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Do strong oligopolies reverse Green Paradox effects?☆

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ABSTRACT

In a competitive market renewable energy subsidies or postponement of carbon pricing tend to boost emissions and global warming in the short run. This so-called Green Paradox effect may be reversed if fossil-fuel firms operate under an oligopoly and the number of members is low enough. A reversal of the Green Paradox always occurs under a fossil fuel monopoly. If the extraction costs of fossil fuel depend on the aggregate remaining stock of reserves, Green Paradox effects vanish if the number of oligopolists becomes infinitely large. For an intermediate number of members, a Green Paradox occurs. The strength of the Green Paradox effect depends non-monotonically on the number of oligopolists. We also show that a Green Paradox is more likely for higher slopes of the demand curve, higher sensitivities of unit extraction costs with respect to remaining reserves, and lower interest rates.

1. Introduction

Second-best climate policies often have unintended and undesirable consequences. This does not only apply to economic distortions resulting from the unavailability of lump-sum finance of public spending and the need to resort to distorting taxes on labour and income, but also to political distortions. The most prominent ones arise from politicians tending to postpone costly or unpopular measures such as pricing carbon and to bring forward popular measures such as subsidies for renewable energies. As has been argued for the first time by Sinn (2008) and taken up by a voluminous literature surveyed by Pittel et al. (2014) and van der Ploeg and Withagen (2015), delaying carbon pricing or subsidizing renewable energy encourages the market to deplete reserves of oil and gas more rapidly. The resulting acceleration of global warming has been dubbed the *Green Paradox* effect. This effect is particularly large if the price elasticity of supply of fossil-fuel reserves is small. A major concern over the use of climate policies such as an announced carbon tax or a subsidy for renewable energy in a world where oil reserves are geographically concentrated is thus that it may depreciate the value of oil reserves and push countries owning the reserves to accelerate their extraction, thereby having the unintended effect of acceleration of global warming.

This issue is even more severe if one takes into account that unit extraction costs typically increase with cumulative extraction and that environmental policy affects not only the path of the extraction of reserves but also the economically viable stock of

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reserves. An increase in a subsidy to renewable energy means more oil reserves must be left untouched which may exacerbate the race to 'burn the last drops of oil'.

A recent paper by van der Ploeg (2020) suggests that these counter-intuitive Green Paradox effects also hold in a market where resource owners are not price takers but act as oligopolists. This contrasts with the monopoly case. Indeed, as has been shown by Gilbert and Goldman (1978), Hoel (1983) and Salant (1979) and more recently by van der Meijden and Withagen (2019), Green Paradox effects are reversed if the assumption of a competitive market for fossil fuel is replaced by a purely monopolistic market for fossil fuel so that market participants act as a cohesive cartel. To be precise, under a monopoly a subsidy to renewable energy decreases short-run extraction if the initial price of fossil fuel is strictly lower than the unit cost of renewables. This is the so-called *Green Orthodox* effect (cf. Michielsen, 2014).

In the present paper we focus on the open-loop Nash equilibrium concept. Furthermore, we distinguish two types of specifications of the extraction cost function: one where per unit extraction cost depends on the total aggregate available stock of fossil-fuel reserves and one where each agent owns its own well, with extraction cost depending on the remaining stock of fossil fuel in that particular well.

The aims of the present paper are twofold. First, we show that van der Ploeg (2020) in deriving the open-loop Nash equilibrium does not allow for the correct transition to the ensuing limit-pricing phase. We describe the correct equilibrium for the case of extraction cost depending on the entire remaining stock of reserves. We show that a Green Orthodox can also occur in an oligopolistic setting with a small number of fossil fuel firms.[1] Second, we discuss the comparative statics of whether Green Paradox or Green Orthodox effects occur with respect to the slope of the energy demand curve, the sensitivity of unit extraction costs with respect to remaining reserves, and the interest rate. We also compare results with the case where unit extraction costs depend on individual rather than aggregate remaining reserves.

The model is presented in Section 2. In that section we also define the two equilibrium concepts employed in the sequel. For the interested reader we show in Appendix D the well-known result that in pure monopoly a Green Orthodox occurs, contrary to Result 3 in van der Ploeg (2020, p. 10). Furthermore, we demonstrate in this appendix that no Green Paradox nor a Green Orthodox occurs if the number of oligopolists becomes infinitely large. However, if extraction costs depend on individual stock of remaining reserves, a Green Paradox materializes if the number of oligopolists goes to infinity. The intuition behind this result is that with individual extraction cost depending on the remaining *aggregate* stock the impact of an individual resource owner on future extraction costs vanishes.

In Section 3, we focus on linear demand and linear marginal extraction cost following van der Ploeg (2020) and derive necessary conditions for an open-loop Nash equilibrium. In Section 4 we perform a quantitative assessment of open-loop Nash equilibrium strategies. We show that, with an oligopolistic market for fossil fuel, the Green Paradox effects of a subsidy on renewables or delayed carbon pricing are reversed if the oligopoly is strong enough. More precisely, we show that there is a critical value for which a subsidy on renewables or delayed carbon pricing leads to Green Paradox effects if the number of members of the fossil-fuel oligopoly is larger than the critical value but there is reversal of Green Paradox effects if the number of members of the oligopoly is below this critical value. We thus show that if resource owners are neither price takers nor able to form a cohesive cartel, the short-run effect on carbon emissions of a subsidy for clean energy depends on the degree of competition between resource owners. Furthermore, we show that, with extraction costs depending on aggregate reserves, the effect of a subsidy for renewables is non-monotonic in the number of members of the oligopoly and that this effect vanishes if the number of members becomes infinitely large. We also show that a Green Paradox is more likely for higher slopes of the demand curve, higher sensitivities of unit extraction costs with respect to remaining reserves, and lower interest rates.

In Section 5 we numerically analyse the case where extraction cost depends on individual rather than total reserves remaining. In this setting, the effect of a renewables subsidy on initial extraction is monotonically increasing in the number of oligopoly members. It is negative for the monopoly case and converges to a positive number if the number of members becomes infinitely large. Section 6 concludes.

Our results highlight the need to adapt climate policies to the specific structure of the market for fossil fuel reserves.

2. The model and equilibrium concepts

There are N identical oligopolists,[2] supplying fossil fuel F_i from resource stocks S_i $(i = 1, 2, \ldots, N)$. We follow van der Ploeg (2020) who focuses on the case in which each oligopolist's unit extraction cost depends on the total stock so that the total extraction cost for oligopolist i is $C(S)F_i$ with $S = \sum_{j=1}^{N} S_j$ and $C'(S) < 0$ and $C(S) \geq 0$. However, we will also present results for the case in which extraction costs of each oligopolist are dependent on its own individual remaining stock, as in Benchekroun et al. (2022).

Supply of renewables is denoted by R. The inverse demand function is $p(F + R)$, with aggregate fossil fuel use given by $F = \sum_{j=1}^{N} F_j$. The unit cost of renewables is b. Without loss of generality, we consider the optimization problem of oligopolist 1. For

[1] There may also be issues with the derivation of the feedback Nash equilibrium in van der Ploeg (2020). The conjectured value function is not correct, at least for the case of a monopoly, where open-loop and the feedback Nash equilibrium naturally coincide. We also discuss the possible consequences of this observation.

