The effect of market structures on the Green Paradox and Green Orthodox in the oil sector

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Abstract

In competitive markets second-best climate policies can result in unintended increasing initial extraction, which is called the Green Paradox effect. The opposite of this, when climate policies result in less initial extraction as a result of strategically used market power, is called the Green Orthodox. As the carbon budget for the Paris Climate Conference goal of 2°C is decreasing rapidly, designing effective climate policies is increasingly important. I show that for the first-best policy of carbon taxes, initial and cumulative extraction is always lowered, for every market structure and level of the tax. But with renewables subsidies, a second-best policy, I find that the design of the extraction cost function in the climate model results in different outcomes. When extraction costs depend on total common reserves, a Green Paradox is found for every market structure. But when extraction costs depend on individual reserves, I find a Green Orthodox for markets with 21 or less producers in the case of large subsidy levels. For small subsidy levels, I only find a Green Orthodox for a duopoly.

1. Introduction

Since the end of the 18th century, the industrial scale on which we have been using fossil fuels for production of goods and energy has brought humanity much welfare. But as with many things in life, the short and long run outcomes of this fossil fuel use are not equally favorable. In the short to medium term, the fuels of the industrial revolution has given our economy a boost like never seen before. But this fuel, now turns out to be indirectly fueling the warming of our climate via the greenhouse effect caused by its' residual products. If this global warming will increase after certain degrees, GDP will be negatively affected (Tol, 2009). Tol (2009) studied all the quality literature related to the economic impact of climate change. He concludes that the effects of moderate global warming (1-2°C) on GDP may be positive, but beyond the 2°C level impacts are very likely to become negative.

But does this outcome justify moderate global warming as the effects on global GDP are positive? When we take a look at how this GDP effect of moderate global warming arises, we see that the strong economies of western countries benefit from reduced heating costs and less cold-related health problems, whereas economies in the tropics are negatively impacted due to losses in agricultural production (Tol, 2009). The fact that the net effect on global GDP is still positive is because the output of western economies is much higher than the economies around the tropics. One could argue that ethically, this negative impact on poorer economies in the world outweighs the positive impact on the richer part of the world, and that therefore we should try to limit global warming as much as possible. But is as much as possible the best solution?

Emitting greenhouse gasses has been free for a long time, and in many sectors and parts of the world it still is. But emitting greenhouse gasses comes with a cost, as these emissions will result in future damages to our economy through global warming. These future damages as a result of carbon emissions are called the 'Social Costs of Carbon' (SCC). The use of fossil fuels result in negative externalities, which should be taxed in order to let the user of it to compensate for the negative effects in advance. Without the pricing of this future damages in todays' fossil fuel price, fossil fuels are too cheap and demand will be higher than socially optimal. So the best solution thus is to set the price of emitting one ton of carbon equal to the discounted future damages to our economy caused by this ton of carbon. This price must rise over time, for two reasons. On the one hand tipping points of climate change will come closer, and therefore the time between emission and damage will reduce. On the other hand, the remaining carbon budget will reduce over time and with rising economic production we potentially have to lose more welfare due to climate damages in absolute terms. The first-best policy is thus to set a tax on greenhouse gas emissions, equal to the SCC. This is economically efficient as firms and people can determine if it is cheaper for them to pay the tax or to abate emissions. The cheapest and easiest emission reductions will naturally be done first using this first-best policy.

Pricing the real costs would result in less emissions, and revenues for governments to compensate damages or invest in green technologies. Although there is consensus in the literature that a carbon price would be the most effective and socially optimal solution to tackle climate change, taxing is an unpopular measure among politicians and citizens. Carattini et al. (2017) researched why taxing is an unpopular climate policy by analyzing voting behavior in a ballot on energy taxes in Switzerland and by conducting surveys. They conclude that in the Swiss referendum the rejected proposed energy tax policy would have much higher chances to win if the tax revenues had been earmarked for green subsidies or other environmental uses instead of replacing the VAT as proposed. Other main findings were that people often think that the government will not spend the tax revenue well and that the economy will become less competitive. And although the Paris Climate Conference in 2015 is already 7 years ago, little climate policies have been implemented since then. The longer we wait with stringent climate policy, the smaller the remaining carbon budget becomes and the more likely it becomes that we have to use increasingly stringent measures in the future if we want to limit global warming to 2 degrees.

