibration, where the emission-factor differential between cartel and fringe is modest, this increase in fossil supply dominates the reduction in damages due to improved sequencing, so climate damages jump upward at the regime switch. Nevertheless, welfare still rises sharply, which implies that in the benchmark calibration the welfare gain from eliminating the sequencing distortion outweighs the increase in climate damages. Apart from this upward jump in the FBSE, climate damages decline monotonically with the carbon tax in all scenarios.

## 4.2 Backstop subsidy

Here, we examine the effects of a backstop production subsidy. Figure 3 shows results for welfare (panel (a)) and climate damage (panel (b)) for subsidy rates ranging from 0 to 50 USD/BOE. To obtain an approximate benchmark for current renewable-energy subsidies, we use EU data for 2023: total renewable subsidies amounted to 61 billion Euro (European Commission, 2025). Using a conversion factor of 6.98 barrels per tonne of oil equivalent (EIA, 2025; IEA, 2025a), total primary energy use in the EU in 2023 was 1208.5 million tonnes of oil equivalent, or 8.44 billion BOE (EEA, 2025a). A renewable share of 24.6 percent (EEA, 2025b) then yields renewable energy consumption of 2.08 billion BOE. This implies an average renewables subsidy rate of 29.4 Euro per BOE (around 32 USD/BOE). At the global level, this number is much lower: with global primary energy consumption of 15 billion tonnes of oil equivalent and global renewables subsidies of 168 billion USD, using the same conversion factors yields a subsidy rate of 14.5 USD/BOE.

Under perfect competition (dash–dotted grey line), welfare declines as the subsidy increases because the subsidy accelerates oil extraction through a Green Paradox effect; and oil was already being extracted too quickly in the absence of carbon pricing. In the feedback von Stackelberg equilibrium (solid black line), welfare responds non-monotonically to the subsidy. A backstop subsidy speeds up oil depletion (thereby weakening the conservation effect) but also affects the sequencing effect, which disappears completely at a subsidy of 32 USD/BOE, close to the current

**Figure 3:** Backstop subsidy: welfare effects



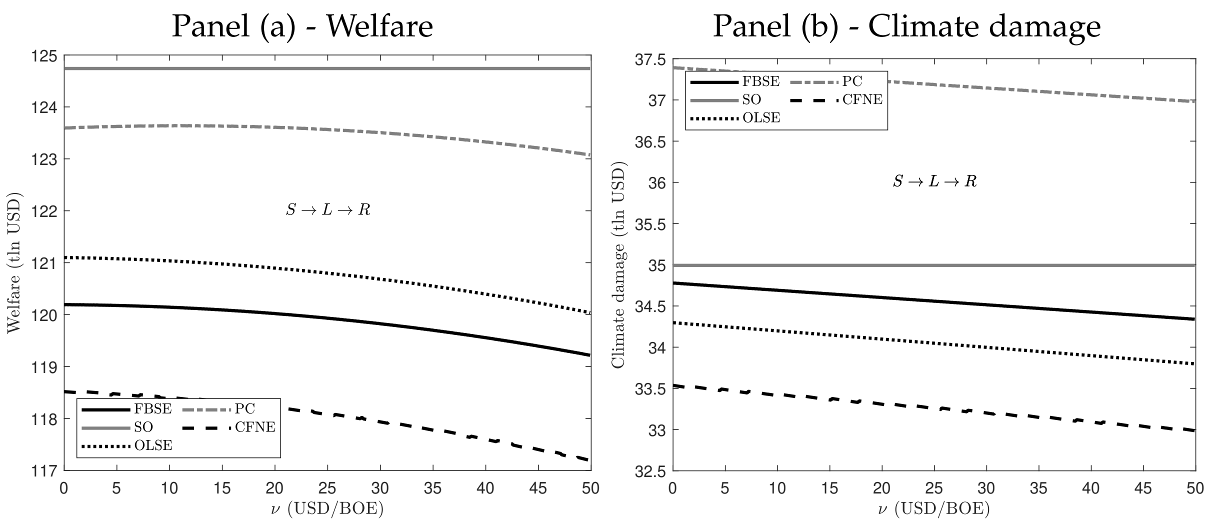

average renewables subsidy in the EU. Once the subsidy exceeds this threshold, the leader can credibly frontload extraction to push the fringe out of the market. Intuitively, a backstop subsidy hurts the fringe disproportionally more, so if the backstop subsidy is sufficiently large, the fringe is weakened enough for the cartel to credibly and profitably push forward its own supply. This forces the extraction order to follow the Herfindahl rule and eliminates the sequencing effect of market power. Interestingly, the current global average subsidy rate of 14.5 USD/BOE lies near the local welfare maximum within the $S \to L \to R$ region. Note that the maximum welfare in the FBSE is 121.53 trillion (tln) USD, which is 97.43 percent of welfare in the social optimum. This is considerably lower than the maximum welfare of 99.98 percent of the social optimum that can be achieved with a carbon tax.