[2] The assumption of identical oligopolists may not be innocuous, in particular not for the case of a feedback Nash equilibrium. We still make this assumption, in order to stay close to the model in van der Ploeg (2020).

a variable x we define $x_{-1} = \sum_{j \neq 1} x_j$ with $j = 1, \ldots, N$. The problem for oligopolist 1 is thus to maximize the present discounted value of its profits,

$$\max \int_0^{\infty} e^{-rt} \left[p(F_1 + F_{-1})F_1 - C(S_1 + S_{-1})F_1 \right] dt,$$

subject to its resource depletion equation,

$$\dot{S}_1 = -F_1 \text{ with } S_1 \geq 0,\ F_1 \geq 0,$$

with a given initial stock, S_{10}, and subject to the condition for making it worthwhile to use fossil fuel rather than renewable energy,

$$b \geq p(F + R).$$

We consider an equilibrium of the following form (cf. van der Ploeg, 2020). There is an initial interval of time ending at $T_1 > 0$ with $p < b$ and $R = 0$, then follows an interval of time until $T_2 > T_1$ with limit pricing at b, where the renewables are kept from the market, whereas from T_2 onward only renewables are supplied to the market. It can be shown that for a large enough price elasticity of energy demand and a sufficiently large initial stock of reserves this is indeed the equilibrium constellation. Moreover, empirical evidence suggests that the price elasticity of energy demand and total reserves are such that this sequence is an equilibrium sequence. See also Section 4.

Two alternative equilibrium concepts are typically considered in differential games: feedback and open-loop Nash. In the feedback Nash equilibrium, at each instant of time all players observe the then prevailing resource stocks and condition their actions on these stocks. The feedback Nash equilibrium can be derived by making use of the Hamilton–Jacobi–Bellman equation, which in the case at hand reads

$$rV_i(S_1, S_2, \ldots, S_N) = \max_{F_i} \left\{ [p(F) - C(S)]F_i - \sum_{j=1}^{N} \frac{\partial V_i(S_1, S_2, \ldots, S_N)}{\partial S_j} F_j \right\}.$$

Here V_i is the value function of player i, i.e., total discounted profits in the equilibrium when the stocks are $S_1, S_2, \ldots, S_N$.

The advantage of considering the feedback Nash equilibrium concept is that it ensures time consistency and subgame-perfectness of the equilibrium (cf. van der Ploeg and de Zeeuw, 1992; Dockner et al., 2000; Basar and Olsder, 1998). However, the feedback equilibrium is quite demanding in terms of information requirements, as all players need to know all stocks at any instant of time. In contrast, in the open-loop Nash equilibrium players condition their policies on the *initial* reserves only: at the beginning of the game each oligopolist chooses an extraction path that satisfies its resource constraint, taking the extraction paths of its competitors over the entire horizon as given. This implies that the information requirement is much more modest. For this reason, in the remainder we will mainly focus on the open-loop Nash equilibrium.

Clearly, in the particular case of a monopoly, the open-loop and feedback Nash equilibria are identical. Moreover, if the number of oligopolists goes to infinity, while keeping the initial aggregate stock fixed, the open-loop Nash equilibrium outcome converges to the perfectly competitive equilibrium.[3]

It has already been shown in the literature that under monopoly a Green Orthodox occurs, whereas – if extraction cost depend on individual reserves – under perfect competition there is a Green Paradox (e.g. Gerlagh, 2011). In our model, where cost depends on the *aggregate* stock, there is no Green Paradox nor a Green Orthodox if the number of oligopolists becomes infinitely large. Intuitively, the effect of an individual oligopolist's extraction on the aggregate stock, and hence on future extraction costs, is negligible in this case. This implies that the scarcity rent will be infinitely small, which rules out an effect of future demand conditions on current extraction. For completeness and for the interested reader we offer proofs of these results in Appendix D.

3. Linear demand and cost functions

From here on we focus on the case of linear demand and cost functions. This suffices to make our point and to calculate the critical number of oligopolists. But most of the results still hold for more general functional forms.[4] Demand is given by $D(p) = \delta_0 - \delta_1 p$, so that the inverse demand function is

$$p = \frac{\delta_0}{\delta_1} - \frac{\sum_{j=1}^{N} F_j + R}{\delta_1}.$$

Total extraction cost of oligopolist i is

$$C(S)F_i = (\gamma_0 - \gamma_1 S)F_i.$$

[3] It is not necessarily the case that as the number of oligopolists goes to infinity in a feedback Nash equilibrium, the outcome converges to the perfect competition outcome. For example, Benchekroun and Withagen (2012) show that this is not the case in a nonrenewable resource cartel-fringe game. However, in their model there exists a fringe with a large stock of reserves, and the fringe takes into account the effects of its stock on the extraction of all oligopolists together. In our analysis, we do not have this player with a large stock of reserves as N goes to infinity. It would be interesting to calculate the correct feedback Nash equilibrium. However, that involves unresolved issues and is beyond the scope of the present paper and is therefore left for future research.

[4] However, with strictly convex extraction cost functions one can have simultaneous supply of fossil fuel and renewables during limit pricing.

We assume $b < \gamma_0$, so that some fossil fuel will be left unexploited. Indeed, with $b < \gamma_0$, full exhaustion would imply supply that makes a loss. Moreover, we assume $S_0 \leq \frac{\gamma_0}{\gamma_1}$ to avoid negative extraction costs. We also adopt the standard convention that when the price is equal to the unit cost of the backstop, supply from the backstop covers the residual demand left after the oligopolists have left the market.

Proposition 1. *There exists $S_m > 0$ such that for $S_0 \geq S_m$, in the open-loop Nash equilibrium, the aggregate extraction path of oil, $F(t)$, is given by*

$$F(t) = \begin{cases} K_1 e^{k_1 t} + K_2 e^{k_2 t} & \text{if } t \in [0, T_1] \\ \delta_0 - \delta_1 b & \text{if } t \in [T_1, T_2] \\ 0 & \text{if } t \in [T_2, \infty) \end{cases}. \quad (1)$$

where (K_1, K_2, T_1, T_2) with $T_2 > T_1 \geq 0$ follows from the following four conditions:

$$K_1 e^{k_1 T_1} + K_2 e^{k_2 T_1} = \delta_0 - \delta_1 b, \quad (2)$$

$$\frac{1}{k_1} K_1 (e^{k_1 T_1} - 1) + \frac{1}{k_2} K_2 (e^{k_2 T_1} - 1) + (\delta_0 - \delta_1 b)(T_2 - T_1) = S_0 - \frac{\gamma_0 - b}{\gamma_1}, \quad (3)$$

$$\frac{\delta_0}{\delta_1} - \frac{F(0)}{\delta_1}\left(\frac{N+1}{N}\right) - (\gamma_0 - \gamma_1 S_0) = \frac{\gamma_1}{rN}(\delta_0 - \delta_1 b) e^{-rT_1}\left(1 - e^{-r(T_2 - T_1)}\right)$$
$$+ \frac{\gamma_1}{N}\left[\frac{1}{k_1 - r} K_1 \left(e^{(k_1 - r)T_1} - 1\right) + \frac{1}{k_2 - r} K_2 \left(e^{(k_2 - r)T_1} - 1\right)\right], \quad (4)$$

$$(T_2 - T_1) - \frac{1}{Nr}(1 - e^{rT_1 - rT_2}) = \frac{1}{\gamma_1 \delta_1 N}. \quad (5)$$