In this paper I focus on the fossil fuel market. In reality, this market consists of a wide range of products with different prices, characteristics and applications. In the oil industry for instance, Saudi oil is the cheapest to produce and most profitable at a production price of a few US dollars per barrel. When oil price increase, more expensive resources become economically profitable to deplete, such as the oil sand reserves. The cost of production of those oil sand reserves can be as much as 70 US dollars per barrel. Major companies and so-called SOCs (State-Owned Companies) own fossil fuel reserves which justify their current market value as these reserves can be sold for a market price in the future. But with climate policies, it is not so sure whether all of these individual reserves can be sold. Climate policies put a cap on maximum global temperature increase, which implies a cap on cumulative emissions of carbon. According to Rogelj et al. (2019), the estimated budget for a cap of 1.5 degrees warming ranges from zero to 1,000 Gt CO2. The estimated budget for 2 degrees warming is around 800 to 2,000 Gt CO2 (Rogelj et al., 2019). McGlade and Ekins (2015) have calculated that the existing conventional reserves alone are equivalent to 2,900 Gt CO_2; much more than the 2°C carbon budget. If we also take into account the non-reserve resources, the total remaining fossil fuel reserves are 11,000 Gt CO_2.

As clearly not all reserves can be burned with a cap on global warming and emissions, this results in a strategic game between fossil fuel resource owners, in which each owner wants to sell as much of its' reserves as possible to avoid stranded assets. This strategic game is intensified by sub-optimal climate policies and the announcement of them, and can result in rather counter-intuitive and unintended outcomes. Sinn (2008) was the first researcher to describe this phenom. By the announcement of more stringent climate policies in the future by governments (or in other words: postponing climate policy today), fossil resource owners see future revenues drop. These resource owners therefore shift extraction in the future to today. Total extraction is lowered over time[1] (more fossil reserves are locked up in the earth), but emissions and global warming in the short run are accelerated. This is called the Green Paradox[2].

Much literature describes the drivers and effects of the Green Paradox. Sinn (2008) was the first to explicitly highlight the importance of involving carbon supply in policy decisions aiming at reducing carbon emissions. Politicians mainly focus at reducing the demand for fossil fuels, neglecting the fact that fossil fuel producers can adjust their pricing and production and therefore society can return to the old 'dirty' equilibrium. Sinn (2008) argues that only policy measures that flatten the global carbon supply curve are effective in mitigating the problem of global warming. He therefore proposes public finance measures, time-invariant carbon taxes, a world-wide emission trading system and source taxes on capital income. Sinn was the first one to introduce the Green Paradox, arguing that second-best policies that intend to flatten the extraction curve in fact steepen it when these policies become or are expected to become more stringent over time. Empirical evidence of this Green Paradox is found by Grafton et al. (2014) for instance, who found evidence that US biofuels subsidies have increased the rate of extraction of US fossil fuel producers.

Hoel (2010) investigated the effects of sub-optimally designed carbon taxes on extraction of fossil fuels using a two-phase model. He actually founds that, contrary to the policy design Sinn (2008) proposes, constant carbon taxes are suboptimal. Hoel (2010) argues that increasing carbon tax rates are optimal, but that a Green Paradox will occur if the growth rate of the tax or the initial height of the tax is not set optimally. In his model, the strategic nature of the fossil fuel market as described earlier in this chapter comes forward. Hoel (2008) finds that:

- A rapidly rising carbon tax induces a weak Green Paradox.
- When extraction costs depend on remaining reserves, total climate costs will go down as a result of a carbon tax (so no strong Green Paradox will occur) even if the carbon tax path induces near-term extraction.
- Because politicians are elected for relative short periods they are unable to commit to long term carbon tax paths. Fossil fuel markets thus develop expectations about the distant future tax rate based on the near-term tax path. A lower than optimal near-term tax rate thus results in expectations of a stronger increasing and higher future carbon tax, as fossil fuel resource owners take the carbon cap as given and expect politicians to do the same. A higher current carbon tax thus will result in lower near-term extraction and a weaker or no Green Paradox.
- A carbon tax does not automatically result in a Green Paradox, but only if the tax rate is set too low.