Panel (b) shows that climate damage increases monotonically with the subsidy in all regimes, reflecting a Green Paradox effect: the subsidy accelerates oil extraction. As with the carbon tax, climate damage jumps up once the subsidy induces the regime switch from $S \to L \to R$ to $C^f \to F \to R$, which eliminates the sequence effect and weakens the conservation effect of market power.

## 4.3 Renewables subsidy

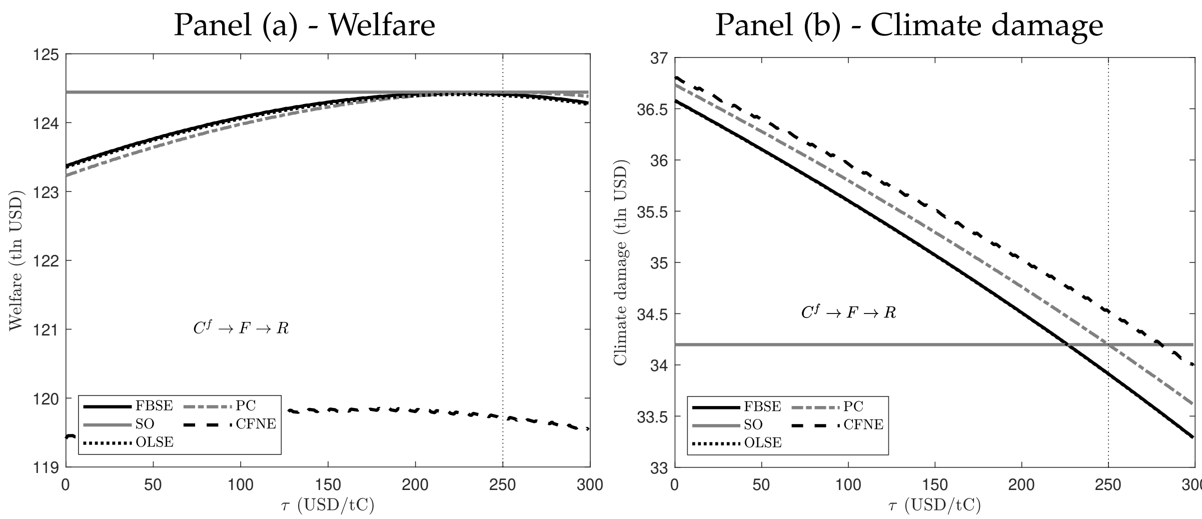
Figure 4 shows the effect of a subsidy for types of renewable energy whose marginal costs increase with the production rate. In contrast to the backstop technology, these renewables are supplied at positive levels throughout. A subsidy shifts the marginal cost curve downward, which implies a downward shift in the oil demand curve faced by the cartel and the fringe. Subsidy rates ranging from 0 to 50 USD/BOE do not induce a regime switch in the FBSE: the extraction sequence remains $S \rightarrow L \rightarrow R$ for all subsidy levels. This contrasts with a backstop subsidy, which directly lowers the effective backstop cost and thereby changes the value of the fossil resources owned by the cartel and the fringe, thereby weakening the fringe's position disproportionately relative to that of the cartel.

**Figure 4:** Renewables subsidy: welfare effects




Panel (b) shows that, unlike a subsidy for the backstop, a renewables subsidy lowers climate damage in all scenarios. However, as panel (a) illustrates, in all equilibria with market power the subsidy reduces welfare because it strengthens the conservation effect: by lowering oil demand, the subsidy slows down the speed of extraction, which was already sub-optimally low due to market power. Under perfect competition, by contrast, the welfare-maximizing subsidy rate is positive and lies around 10.5 USD/BOE. The effects of a renewables subsidy on the residual demand function for oil and therefore on climate damage is similar to a carbon tax. However, the effect is smaller, so that a subsidy over the considered range does not lead to a regime shift. Compare panel (b) of Figure 4 with panel (b) of Figure 2.