Proof. See Appendix A. ■

The conditions in Proposition 1 are obtained from the optimality conditions of each individual extraction path along with the resource constraints. More specifically, with our functional forms we find for $p < b$ that the necessary conditions for optimality of extraction read

$$\left(\frac{\delta_0}{\delta_1} - \frac{F}{\delta_1}\right) - \frac{F}{N\delta_1} - (\gamma_0 - \gamma_1 S) = e^{rt}\lambda_i, \quad (6)$$

$$-\dot{\lambda}_i = e^{-rt}\gamma_1 \frac{F}{N}. \quad (7)$$

Eq. (6) states that marginal profit (i.e., marginal revenue minus marginal extraction cost) for each oligopolist should equal the shadow value of reserves, denoted by λ_i. Eq. (7) states that the rate of decline of the shadow value of reserves equals the present discounted value of the increase in unit extraction cost resulting from depletion from an additional unit of reserves. These conditions give rise to a second-order linear differential equation in the aggregate extraction rate (see Appendix A). The solution can be written as Eq. (1) with $t \in [0, T_1]$. Here K_1 and K_2 are the constants of integration that still need to be determined and the exponents k_1 and k_2 are the characteristic roots of the differential equation for the extraction rate with $k_1 + k_2 = r$ (see Appendix A). These roots only depend on the parameters of the functional forms employed. At the transition to limit pricing, which takes place at T_1, there should be no jump in the energy price and energy supply must be continuous, which yields Eq. (2).

The first two terms on the left-hand side of Eq. (3) represent total extraction in the first period, using (1) with $t \in [0, T_1]$. The third term is aggregate extraction in the second period from (1) with $t \in [T_1, T_2]$. Aggregate extraction corresponding to all three terms on the left-hand side must equal the initial stock of reserves, S_0, minus the stock that remains unexploited, which corresponds to the right-hand side of Eq. (3). The unexploited stock of reserves is found from setting instantaneous profits equal to zero at the switch to the carbon-free phase at time $t = T_2$, i.e., $b - (\gamma_0 - \gamma_1 S(T_2)) = 0$.

The initial shadow value of reserves, $\lambda_i(0)$, follows from the necessary condition in the first interval that the initial shadow value of reserves should equal marginal profits at time zero, so that

$$\left(\frac{\delta_0}{\delta_1} - \frac{F(0)}{\delta_1}\right) - \frac{F(0)}{N\delta_1} - (\gamma_0 - \gamma_1 S(0)) = \lambda_i(0) = \lambda(0).$$

This explains Eq. (4). Finally, note that $T_2 - T_1$ is the length of the limit-pricing phase. Eq. (5) then follows from a further inspection and interpretation of the shadow price of reserves at T_1, the instant of time where the transition to limit pricing takes place. The necessary condition just before T_2 is that marginal profits at the transition to limit pricing should equal the shadow value of reserves at that point of time, so that

$$\left(\frac{\delta_0}{\delta_1} - \frac{F(T_1)}{\delta_1}\right) - \frac{F(T_1)}{N\delta_1} - (\gamma_0 - \gamma_1 S(T_1)) = e^{rT_1}\lambda(T_1).$$

Since $\lambda(T_2) = 0$ follows from the transversality condition with $S(T_2) > 0$, we also have that

$$\lambda_i(T_1) = \int_{T_1}^{T_2} e^{-rt}\gamma_1 \frac{F(t)}{N} dt = \frac{\gamma_1(\delta_0 - \delta_1 b)}{rN}\left(e^{-rT_1} - e^{-rT_2}\right).$$

Table 1
Calibration.

Parameter	Description	Value	Unit
δ_0	Vertical intercept energy demand function	10	GtC
δ_1	Slope energy demand function	3/340	tC/US$
γ_0	Vertical intercept unit extraction cost function	762.76	US$
γ_1	Slope unit extraction cost function	1.1417	US$/tC
r	Interest rate	0.05	Perunage
b	Marginal cost of renewables	610.21	US$
S_0	Initial oil stock (in 2010)	595	GtC

So, marginal profits at the transition to limit pricing, i.e., at $t = T_1$, should equal the cost savings during the ensuing limit-pricing phase from $t = T_1$ to $t = T_2$ of an additional amount of reserves at the beginning of the limit-pricing phase T_1.

In van der Ploeg (2020) the constant of integration K_1 corresponding with the positive eigenvalue k_1 is set equal to zero. The path obtained results in finite extraction even when time tends to infinity and yields a Green Paradox even for $N = 1$. However, such a path does not satisfy the transition condition (3) of Proposition 1. Due to the final phase of limit pricing, it is not appropriate to impose that in the pre-limit-pricing phase, the extraction path tends to zero when time tends to infinity, since the pre-limit-pricing phase has a finite duration.

4. Quantitative assessment

Here we examine with the aid of numerical examples the impact of a cut in the cost of renewable energy b on initial extraction and emissions $F(0)$. We also perform a sensitivity analysis on crucial parameters such as the number of oligopolists (N), the slope of the demand curve (δ_1), the sensitivity of unit extraction costs with respect to remaining reserves (γ_1) and the interest rate (r).

4.1. Parameter values

Table 1 shows the parameter values that we have chosen. For the parameters of the extraction cost function we have estimated a linear regression line through the data on production costs and ultimately recoverable oil resources from McGlade and Ekins (2015). This yields $\gamma_0 = 762.76$ US$ and $\gamma_1 = 1.1417$ US$/tC.[5] The initial stock of reserves corresponds to the ultimately recoverable oil resources reported in McGlade and Ekins (2015). Details about the calibration of the parameters of the extraction cost function can be found in Appendix B.

We have chosen the demand function parameters such that the demand function runs through the point $(F, p) = (4, 680)$, which corresponds to a demand of 34 billion barrels at a price of 80 US$ per barrel, with a price elasticity of energy demand in that point equal to 1.5. This price elasticity of demand allows for the existence of a pre-limit-pricing phase for any number of oligopolists, if the initial stock of reserves is large enough.[6]

The annual interest rate has been set to 5 percent in the benchmark scenario. Finally, we have set the marginal cost of renewables equal to 80 percent of the vertical intercept of the extraction function. This implies that under *laissez-faire* 134 GtC, amounting to 22.5 percent of the ultimately recoverable oil reserves, remains unexploited.