Ploeg and Withagen (2012) found that under certain conditions, under monopoly the Green Paradox arises. Furthermore they find that if there is already a lot of CO_2 in the atmosphere, it is socially optimal to lower extraction rates. This is quite intuitive; as cumulative emissions increase, the carbon budget decreases and tipping points in the climate system will come closer. If we take the development of technology as given and constant, lower extraction rates buys us more time and will result in better and cheaper climate change adaption technologies if the temperature cap is reached. Slower extraction is socially optimal from a climate-perspective. Furthermore they find that subsidizing the backstop technology leads to a bigger final stock of fossil fuel reserves and a higher rate of extraction in the last period before switching to the backstop technology. Winter (2013) finds the same result but does not define the price cut of the backstop technology as a subsidy but as a breakthrough, which is technically the same.

[1] This is the case with a weak green paradox.

[2] There is a weak and a strong paradox. The weak green paradox means that fossil fuels are extracted more quickly and thus global warming accelerates. A strong green paradox implies that the cumulative discounted damages resulting from global warming are increased by second-best climate policies (Jensen et al. 2020).

Ploeg and Withagen (2012) also consider the effect of market structures on extraction, and find that under monopoly initial extraction is lower than under perfect competition. Van der Meijden and Withagen (2019) also find that under monopoly, a renewables subsidy or a carbon tax lower initial and cumulative extraction. This is called a Green Orthodox, and the possibility of this phenom is confirmed by Wang and Zhao (2018). They find that if the backstop technology has no capacity constraints, renewable subsidies lead to a Green Paradox in a perfect competitive market, but might lead to a Green Orthodox under certain conditions in a monopoly market. Various studies thus have shown that the market structure plays an important role when considering the effects of environmental policies on climate outcomes, and the Green Paradox and Orthodox specifically (cf. Winter (2013), Ploeg and Withagen (2012), Van der Meijden and Withagen (2019), Van der Meijden et al. (2015), Van der Ploeg (2016), Van der Ploeg (2020), Eichner and Pethig (2011), Benchekroun et al. (2022) and Grafton et al. (2012)).

In this paper, I will analyze how the Green Paradox and Orthodox is affected by different market structures. Some fossil fuel markets, like the market for coal and gas, are rather competitive. But in the oil market, we see major companies and SOCs having large market shares and market power, or as in the case of OPEC some of these producers are even openly working together in a cartel. Therefore the oil market could be describes as an oligopoly market. SOCs together account for more than 55% of the world's oil production, and most of them have a extremely large market share in their domestic market.

Van der Meijden et al. (2015) analyzed the conditions and effects of the Green Paradox in a two-period, two-region mode. As in this paper a one-region model is used, I only mention the relevant findings of Van der Meijden et al. (2015) for this paper. They argue that a serious shortcoming of most of the research is that the interest rate is exogenously modelled. They argue that an increase in the future carbon tax results in more current extraction and output. If the interest rate is kept the same under the new output, there is an excess of supply. To increase demand to levels where it meets supply again, consumers should be encouraged to spend more money in the near-term. Therefore, the interest rate should be lowered, resulting in less current extraction. The Green Paradox is less strong in models where the interest rate decreases as tax rates increase. Eichner and Pethig (2011) and Van der Ploeg (2016) find comparable results. In this paper I keep the interest rate constant, so the Green Paradox/Orthodox effects I find should be seen as a upper limit of a bandwidth.

Van der Meijden and Smulders (2017) conducted interesting research on the drivers behind a transition from fossil to renewable energy. They conclude that expectations and strategic behavior matter a lot. If investors and producers think that a shift to a backstop technology will happen in the future, less (more) money is invested in fossil (renewable) technology and therefore price differences between the two technologies will decrease. This decreased price difference than makes it even more likely that the shift will happen, inducing more (less) investments in the backstop (fossil) technology. The government has a major role in this; by setting ambitious environmental policies which clearly steer the economy towards a clean economy, they shape the conditions under which rational investors and producers than will make this self-fulfilling prophecy of a shift to a clean economy happen. From a different angle than the research of Meijden et al. (2015), Ploeg and Withagen (2012), Hoel (2010) and Winter (2013), this research of Van der Meijden and Smulders (2017) confirms that the environmental policy design of governments has a large effect on the way our economy will shift towards a green economy.