**Figure 5:** Core-OPEC (cartel) vs. Rest of OPEC and non-OPEC



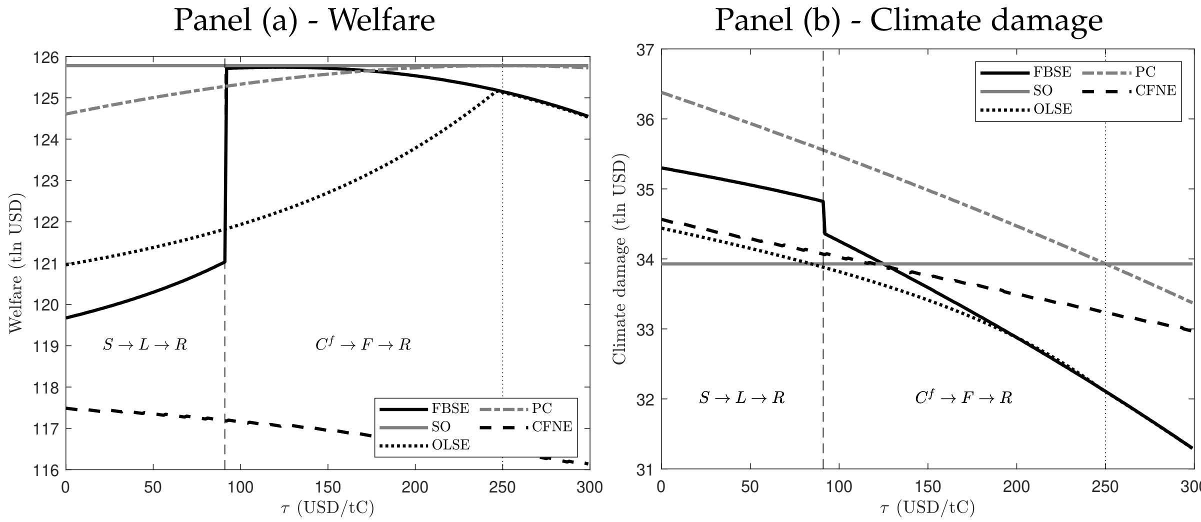

*Notes:* The figure shows the effect of a carbon tax on welfare (panel (a)) and climate damages (panel (b)) in the scenario where the cartel consists of Kuwait, Saudi Arabia and the United Arab Emirates, whereas the fringe consists of the other OPEC members and the non-OPEC members.

## 4.4 Carbon tax in alternative scenarios

Figure 5 shows the welfare and climate-damage effects for the "core-OPEC" scenario, where the cartel consists of Kuwait, Saudi Arabia, and the United Arab Emirates. In the FBSE, a small cartel stock implies a $C^f \to F \to R$ equilibrium: the cartel prefers to exhaust its relatively scarce, low-cost reserves first by serving the market at the fringe's competitive price, rather than sharing the market in an $S$-phase. Since the fringe stock is much larger than the cartel's, a short phase of simultaneous supply would not come close to exhausting the fringe, but would merely shift market share toward a higher-cost and dirtier producer. A carbon tax reinforces this logic, because it raises the fringe's effective extraction cost by more than the cartel's. Hence, throughout the range of tax rates considered, the economy remains in the $C^f \to F \to R$ regime.

Across all equilibrium concepts, welfare is non-monotonic in the carbon tax and reaches its maximum below the Pigouvian level (panel (a)). Climate damages, by contrast, decline monotonically with the tax (panel (b)). Note that at a carbon tax of 150 USD/tC, under FBSE welfare in the benchmark scenario in which the cartel consists of all OPEC members exceeds welfare in the core-OPEC scenario (compare panels (a) of the Figures 2 and 5).

**Figure 6:** Cleaner cartel and dirtier fringe




*Notes:* The figure shows the effect of a carbon tax on welfare (panel (a)) and climate damages (panel (b)) in the scenario where the cartel consists of OPEC-countries and the fringe of non-OPEC countries, but with a larger disparity in emission factors between the cartel and the fringe than in the benchmark scenario (in such a way that the total carbon content of the initial reserves remains unchanged).

Finally, we consider the scenario with a larger emission factor disparity between the cartel and the fringe. Panel (a) of Figure 6 shows that the upward jump in welfare occurs at a lower carbon tax rate of 92 USD/tC. The second-best carbon tax is 123 USD/tC and delivers welfare equal to 99.97 percent of the social optimum. Panel (b) shows that at the regime switch from $S \to L \to R$ to $C^f \to F \to R$, climate damage now jumps *down*. Because emission factors differ substantially, the elimination of the sequence effect dominates the weakening of the conservation effect. A carbon tax of 92 USD/tC therefore produces both an upward jump in welfare and a downward jump in climate damage, yielding welfare equal to 99.95 percent of that in the social optimum (compared to 95.14 percent without a carbon tax).

# 5 Technical change

In this section, motivated by recent technological improvements that have affected both the extraction costs of the fringe (e.g. Kaplan, 2023) and the costs of the backstop technology (e.g. Way et al., 2022, p. 2057), we examine separately the impact of each change on equilibrium outcomes and the resulting implications for climate policy.

## 5.1 Technical change in oil extraction

We illustrate the role of the fringe's extraction cost $k^f$, which equals 39 USD/bbl in the benchmark case but has changed and may change further due to technical progress. For example, the weighted average break-even oil price for the Canadian oil sands sector has fallen by 41% between 2015 and 2023 (Kaplan, 2023).[5]