4.2. Critical number of oligopolists for a Green Paradox

Fig. 1 shows frontiers that depict parameter combinations for which the change in initial extraction upon a decrease in the cost of renewable energy equals zero. Hence, along these frontiers there is neither a Green Paradox nor a Green Orthodox; the initial rate of fossil fuel extraction is unaffected. Below (above) each frontier a Green Orthodox (Paradox) occurs. The solid frontiers correspond to the benchmark case of an annual interest rate of 5 percent, whereas the dotted frontiers correspond to the case with a higher annual interest rate of 7.5 percent. Panel (a) has the slope of the extraction cost function on the vertical axis, and panel (b) the slope of the demand function. In both panels, the number of oligopolists is on the horizontal axis and the dashed–dotted vertical line indicates the benchmark values of the slope parameters.

In the benchmark calibration, the number of oligopolists for which there is neither a Green Orthodox nor a Green Paradox equals $N = 2.8$. Restricting attention to integers, this implies that a monopoly and duopoly would result in decreases in initial extraction and, hence, a Green Orthodox effect if renewable energy becomes cheaper. But if the number of oligopolists exceeds two, initial extraction goes up if the cost of renewables falls and a Green Paradox effect occurs.

Each frontier in Fig. 1 slopes monotonically downwards. This implies that for steeper demand and extraction cost functions, the amount of oligopolists needed to obtain a Green Paradox instead of a Green Orthodox is smaller. The reason is that steeper demand and extraction cost functions imply a shorter duration of the limit-pricing phase, so that the outcome is closer to the

[5] We have converted the amounts in barrels of oil to GtC by assuming that each barrel of oil contains 117.19 kg carbon (cf. EPA, 2020).

[6] If the price elasticity of energy demand at $p = b$ would be smaller than unity, a monopolist would choose a limit-pricing strategy throughout, irrespective of the initial stock of reserves. See also Andrade de Sá and Daubanes (2016).

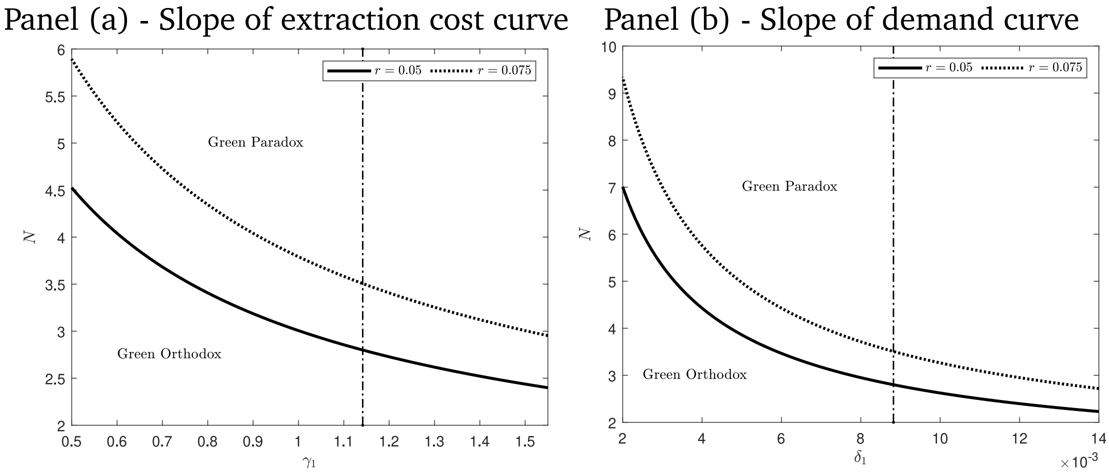

Fig. 1. Green Paradox–Orthodox Frontiers.
Notes: The solid (dotted) frontiers show parameter combinations for which the change in initial extraction upon a decrease in the costs of renewable energy equals zero, for $r = 0.05$ ($r = 0.075$). Above each frontier, a Green Paradox occurs, i.e., initial extraction goes up. Below each frontier, a Green Orthodox occurs, i.e., initial extraction goes down. The benchmark values for the slope of the extraction cost function, γ_1, (panel (a)) and the slope of the demand function, δ_1, (panel (b)) are indicated by the dashed–dotted vertical lines.

perfectly competitive equilibrium. Furthermore, the dotted frontiers (corresponding to $r = 0.075$) are located above the solid ones (corresponding to $r = 0.05$), so that a higher interest rate requires a larger minimum number of oligopolists to obtain a Green Paradox.

Furthermore, it can be shown that if there is a Green Orthodox effect, its strength is decreasing in the slopes of the energy demand curve (δ_1) and the extraction cost curve (γ_1). If there is a Green Paradox effect, its strength is also decreasing in these slopes, but the effect is more modest than the case of a Green Paradox. Finally, a Green Orthodox is more likely if the slopes of the demand and extraction cost curves are small. Details and figures can be found in Appendix C.

Summing up, Green Paradox effects are more likely for a larger number of oligopolists, higher slopes of the energy demand curve, higher sensitivities of unit extraction costs with respect to remaining fossil-fuel reserves, and lower interest rates.

5. Cost depending on individual stocks

The assumption that extraction cost depends on the aggregate stock of reserves follows van der Ploeg (2020). Since in the real world many fossil fuel wells are spatially dispersed, the alternative assumption with extraction cost depending on the individual remaining stock of fossil fuel is worth considering.[7] To ensure that the aggregate extraction cost function is independent of the number of oligopolists, we consider the specification $G(S_i) = \gamma_0 - N\gamma_1 S_i$. In a symmetric equilibrium with $S_i = \frac{S}{N}$, the aggregate extraction cost function then coincides with the individual extraction cost function $C(S)$ of our benchmark model: $\gamma_0 - N\gamma_1 \frac{S}{N} = \gamma_0 - \gamma_1 S = C(S)$. Alternative assumptions are possible, but this one works well for our purpose.

For the sake of brevity, we concentrate on the open-loop Nash equilibrium and mainly perform a numerical exercise. For an analytical treatment of the cases where $N = 1$ and $N = \infty$, the reader is referred to Appendix D. Here, the main aim is to provide an impression of the differences that occur in the two approaches to modelling extraction costs.

Fig. 2 shows the strength of the Green Orthodox or Paradox effect for a range of values for the number of oligopolists. It has the elasticity of initial fossil fuel use with respect to the backstop price on the vertical axis. A positive (negative) elasticity corresponds to a Green Orthodox (Paradox). The black curve shows the benchmark case in which unit extraction costs depend on aggregate reserves, whereas the grey curve depicts the case where unit extraction costs depend on individual reserves.

The grey curve is monotonically downward sloping. This result is well-known in the literature. With N small, there is a Green Orthodox. Moreover, the scarcity rent does not vanish if the number of oligopolists becomes large (see Appendix D.3). The point is that for N going to infinity the limit pricing phase collapses, so that we are in a world with perfect competition where the Green Paradox holds. The black curve – corresponding to the case in which unit extraction costs depend on aggregate reserves – shows that in our calibrated model a Green Orthodox occurs for a duopoly. For a larger number of oligopolists, a Green Paradox is obtained. A remarkable feature is the non-monotonicity of the black curve. This is due to the assumption that extraction costs of an individual oligopolist depend on the aggregate remaining stock. Intuitively, the scarcity rent converges to zero if the number of oligopolists goes to infinity because individual decisions then have a negligible effect on future extraction costs if these depend on the aggregate instead of on individual reserves (see Appendix D.2). The elasticities that we find are rather modest, varying from −0.0014 percent to 0.0049 percent for the benchmark case and from −0.0059 percent to 0.018 if extraction costs depend on individual reserves.