The aim of this paper is to show how different levels of a carbon tax and a green subsidy affect the Green Paradox and orthodox, and which effect fossil fuel market structures have on this. I use a model of a recent paper by Van der Ploeg (2020) as a basis for this paper. In this model, the market for energy initially consists of a price competitive fossil fuel with greenhouse gas emissions as a residual product, and a more expensive clean, zero emission, backstop technology. I am mainly focusing on less competitive fossil markets as according to the literature the tipping point between the Green Paradox and Green Orthodox typically arise with a lower number of producers in the market. As the oil sector is a less competitive fossil fuel market, I will be therefore referring to oil in the remainder of this paper. As in almost all markets in the world there are at least two producers of oil, I will leave monopoly markets for further research and will not include this in my analysis. Following Fischer and Salant (2017) and Michielsen (2014) I deviate from dirty backstops, and interpret the backstop technology as a perfect scalable clean alternative to oil, without capacity constraints. The model consists of three phases. First there is a Hotelling Pricing phase, which is characterized by a price path where a markup for selling a finite good, the scarcity rent, is rising over time at the rate of interest. This way, the present value of extracting a marginal unit of oil out of the earth will be the same in every period. At the end of the Hotelling Pricing phase the price of oil reaches the price of the backstop. When considering market structures and the shift to a backstop technology, a perfect substitute for oil, various literature have found evidence for a strategic pricing phase after the Hotelling Pricing phase (first introduced by Hoel (1978)). This strategic pricing phase is called the Limit Pricing phase, and is characterized by oil producers setting the price of their product just below the backstop price to keep renewables out of the market. Brown and Huntington (2017) have found evidence that OPEC is using Limit Pricing strategy in certain periods to strengthen or maintain its' market position. As extraction costs negatively depend on remaining reserves, in each period extraction costs go up. During the Limit Pricing phase the price of oil cannot increase, but with increasing extraction costs the end of this phase is unavoidable as oil producers will only supply when the total costs of producing a unit is lower than the market price for that unit.

Van der Ploeg (2020) uses a feedback and open-loop Nash equilibrium variant of the model. As the differences in the results are quite small, I will focus on the open-loop model. Van der Ploeg (2020) finds that more market power in the oil market increases the duration of the period of Limit Pricing. Furthermore, he concludes that weaker market structures intensify the race to burn the last ton of carbon; extraction is higher and the carbon free era is brought forward. He uses extraction costs dependent on global stock of reserves, whereas I let costs depend on own reserves. This is more realistic, as contrary to Van der Ploeg's (2020) model, depletion of an oil field in Siberia now does not affect the extraction costs of an oil field in Saudi Arabia in my model. In this paper, I show how using this alternative cost function affects outcomes of the model.

In his model, Van der Ploeg constructs two scenarios; in the Business as usual (BAU) scenario the subsidy on the backstop technology is zero, and in the SCC scenario the safe carbon budget for reaching the 2°C is enforced by introducing a second-best fixed subsidy v. He finds that in the SCC scenario, the subsidy leads to a weak Green Paradox as extraction is higher than in the BAU scenario and the end of the Limit Pricing phase is earlier in time, but cumulative emissions are lower.

In a second analysis, Van der Ploeg (2020) investigates the effect of market power on the fossil fuel market for the two scenarios (BAU and SCC). For different N of fossil fuel producers in the market, the effect on duration of Limit Pricing, price and emissions is analyzed. Van der Ploeg (2020) concludes that as N increases, the duration of the Limit Pricing phase and the initial fossil fuel price p_0 decreases and the ending of the fossil fuel era comes forward in time. For the SCC scenario, if N increases, the carbon budget is spent more during the Hotelling Pricing phase and less during Limit Pricing. Thus in both analyses, a Green Paradox is found.

The contribution of this paper to the existing literature is that I will both analyze the effect of a carbon tax and a renewables subsidy for different market structures in one framework, where I compare two types of extraction cost functions. One costs function depends on own remaining reserves, and the other cost function depends on total remaining reserves. Ploeg (2020) uses the latter, whereas I argue the first is more intuitive and applicable to the real world. Most of the existing research is focused on one policy measure or one type of market structure, so combining all using one model with two alterative cots functions will provide useful, new insights. Benchekroun et al. (2022) also investigate the case where extraction costs depend on remaining individual instead of common reserves. They find that the effects of a renewables subsidy are much larger and that a Green Orthodox occurs with a higher amount of players in the market.

The structure of this paper is as follows. In the next section, the model will be presented and specific focus will be on the adjusted cost function. After that, I will analyze how the Green Paradox effects change in my model compared to the model of Van der Ploeg (2020) and how market structures play a role. Then I will analyze how a renewable subsidy and a carbon tax affect the Green Paradox and Green Orthodox in different market structures. I end with a conclusion.