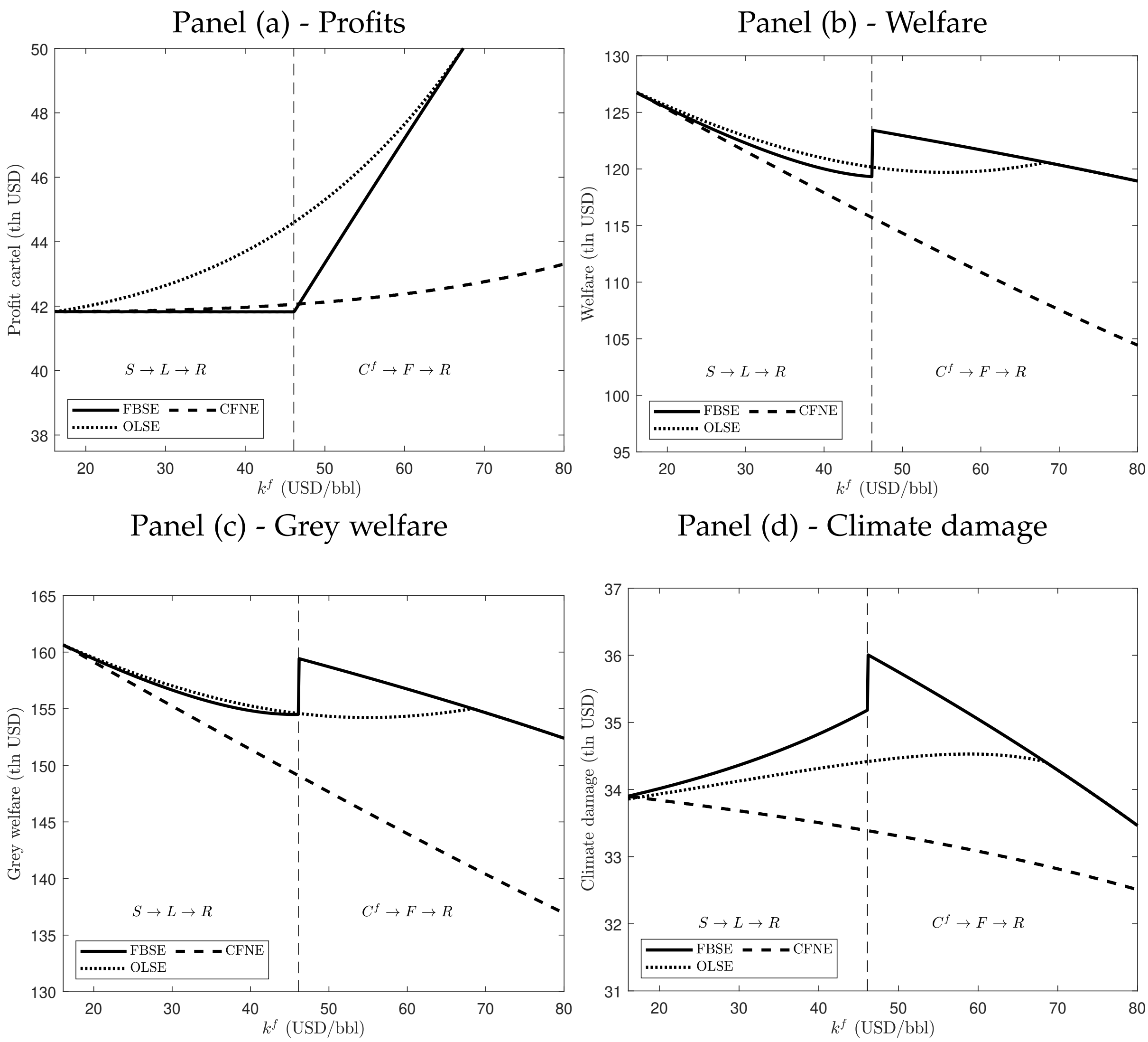
We compare the equilibrium outcomes for a range of values of the marginal extraction cost of the fringe. Instead of allowing for exogenously decreasing extraction costs over time (cf. André and Smulders, 2014), we compare scenarios with different constant marginal extraction costs. In Figure 7, we vary $k^f$ from 16.1 (slightly above $k^c$) to 80. Figure 7 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 $k^c = k^f = 16$. While the industry's production path is unique, the market shares of the cartel and the fringe are not. Both players are indifferent between the exact moment at which 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 46 USD/bbl), cartel profit is lower under feedback von Stackelberg than under Nash–Cournot (see Section 3.2). In this range, the profit-maximizing sequence is $S \to L \to R$, and cartel profits are independent of $k^f$. The reason is that because of the time consistency requirement, the cartel cannot benefit from a cost increase of the fringe. For larger $k^f$, however, the feedback equilibrium switches to $C^f \to F \to R$, 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. For the range of $k^f$ we consider, welfare under FBSE can differ substantially from the OLSE. The reason can be best

[5] Extraction costs for the cartel are relatively stable, reflecting the nature of conventional oil resources and the maturity of the extraction technologies employed by cartel members. For this reason, we focus on a change in the fringe's marginal extraction costs.