[7] van der Ploeg (2020) briefly discusses this case in his Appendix 5.

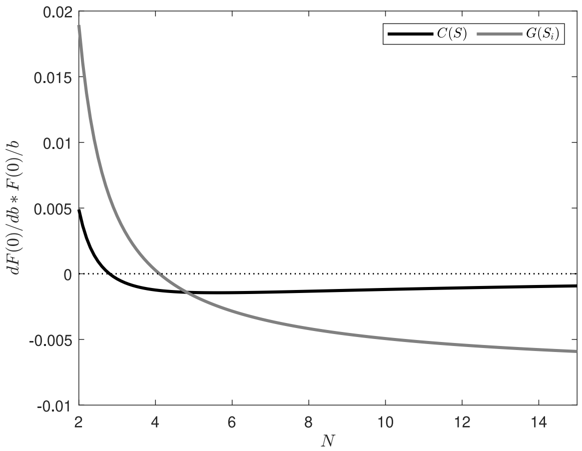

Fig. 2. Strength of Green Paradox–Orthodox effects.
Notes: The figure shows the elasticity of initial fossil fuel use with respect to the backstop price for various values of the number of oligopolists. If this elasticity is positive, there is a Green Orthodox effect. If it is negative, there is a Green Paradox effect. The black curve labelled $C(S)$ corresponds to the benchmark model in which unit extraction costs depend on aggregate reserves. The grey curve labelled $G(S_i)$ corresponds to the case where unit extraction costs of each oligopolist depend on its own reserves.

6. Conclusion

We have shown that the impact of a subsidy for renewable energy on fossil-fuel extraction and emissions crucially depends on the market structure. Given the popular resistance to carbon pricing (witness the Yellow Vest Protests in France), the use of a politically more feasible subsidy to renewable energy can achieve an immediate reduction in emissions of carbon *only* if the oligopolistic fossil fuel industry is ‘strong enough’. We have a correct treatment of the problem examined in van der Ploeg (2020), which allows us to reconcile the Green Paradox analysis in that model in the case of a monopoly with existing results in the literature (e.g. van der Meijden and Withagen, 2019). We have shown that Green Paradox effects are more likely than Green Orthodox effects for weaker oligopolies, higher slopes of the energy demand curve, higher sensitivities of unit extraction costs with respect to remaining fossil-fuel reserves, and lower interest rates. Furthermore, we have demonstrated for the case in which extraction costs depend on aggregate reserves that no Green Paradox nor a Green Orthodox occurs if the number of oligopoly members becomes infinitely large.

We have limited ourselves to the Green Paradox and the Green Orthodox, in what is called the weak version, namely considering the effect of policies to reduce the cost of renewables on initial extraction. The dynamic welfare effect of such policies are clearly important as well. Examining these effects would require substantially extending the model to include the societal benefits of the reduction of emissions over the entire horizon. Moreover, it would be interesting to determine the feedback Nash equilibrium and to examine how Green Paradox effects differ from those under the open-loop Nash equilibrium. This is left for future work.

Declaration of competing interest

The authors declare that they have no (financial) conflicts of interest.

Data availability

Data will be made available on request.

Acknowledgment

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Appendix A. Proof of Proposition 1

The necessary conditions along the first interval $[0, T_1]$ read

$$\left[\left(\frac{\delta_0}{\delta_1} - \frac{\sum_{j=1}^{N} F_j}{\delta_1}\right) - \frac{F_i}{\delta_1} - \left(\gamma_0 - \gamma_1 \sum_{j=1}^{N} S_j\right)\right] = e^{rt}\lambda_i, \tag{A.1}$$

$$-\dot{\lambda}_i = e^{-rt}\gamma_1 F_i. \tag{A.2}$$

These necessary conditions give rise to a second-order differential equation:

$$\ddot{F}\frac{1}{\delta_1}\left(\frac{N+1}{N}\right) - r\dot{F}\frac{1}{\delta_1}\left(\frac{N+1}{N}\right) - r\gamma_1 F + \gamma_1 \dot{F}\left(\frac{N-1}{N}\right) = 0.$$

The general solution of the second order differential equation reads

$$F(t) = K_1 e^{k_1 t} + K_2 e^{k_2 t},$$

with

$$k_1 = \frac{1}{2}\left(r - \gamma_1\delta_1\frac{N-1}{N+1} + \sqrt{\left(r - \gamma_1\delta_1\frac{N-1}{N+1}\right)^2 + 4r\gamma_1\delta_1\frac{N}{N+1}}\right),$$

$$k_2 = \frac{1}{2}\left(r - \gamma_1\delta_1\frac{N-1}{N+1} - \sqrt{\left(r - \gamma_1\delta_1\frac{N-1}{N+1}\right)^2 + 4r\gamma_1\delta_1\frac{N}{N+1}}\right).$$

In addition to the constants of integration K_1 and K_2 we need to determine the transition times T_1 and T_2. This can be done in the following four steps.

(i) Continuity at T_1. In the limit-pricing phase we have $F = \delta_0 - \delta_1 b$. Continuity of supply at T_1 then gives condition (2).

(ii) Resource constraint. The amount of fossil fuel left unexploited at T_2 equals $S(T_2) = \frac{\gamma_0 - b}{\gamma_1}$. This follows from the fact that at T_2 profits for the oligopolists should be zero. An alternative argument is that at T_2 the Hamiltonian vanishes. Hence,

$$\int_0^{T_1} F(t)dt + \int_{T_1}^{T_2} F(t)dt = S_0 - S(T_2) = S_0 - \frac{\gamma_0 - b}{\gamma_1},$$

with

$$F(t) = K_1 e^{k_1 t} + K_2 e^{k_2 t},\ 0 \le t < T_1$$

and

$$F(t) = \delta_0 - \delta_1 b,\ T_1 \le t \le T_2.$$

This gives condition (3).

(iii) Initial extraction. It follows from the differential equation for λ_i that

$$\lambda_i(T_1) - \lambda_i(0) = -\int_0^{T_1} e^{-rt}\gamma_1\frac{F(t)}{N}dt,$$

$$\lambda_i(T_2) - \lambda_i(T_1) = -\int_{T_1}^{T_2} e^{-rt}\gamma_1\frac{F(t)}{N}dt.$$

Since $S_i(T_2) > 0$ by assumption we have $\lambda_i(T_2) = 0$. Therefore we can write

$$\lambda_i(0) = \frac{\gamma_1}{rN}(\delta_0 - \delta_1 b)e^{-rT_1}\left(1 - e^{-r(T_2 - T_1)}\right) + \frac{\gamma_1}{N}\left[\frac{1}{k_1 - r}K_1\left(e^{(k_1 - r)T_1} - 1\right) + \frac{1}{k_2 - r}K_2\left(e^{(k_2 - r)T_1} - 1\right)\right]. \quad \text{(A.3)}$$

Evaluating (6) at $t = 0$ yields

$$\lambda_i(0) = \frac{\delta_0}{\delta_1} - \frac{F}{\delta_1}\left(\frac{N+1}{N}\right) - (\gamma_0 - \gamma_1 S(0)). \quad \text{(A.4)}$$

By combining the latter two expressions, we find condition (4).