2. The model

I follow the model of Van der Ploeg (2020). Therefore I will only introduce the most important aspects of the model here and clarify what adjustments have been made to the model in order to let extraction costs depend on individual reserves.

2.1. The model

In the global market for energy, there are two perfect substitutes. There is an initially cheaper oil alternative with market price p and a clean backstop technology with market price b. Total energy demand is given by $D(p) = R + F$, with F denoting oil demand and R denoting renewable energy demand. There are a number N of identical oil producers with an equal market share. Oil extraction costs $G(S)$ depend negatively on remaining reserves S. As defined by the oil depletion equations;

$$\dot{S}_i = -F_i \leq 0, \qquad S_i(0) = S_{i0} \geq 0, \qquad \int_0^\infty F_i(t)dt \leq S_{i0} \tag{1}$$

the change in in-situ reserves of producer i is equal to the share of oil demand F this producer have served, initial reserves are larger than zero and total oil demand cannot exceed total in-situ reserves in equilibrium. Once $p > b$, total oil demand drops to zero and the world will totally switch to the clean backstop technology.

If $F > 0$, producers set marginal revenue equal to marginal extraction cost and a mark-up for the scarcity characteristics of the good, the scarcity rent. This scarcity rent arises from the fact that choosing between extraction now and in the future has consequences for extraction costs. The scarcity rent therefore can be defined as the NPV of all future decreased extraction costs of other extracted units of oil as a result of holding one unit in the ground today:

$$s_i(t) = -\int_0^\infty e^{\left(-r(t'-t)\right)} G'\big(S(t')\big)F_i(t')dt' \tag{2}$$

The differential equation of the price of oil, with r as the interest rate, ε as the price elasticity of global energy demand and θ as the super-elasticity of global energy demand, is as follows:

$$\dot{p} = r\left[p - \frac{N\varepsilon}{N\varepsilon-1}G(S)\right]\left(\frac{N\varepsilon-1}{N\varepsilon-1+\theta}\right) \tag{3}$$

From this equation, we can already see what effect market structures have on the price path of oil. The second term in the square brackets increases when the number of competitors N in the market decreases, thereby decreasing the outcome of the equation and thus smoothening the price path. In other words; more market power leads to a slower ricing price path of oil, which could have consequences on other market outcomes such as amount of stranded assets. These stranded assets are defined as the total number of oil reserves that remain unexploited in the ground after the world has switched to the backstop technology. As these reserves will never be burned and transformed into greenhouse gasses, the larger the amount of stranded assets is the smaller the global temperature increase will eventually be. In the model there are two important moments in time where we want to know the remaining amount of reserves (or cumulative amount of emissions as the opposite). S_1 is the amount of remaining reserves at the end of the Hotelling Pricing phase, and S_2 is the amount of remaining reserves at the end of the Limit Pricing phase, or stranded assets. Although the exact relationship between cumulative emissions of CO2e into the atmosphere and earth surface global temperature increase remains an issue under debate, there is consensus that there is a positive relation between the two. Therefore in this paper, I assume a negative relationship between the amount of stranded assets S_2 and global warming.

The model can be solved by backward induction, starting at the end of the fossil era and calculating back towards the starting point at T_0. Therefore, the remainder of this model section describes the three phases of the model by starting at the last phase, the carbon free era.

2.1.1 The model: Phase 3, $t > T_2$

The carbon free era starts at the point where the price of fossil fuel becomes equal to the price of the backstop. More specifically, if the marginal revenue of fossil fuel becomes equal to the price of the backstop, the end of the Limit Pricing phase T_2 is reached and the demand for oil F becomes zero. As we know from the model that the following condition must hold:

$$b = \gamma_0 - \gamma_1 S \tag{4}$$

and b, γ_0 and γ_1 are parameters for the backstop price, the vertical intercept of the extraction cost function and the slope of the extraction cost function respectively, the model can be solved for total amount of remaining reserves S_2.

2.1.2 The model: Phase 2, $T_1 \leq t < T_2$

During this phase, renewable producers are kept out the market as fossil fuel producers set p just under the price of the backstop:

$$p = b - \frac{1}{\infty} \tag{5}$$

For every period, the extraction rate is known with the following function:

$$F = \delta_0 - \delta_1 p \tag{6}$$

The duration of the Limit Pricing phase is known:

$$(T_2 - T_1) - \frac{1}{rN}\left(1 - e^{-r(T_2 - T_1)}\right) = \frac{1}{N\delta_1\gamma_1} \tag{7}$$

As for every period during this phase the extraction rate is known using (6) and the total duration of the Limit Pricing phase is given by (7), the total extraction during this phase can be calculated and subtracted from S_2 to get the amount of remaining reserves S_1 at the start (end) of the Limit Pricing phase (Hotelling Pricing phase).