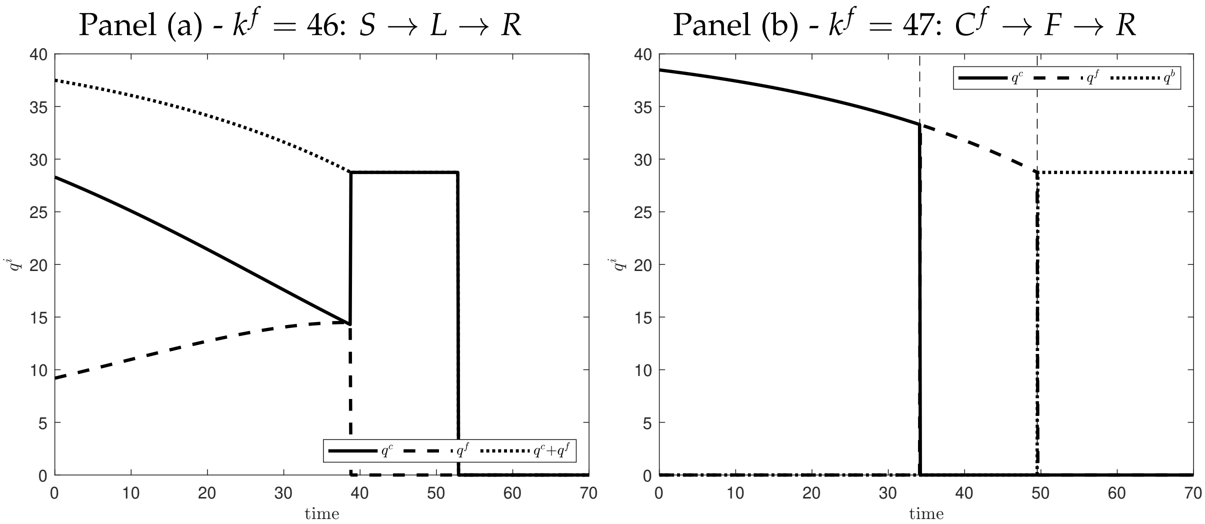
**Figure 7:** Cost-reducing technical change in oil extraction




*Notes:* The figure illustrates how varying the fringe's extraction cost $k^f$ affects outcomes under three equilibrium concepts. The vertical dashed line marks the border between the $S \to L \to R$ and $C^f \to F \to R$ regimes.

understood by moving from a high $k^f$ to a low $k^f$. For a high $k^f$ (around 68 USD/bbl), the competitive price $P^f$ is high, and the cartel wants to push its supply forward. Commitment is no issue in that case, as the cartel can credibly announce that it wants to be the sole supplier; the OLSE and FBSE coincide. For a lower $k^f$, the OLSE will feature an additional phase of limit pricing, which decreases welfare but increases profits of the cartel. However, this is time-inconsistent and therefore does not happen under FBSE. When $k^f = 46$, the cartel faces increasing competition from the fringe and therefore finds it profitable to allow for a phase of simultaneous supply, which will decrease welfare, as the sequencing effect appears.