(iv) The length of the limit-pricing phase. We have

$$\lambda_i(T_1) = \int_{T_1}^{T_2} e^{-rt}\gamma_1\frac{F(t)}{N}dt = \frac{\gamma_1(\delta_0 - \delta_1 b)}{rN}\left(e^{-rT_1} - e^{-rT_2}\right).$$

Also $S_i(T_1) = (T_2 - T_1)F_i + \frac{\gamma_0 - b}{N\gamma_1}$. Consider the necessary condition at instant of time T_1^-:

$$\left[\frac{\delta_0}{\delta_1} - \frac{F(T_1)}{\delta_1} - \frac{F(T_1)/N}{\delta_1} - \left(\gamma_0 - \gamma_1 S(T_1)\right)\right] = e^{rT_1}\lambda_i(T_1).$$

With $F(T_1) = \delta_0 - \delta_1 b$, $S(T_1) = (T_2 - T_1)F + \frac{\gamma_0 - b}{\gamma_1}$ and $e^{rT_1}\lambda_i(T_1) = \frac{\gamma_1(\delta_0 - \delta_1 b)}{rN}(1 - e^{rT_1 - rT_2})$ we find condition (5), which is equal to equation (11) in van der Ploeg (2020). From this condition it can be noted that $T_2 - T_1$ vanishes as N goes to infinity.

So we have 4 equations, (2)–(5), from which in principle the 4 unknowns K_1, K_2, T_1 and T_2, and thereby the equilibrium, can be solved.

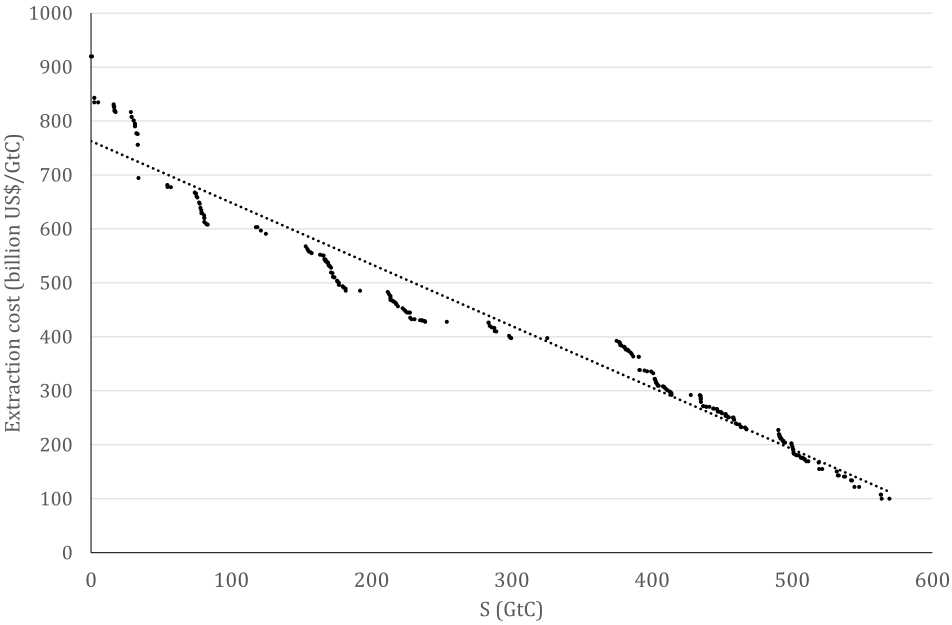

Fig. 3. Extraction cost data.
Notes: Reservoirs are ordered from high to low extraction costs. Each reservoir in the data is shown by a dot in the figure. The horizontal coordinate of each dot corresponds to the amount of oil in a particular reservoir (in GtC) including all reservoirs with higher extraction costs. The vertical coordinate gives the extraction cost (in billion US$ per GtC). The figure also shows the (dotted) least-squares regression line.

Table 2
Parameters extraction cost function.

Coefficient	Estimate	st. error	t-value
γ_0	762,7643	4,671	163,296
γ_1	−1,14171	0,013	−86,450

Finally, we discuss the existence and uniqueness of the solution to the system (2)–(5). First note that for any γ_1, δ_1, N and r, there exists a unique $T_2 - T_1 \equiv \tau$ that solves (5). Now to examine the solution K_1, K_2, T_1 of (2)–(4) as a function of γ_1, δ_1, N, r and S_0 we can reinterpret the system (2)–(4) as a system that characterizes K_1, K_2, S_0 given γ_1, δ_1, N, r and T_1. This turns out to be a linear system of 3 Eqs. (2)–(4) and three unknowns K_1, K_2, S_0. The three equations are clearly linearly independent and therefore the solution is unique: for any γ_1, δ_1, N, r and T_1 there exists a unique vector (K_1, K_2, S_0) that solves (2)–(4), i.e., there is a one to one relationship between T_1 and S_0.

Note that $S_m = \left(\delta_0 - \delta_1 b\right)\tau$, that is for a solution to have $T_1 > 0$ the initial stock must be larger than S_m. If $S_0 < S_m$ then $T_1 = 0$. ■

Appendix B. Estimation of the extraction cost function

We use data on ultimately recoverable oil resources and production costs from McGlade and Ekins (2015), which we have converted from barrels of oil to GtC by assuming that each barrel of oil contains 117.19 kg carbon (cf. EPA, 2020). We have ordered all reservoirs in the data from high to low extraction costs.

Fig. 3 provides an overview. Each reservoir in the data is depicted by a dot in the figure. The horizontal coordinate of each dot corresponds to the amount of oil in a particular reserve (in GtC) including all reserves with higher extraction costs. The vertical coordinate gives the extraction cost (in billion US$ per GtC).

To estimate the parameters of our extraction cost function $C(S) = \gamma_0 - \gamma_1$, we regress the unit extraction costs in the data on the cumulative amount of oil in the reservoirs, by using OLS. Table 2 shows the results. The estimated extraction cost function is shown by the dotted line in Fig. 3.