**Figure 8:** Time paths in different extraction regimes

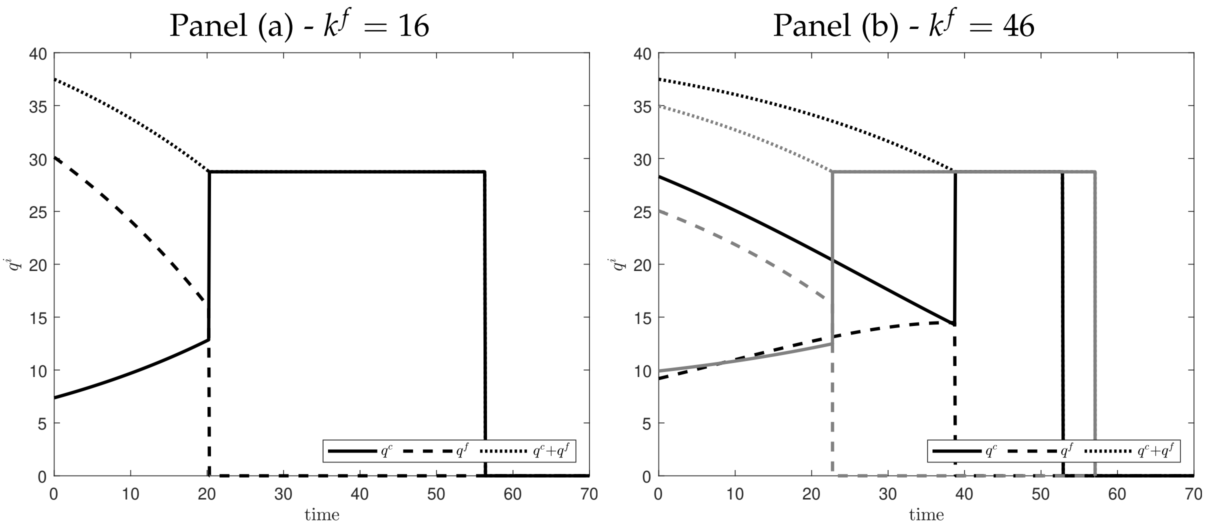



Grey welfare (panel (c)) shows a similar pattern as welfare does. Panel (d) shows climate damage. Interestingly, in FBSE and OLSE, climate damage is non-monotonic in the fringe's marginal extraction cost, whereas in CFNE, the relationship is negative. The reason is that in the region with $S \to L \to R$, the initial price is independent of $k^f$. Still, the fringe's profit per barrel must grow at the rate of interest, according to the Hotelling rule. This implies that an increase in $k^f$ increases the duration of the simultaneous supply regime, and the cumulative extraction of the cartel during this regime. Hence, limit pricing will be of shorter duration and the cartel's stock will be depleted sooner. This implies that, counterintuitively, an increase in $k^f$ increases climate damage in FBSE.[6] In the $C^f \to F \to R$ region, the expected negative relation-

[6] A similar mechanism applies to the $C^f - F - L - R$ regime in the OLSE, where the duration of the limit-pricing regime also becomes shorter if the extraction cost of the fringe increases.

ship between $k^f$ and climate damage prevails. At the regime switch, climate damage jumps up as the elimination of the sequencing effect is dominated by the decrease in the conservation effect when moving from $S \rightarrow L \rightarrow R$ to $C^f \rightarrow F \rightarrow R$.

**Figure 9:** Time paths for different extraction costs within $S \rightarrow L \rightarrow R$




*Notes:* The grey lines in panel (b) correspond to the CFNE. In panel (a), the FBSE and the CFNE coincide, because $k^c = k^f = 16$.

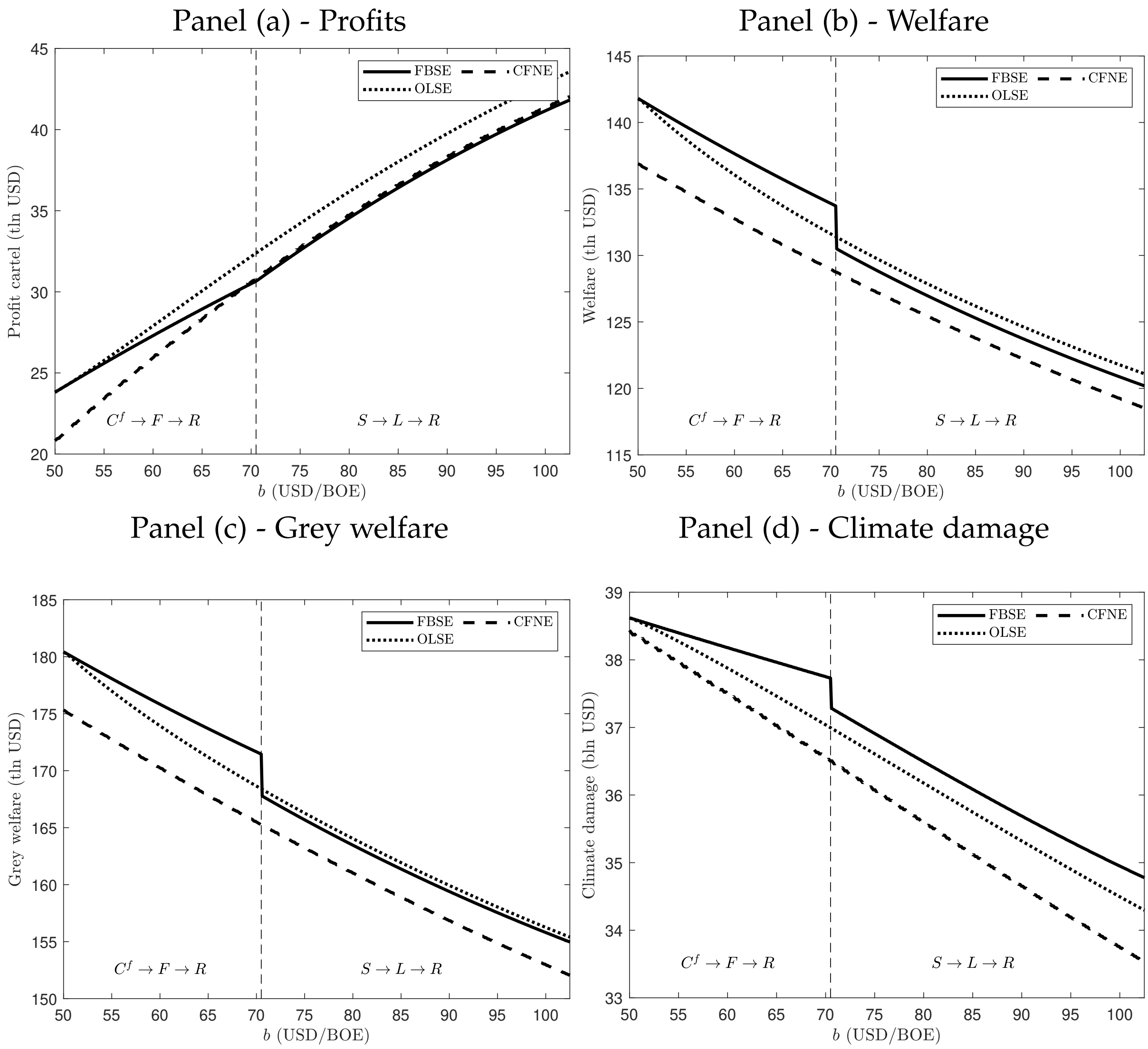
Figure 8 clarifies the consequences of the regime shift indicated by the dashed vertical line in Figure 7: panel (a) shows the extraction time paths for the case with $k^f = 46$, where the equilibrium sequence reads $S \rightarrow L \rightarrow R$, whereas panel (b) shows the outcome for $k^f = 47$, when $C^f \rightarrow F \rightarrow R$ applies. When moving from panel (a) to panel (b), extraction paths differ considerably, as an initial phase of simultaneous supply and a later phase of limit pricing appear in panel (a) but not in panel (b).