Appendix C. Sensitivity with respect to slopes of cost and demand curves

Fig. 4 shows the effect of the slopes of the extraction cost curve (panel (a)) and the demand curve (panel (b)) on the Green Orthodox and Green Paradox effects. In each panel, we have depicted the elasticity of the initial extraction with respect to the unit

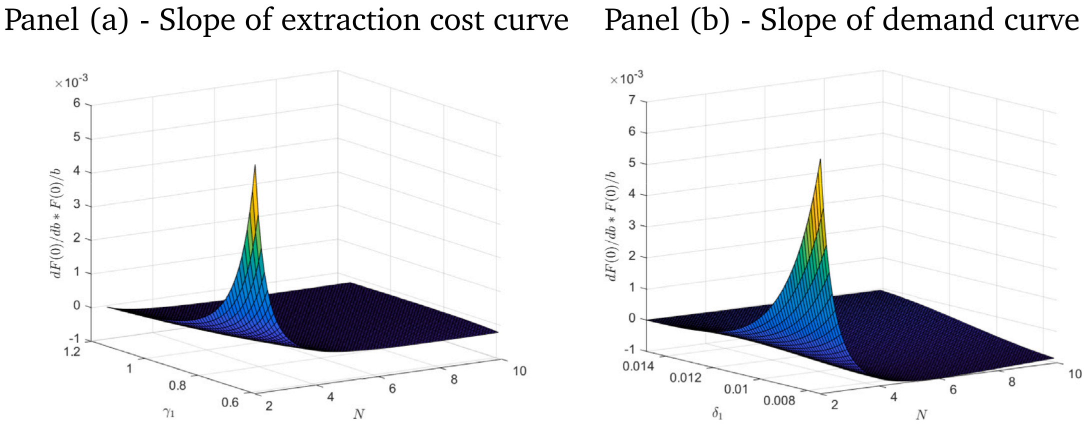

Fig. 4. Strength of Green Paradox–Orthodox effects.
Notes: The figure shows the elasticity of initial fossil fuel use with respect to the backstop price for various values of the number of oligopolists. If this elasticity is positive, there is a Green Orthodox effect. If it is negative, there is a Green Paradox effect.

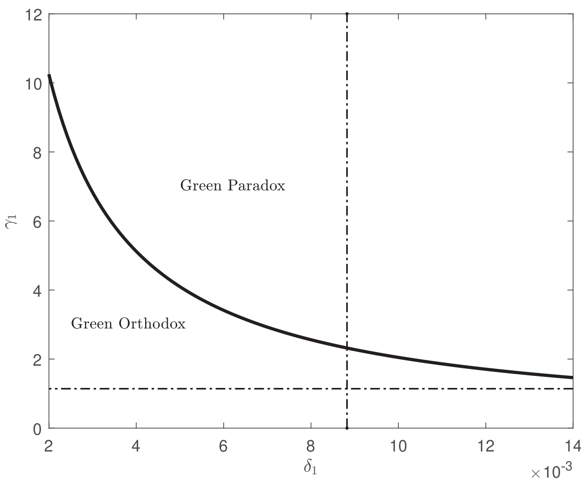

Fig. 5. Green Paradox vs. Orthodox: Robustness.
Notes: The frontier shows parameter combinations for which the change in initial extraction upon a decrease in the costs of renewable energy equals zero. Above the frontier, a Green Paradox effect occurs, i.e., initial extraction goes up. Below the frontier, a Green Orthodox occurs, i.e., initial extraction goes down. The benchmark values for the slope of the extraction cost function, γ_1, and the slope of the demand function, δ_1, are indicated by the dashed–dotted vertical lines. Note that extraction initial costs may be negative along the frontier for high values of γ_1.

cost of renewables on the vertical axis. A positive (negative) elasticity corresponds to a Green Orthodox (Paradox). Green Orthodox effects are declining in the slopes of the tho curves. Green Paradox effects as well, but to a smaller extend.

Fig. 5 depicts for which combinations of the slope parameter a Green Paradox or a Green Orthodox occurs for the case of a duopoly ($N = 2$). The downward-sloping frontier corresponds with combinations of the slope parameter for which the elasticity of initial fossil fuel use with respect to the backstop price is equal to zero. The horizontal and vertical dashed–dotted lines indicate the calibrated values of the slope parameters.

Appendix D. Monopoly and perfect competition

D.1. Proof of the case with $N = 1$

The Hamiltonian of oligopolist 1 reads

$$\mathcal{H}_1 = e^{-rt}\left[p(F_1 + F_{-1}(t))F_1 - C(S_1 + S_{-1}(t))F_1\right] - \lambda_1 F_1,$$

where λ_1 is the co-state variable, i.e., the marginal value of additional reserves. Along the first interval of time where $p(t) < b$, the necessary conditions read

$$0 = e^{-rt}\left[p'(F_1+F_{-1})F_1 + p(F_1+F_{-1}(t)) - C(S_1+S_{-1}(t))\right] - \lambda_1, \tag{A.5}$$

$$-\dot{\lambda}_1 = e^{-rt}C'(S_1+S_{-1}(t))F_1. \tag{A.6}$$

Use the expression for the co-state variable λ_1 from (A.5) into the expression for the Hamiltonian to get

$$\mathcal{H}_1(0) = -p'(F_1(0))F_1^2(0).$$

Take the partial derivative of $\mathcal{H}_1$. It equals

$$\begin{aligned}\frac{\partial \mathcal{H}_1}{\partial t} &= -re^{-rt}[p(F_1+F_{-1}(t))F_1 - C(S_1+S_{-1}(t))F_1]\\ &\quad + e^{-rt}[p'(F_1+F_{-1}(t))F_1\sum_{j\neq 1}\dot{F}_j - C'(S_1+S_{-1}(t))F_1\sum_{j\neq 1} -F_j].\end{aligned}$$

Hence,

$$\int_0^{T_2}\frac{\partial \mathcal{H}_1}{\partial t}dt = -rW_1 + \int_0^{T_2} e^{-rt}[p'(F_1+F_{-1}(t))F_1\sum_{j\neq 1}\dot{F}_j - C'(S_1+S_{-1}(t))F_1\sum_{j\neq 1}F_j],$$

with W_1 equilibrium profits of oligopolist 1. Next we use

$$\int_0^{T_2}\frac{d\mathcal{H}_1}{dt}dt = \mathcal{H}_1(T_2) - \mathcal{H}_1(0) = -\mathcal{H}_1(0),$$

since $\mathcal{H}_1(T_2) = 0$ because T_2 must be chosen optimally. Moreover, we know from, e.g., Seierstad and Sydsaeter (1987, p. 86) that $\frac{\partial \mathcal{H}_1}{\partial t} = \frac{d\mathcal{H}_1}{dt}$. Therefore

$$\begin{aligned} rW_1 &= -p'(F_1(0)+F_{-1}(0))F_1^2(0)\\ &\quad + \int_0^{T_2} e^{-rt}\left[p'(F_1+F_{-1}(t))F_1\sum_{j\neq 1}\dot{F}_j + C'(S_1+S_{-1}(t))F_1\sum_{j\neq 1}F_j\right].\end{aligned}$$

If $N=1$ then $F_{-1}(t) = \dot{F}_{-1}(t) = 0$. This gives

$$rW_1 = -p'(F_1(0))F_1^2(0).$$

Moreover, it goes without saying that total discounted profits for player 1 are lower the lower is the price of the backstop. So

$$drW_1/db = [-p''(F_1(0))F_1^2(0) - 2p'(F_1(0))F_1(0)]dF_1(0)/db > 0.$$

Making the innocuous assumption that instantaneous profits, $p(F_1)F_1 - C(S)F_1$, are concave in supply, the expression between brackets is positive and therefore $dF_1(0)/db > 0$. Hence, lower b yields lower $F_1(0)$, a Green Orthodox. ■