Furthermore, Figure 9 shows the extraction paths within the $S \rightarrow L \rightarrow R$ regime to the left of the dashed vertical line in Figure 7, for different values of the fringe's unit extraction cost. Whereas in the CFNE an increase in $k^f$ increases the initial price and delays depletion, in the FBSE the initial price remains unchanged, the duration of the simultaneous supply regime goes up and depletion occurs earlier.

## 5.2 Technical change in the backstop sector

In this subsection, we investigate the role of the backstop cost. We examine the effect of cost reductions, which could be driven by technical change. Instead of allowing for exogenously decreasing unit costs of the backstop technology over time (cf. Fischer

**Figure 10:** Cost-reducing technical change in the backstop sector




*Notes:* The figure shows how the backstop cost $b$ affects outcomes in the benchmark scenario. The vertical dashed line marks the border between the $C^f \to F \to R$ and $S \to L \to R$ regimes. Panel (a) reports cartel profit, panel (b) total welfare, panel (c) grey welfare (excluding climate damages), and panel (d) climate damages.

and Salant, 2017), we compare scenarios with different constant unit costs of the backstop technology. Figure 10 illustrates how the backstop cost $b$ affects outcomes in the benchmark scenario. For low values of $b$, the equilibrium sequence is $C^f \to F \to R$; for $b > 71$, it switches to $S \to L \to R$, as indicated by the vertical dashed lines.

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 appearance of the sequencing effect.

Panel (d) highlights implications for climate damage. 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 scarcity rents. Moreover, if $b$ falls below 71, the equilibrium switches to $C^f \to F \to R$ and climate damage jumps up as the weakening of the conservation effect dominates the elimination of the sequencing effect.

# 6 Conclusion

This paper has analyzed how leadership and commitment interact with cost and emission factor heterogeneity, climate policy and technical change in a dynamic cartel–fringe model featuring exhaustible resources, renewable energy, a backstop and climate damages. By comparing Nash–Cournot, open-loop von Stackelberg, and feedback von Stackelberg equilibria, we showed how market structure shapes extraction regimes, welfare, and emissions in ways that need not be monotonic or marginal and may be counterintuitive at first sight.

First, leadership substantially alters extraction behavior, but its welfare and climate implications depend critically on commitment. With commitment, the cartel can dictate the extraction order and eliminate the sequencing distortion that characterizes the Nash–Cournot equilibrium. Without commitment, however, the leader must follow time-consistent strategies, which sharply restricts its ability to manipulate the fringe. As a result, the feedback equilibrium can generate higher climate damages and lower cartel profits than both the Nash–Cournot and the open-loop von

Stackelberg equilibrium. In our benchmark scenario with a social cost of carbon equal to 250 USD/tC, market power without leadership reduces climate damages by 3.9 trillion (tln) USD, compared to the perfectly competitive equilibrium. With leadership, climate benefits of market power are reduced to 3.1 tln USD if the leader can commit to its announced supply path and to 2.6 tln USD if the leader cannot commit.

Second, welfare is governed by the interaction between the conservation effect and the sequencing effect, and these channels respond non-smoothly to policies and parameters. In the benchmark scenario, the sequencing distortion is the dominant source of welfare loss. Eliminating it through a regime switch from $S \to L \to R$ to $C^f \to F \to R$ produces large discrete welfare gains. For example, under the feedback von Stackelberg equilibrium, welfare jumps up with 3.7 trillion USD to 99.98 percent of the social optimum when a carbon tax is increased from 150 to 151 USD/tC. In general, the possibility of this regime switch implies that small changes in policies (but also in costs or reserve distributions) can trigger discontinuous changes in welfare and climate damages.