D.2. Proof of the case with $N \to \infty$

Let us assume, in accordance with van der Ploeg (2020), that some fossil fuel is left in the ground. This is the case if the equation $b = C(S)$ has a positive solution. Then $\lambda_1(T_2) = 0$, from transversality. Intuitively, there is no value in having more fossil fuel anymore. From (A.6), we have

$$\lim_{N\to\infty}\lambda_i(0) = \lim_{N\to\infty}\int_0^{T_2} e^{-rt}\gamma_1\frac{F(t)}{N}dt = 0, \tag{A.7}$$

as T_2 and F_i are finite. Hence, the Hotelling rent is zero throughout, meaning that the fossil fuel price is equal to the marginal extraction cost. Therefore, there is no Green Paradox nor Orthodox. ■

D.3. Proof of the case with $N \to \infty$ when costs depend on individual stocks

We now consider the extraction cost function $G(S_i) = \gamma_0 - N\gamma_1 S_i$, implying that extraction costs depend on individual reserves. The necessary conditions along the first interval $[0, T_1]$ read

$$\left[\left(\frac{\delta_0}{\delta_1} - \frac{F}{\delta_1}\right) - \frac{F_i}{\delta_1} - (\gamma_0 - N\gamma_1 S_i)\right] = e^{rt}\lambda_i, \tag{A.8}$$

$$-\dot{\lambda}_i = e^{-rt}N\gamma_1 F_i. \tag{A.9}$$

Let us assume, in accordance with van der Ploeg (2020), that some fossil fuel is left in the ground. This is the case if the equation $b = G(S_i)$ has a positive solution. Then $\lambda_1(T_2) = 0$, from transversality. Intuitively, there is no value in having more fossil fuel anymore. From (A.9), we have

$$\lambda_i(0) = \int_0^{T_2} e^{-rt}\gamma_1 F(t)dt > 0. \tag{A.10}$$

Furthermore, at instant of time T_1 we get

$$\lambda_i(T_1) = \int_{T_1}^{T_2} e^{-rt}\gamma_1 F(t)dt = \frac{\gamma_1(\delta_0 - \delta_1 b)}{r}\left(e^{-rT_1} - e^{-rT_2}\right). \tag{A.11}$$

First-order condition (A.8) at instant of time T_1 reads

$$\left[\frac{\delta_0}{\delta_1} - \frac{F(T_1)}{\delta_1} - \frac{F(T_1)/N}{\delta_1} - \left(\gamma_0 - N\gamma_1 S_i(T_1)\right)\right] = e^{rT_1}\lambda_i(T_1). \tag{A.12}$$

Furthermore, we have $F(T_1) = \delta_0 - \delta_1 b$ and $b = \gamma_0 - N\gamma_1 S_i(T_2)$. This yields

$$S(T_1) = (T_2 - T_1)(\delta_0 - \delta_1 b) + \frac{\gamma_0 - b}{\gamma_1}. \tag{A.13}$$

We combine (A.11)–(A.13) to obtain the equivalent of (5) for the case in which extraction costs depend on individual stocks:

$$(T_2 - T_1) - \frac{1}{r}(1 - e^{rT_1 - rT_2}) = \frac{1}{\gamma_1\delta_1 N}. \tag{A.14}$$

From this condition it can be noted that $T_2 - T_1$ vanishes as N goes to infinity. Moreover, if N goes to infinity, the first-order condition (A.8) boils down to[8]

$$\left[\frac{\delta_0}{\delta_1} - \frac{F(T_1)}{\delta_1} - \left(\gamma_0 - N\gamma_1 S_i(T_1)\right)\right] = e^{rT_1}\lambda_i(T_1). \tag{A.15}$$

Together with (A.9) this gives the Hotelling rule for $t < T_1$, i.e.,

$$\dot{p}(F(t)) = r\left[p(F(t)) - G(S_i(t))\right]. \tag{A.16}$$

From (A.10) it is clear that the Hotelling rent is positive initially. Hence, for $N \to \infty$ there is no limit-pricing phase and until $T_1 = T_2$ the resource price evolves over time according to the Hotelling rule. This implies that we are in a world of perfect competition, where the Green Paradox holds. ■

References

Basar, T., Olsder, G.J., 1998. Dynamic Noncooperative Game Theory, second ed. In: Classics in Applied Mathematics, Society for Industrial and Applied Mathematics.

Benchekroun, H., van der Meijden, G., Withagen, C., 2022. Economically Exhaustible Resources in an Oligopoly-Fringe Model with Renewables. Available at SSRN: https://ssrn.com/abstract=4280690 or https://papers.ssrn.com/abstract=4280690.

Benchekroun, H., Withagen, C., 2012. On price taking behavior in a nonrenewable resource cartel–fringe game. Games Econom. Behav. 76, 355–374.

Dockner, E.J., Jorgensen, S., Long, N.V., Sorger, G., 2000. Differential Games in Economics and Management Science. Cambridge University Press, Google-Books-ID: TMJWWMsE1_AC.

EPA, 2020. AVoided Emissions and geneRation Tool (AVERT).

Gerlagh, R., 2011. Too much oil. CESifo Econ. Stud. 57, 79–102.

Gilbert, R.J., Goldman, S.M., 1978. Potential competition and the monopoly price of an exhaustible resource. J. Econom. Theory 17, 319–331.

Hoel, M., 1983. Future conditions and present extraction: A useful method in natural resource economics. Resour. Energy 5, 303–311.

McGlade, C., Ekins, P., 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. Nature 517, 187–190.

van der Meijden, G., Withagen, C., 2019. Limit pricing, climate policies, and imperfect substitution. Resour. Energy Econ. 58, 101118.

Michielsen, T.O., 2014. Brown backstops versus the green paradox. J. Environ. Econ. Manag. 68, 87–110.

Pittel, K., van der Ploeg, F., Withagen, C., 2014. Climate Policy and Nonrenewable Resources: The Green Paradox and Beyond. MIT Press.

van der Ploeg, F., 2020. Race to burn the last ton of carbon and the risk of stranded assets. Eur. J. Political Econ. 64, 101915.

van der Ploeg, F., Withagen, C., 2015. Global warming and the Green Paradox: A review of adverse effects of climate policies. Rev. Environ. Econ. Policy 9, 285–303.

van der Ploeg, F., de Zeeuw, A.J., 1992. International aspects of pollution control. Environ. Resour. Econ. 2, 117–139.

Andrade de Sá, S., Daubanes, J., 2016. Limit pricing and the (in)effectiveness of the carbon tax. J. Public Econ. 139, 28–39.

Salant, S.W., 1979. Staving off the backstop: Dynamic limit pricing with a kinked demand curve. In: Pindyck, R. (Ed.), Advances in the Economics of Energy and Resources. JAI Press, Greenwich, Conn..

Seierstad, A., Sydsaeter, K., 1987. Optimal Control Theory with Economic Applications. North Holland.

Sinn, H.-W., 2008. Public policies against global warming: A supply side approach. Int. Tax Public Finance 15, 360–394.

[8] Note that $N \to \infty$ implies $S_i \to 0$, because each oligopolist becomes atomistic. So, strictly speaking, each oligopolist then owns a marginal unit for the resource with a given marginal extraction cost. This marginal extraction cost differs between the oligopolists such that the aggregate extraction cost function reads $\gamma_0 - \gamma_1 S$.