Third, climate policies interact strongly with market structure. In our benchmark calibration with a social cost of carbon of 250 USD/tC, the welfare-maximizing (second-best) carbon tax under feedback von Stackelberg leadership lies approximately 100 USD/tC below the Pigouvian level, yet delivers welfare above 99 percent of the social optimum. By contrast, further increasing the tax toward the Pigouvian benchmark reduces welfare because market power induces excessive conservation. Backstop subsidies can also eliminate sequencing distortions and raise welfare: a subsidy of around 32 USD/BOE, close to current EU renewable-support levels, removes the sequencing effect and maximizes welfare. However, such subsidies accelerate extraction and raise climate damages through a Green Paradox effect. Renewables subsidies operate differently: while they consistently reduce emissions, they generally lower welfare when market power is present by reinforcing the already excessive conservation effect, whereas under perfect competition the optimal subsidy is modest, at about 10 USD/BOE.

Fourth, technical change can generate sharp and counterintuitive responses. Cost reductions in fringe extraction or in the backstop technology can move the industry across equilibrium regimes, thereby changing the composition and timing of supply. These regime shifts alter the duration of simultaneous-supply phases and give rise to non-monotonic effects on welfare and climate damages. As a result, reductions in the fringe's marginal extraction cost can be welfare-reducing under both open-loop and feedback von Stackelberg equilibria, whereas reductions in the unit cost of the backstop may instead generate discrete upward jumps in welfare. Moreover, in the benchmark scenario, climate damages are non-monotonic in the fringe's marginal extraction cost. Starting from a relatively high-cost fringe, moderate cost declines increase climate damages by accelerating extraction. When cost reductions are sufficiently large to induce a regime switch, however, climate damages drop discontinuously, and further declines in the fringe's extraction cost reduce damages even more. These findings underscore that technological progress does not necessarily translate into welfare or climate improvements.

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 gradual endogenous technical change and learning in extraction and clean energy would enrich the analysis and help connect the strategic extraction problem more directly to the literature on directed and innovation-led energy transitions (cf. Lemoine, 2024). Second, modelling endogenous investment in exploration, drilling, and renewable capacity could capture more fully the interaction between market power and cumulative fossil-fuel use during the energy transition (cf. Van den Bijgaart and Rodriguez, 2023; Kellogg, 2024). Third, a more granular calibration using detailed micro-level data on extraction costs and emissions could refine welfare estimates and improve policy relevance, in the spirit of recent work on misallocation and carbon misallocation in global oil extraction (cf. De Cannière, 2025). Finally, it would be interesting to allow for more sophisticated strategic behavior by exploring multi-cartel settings or strategic interactions across fuels, building on recent work on dynamic climate-policy commitment problems in markets with competing fossil and renewable energy sources (cf. Harstad and Holtsmark, 2026).

# A Appendix

In this appendix, we formally define the three equilibrium concepts used in the main text. More details can be found in Elgersma et al. (2026). We define the residual demand function for the non-renewable resources as

$$D(p(t)) = \begin{cases} \frac{1}{\beta}(\alpha - p(t)), & \text{if } p(t) \leq b, \\ 0, & \text{if } p(t) > b. \end{cases}$$

## 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 $\left(p^{NC}(\cdot), q^{f,NC}(\cdot)\right)$ such that

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

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

$$\int_0^\infty [p^{NC}(t) - k^c]\left(D\left(p^{NC}(t)\right) - q^{f,NC}(t)\right) e^{-rt} dt$$
$$\geq \int_0^\infty [p(t) - k^c]\left(D(p(t)) - q^{f,NC}(t)\right) e^{-rt} dt \text{ for all } p \in \Sigma_C\left(S_0^c, q^{f,NC}\right),$$

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

## Von Stackelberg

A von Stackelberg leader effectively both determines the price and the extraction of the fringe. A von Stackelberg equilibrium then is a couple of paths $\left(p^S, q^{f,S}\right)$ such that

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

Moreover, in an OLSE it must hold that

$$\begin{aligned}
&\int_0^\infty \left[p^S(t) - k^c\right]\left(D\left(p^S(t)\right) - q^{f,S}(t)\right)e^{-rt}dt \\
&\geq \int_0^\infty \left[p(t) - k^c\right]\left(D(p(t)) - q^{f,S}(t)\right)e^{-rt}dt \text{ for all } (p, q^{f,S}) \in \Sigma_C\left(S_0^c, q^{f,S}\right).
\end{aligned} \tag{A.1}$$

In a FBSE, instead of (A.1) it is required that

$$\begin{aligned}
&\int_z^\infty \left[p^S(t) - k^c\right]\left(D\left(p^S(t)\right) - q^{f,S}(t)\right)e^{-rt}dt \\
&\geq \int_z^\infty \left[p(t) - k^c\right]\left(D(p(t)) - q^{f,S}(t)\right)e^{-rt}dt \text{ for all } p \in \Sigma_{C,z}\left(S_z^c, q^{f,S}\right)
\end{aligned}$$

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

$$\Sigma_{C,z}\big(S_z^c, q^{f,S}\big) = \Big\{p(\cdot) : \int_z^\infty \big(D\big(p(\cdot)\big) - q^{f,S}(\cdot)\big)\,dt = S_z^c\Big\}.$$

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

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