2.1.3 The model: Phase 1, $T_0 \leq t < T_1$

From the start of the Limit Pricing phase, both p and S_1 are known. As the initial global reserves S_0 marks the starting point of this phase, the price and extraction path during the Hotelling Pricing phase can be backwards constructed using the differential equations:

$$\dot{S} = -(\delta_0 - \delta_1 p) \tag{8}$$

$$\dot{p} = r\left[p - \frac{N}{N+1}(\delta_0 - \delta_1 S) - \frac{1}{N+1}\frac{\delta_0}{\delta_1}\right] - \delta_1 \frac{1-N}{N+1}(\delta_0 - \delta_1 p) \tag{9}$$

2.2. The adjusted Model

When extraction costs depend on individual reserves, the model must be adjusted. The differential equation for the fossil fuel price becomes:

$$\dot{p} = r\left[p - \frac{N}{N+1}(\delta_0 - \delta_1 S) - \frac{1}{N+1}\frac{\delta_0}{\delta_1}\right] \quad (10)$$

and the duration of the Limit Pricing phase becomes:

$$(T_2 - T_1) + \frac{1}{r}\left(e^{-r(T_2-T_1)} - 1\right) = \frac{1}{N\delta_1\gamma_1} \quad (11)$$

2.3. The extension of the Model

Furthermore, I analyze the climate damages from GHG emissions as a result of burning the oil being sold in each period. For the construction of a price path of CO2 I assume a growth rate of 5%, larger than the historical long run economic growth rate of 1.8% used by Bansal et al. (2017). The reason I use a larger growth rate is because I assume politicians are nowadays more committed to limiting global warming than a few years ago due to increased urgency and awareness in society. The purpose of using the SCC in this paper is solely to be able to analyze the strong Green Paradox effect, therefore the price path of the SCC is kept very simplistic. This analysis however is very sensitive to the design of the price path of the SCC and the discount rate. If the growth rate of the SCC is set marginally higher (lower) than 5%, the Net Present Value (NPV) of future climate damages become more (less) worth per unit. When the price path of the SCC is fixed but the discount rate used increases (decreases), the NPV of future damages decrease (increase). The function introduced to calculate the NPV of the SCC is:

$$NPV\ SCC = \sum_0^{T_2} \dot{S} p_{scc} e^{-rt} \quad (12)$$

with $\dot{S}$ as the extraction in each period, p_{scc} as the Social Cost of Carbon in each period, r is the discount factor and t is the number of periods since T_0.

3. Results

In this section, the effect of market structures, different extraction cost functions, renewable subsidies and carbon taxes on the Green Paradox effect is analyzed. I follow Benchekroun et al. (2022) for the calibration of the model, using the following parameter values:

Table 1: Model parameter values for calibration

Parameter	Value	Unit
$\boldsymbol{\delta_0}$	10	GtC
$\boldsymbol{\delta_1}$	3/340	tC/US$
$\boldsymbol{\gamma_0}$	762.76	US$
$\boldsymbol{\gamma_1}$	1.1417	US$/tC
$\boldsymbol{r}$	5	%
$\boldsymbol{b}$	610.21	US$
$\boldsymbol{S_0}$	595	GtC

3.1. Individual versus common dependent extraction costs and increasing market power

In the table below, the difference in the model outcomes when using the alternative extraction cost function, as well as increasing the number of oil producers are presented. For the analysis of the difference in model outcomes when using the adjusted model, no renewable subsidies or carbon taxes were modelled in order to see purely the effect of using this different model.

Table 2: Results of (i) using extraction costs dependent on individual amount of reserves and (ii) increasing N in the model

Parameter	(i) Difference compared to Ploeg (2020) function	(ii) Lower N results in:
Initial price	+	+
Initial extraction	-	-
Duration HP	-	-
Total extraction during HP	-	-
Duration LP	+	+
Total extraction during LP	+	+
Extraction rate during LP	N/A	N/A
Stranded assets	N/A	N/A
Duration fossil era	+	+
NPV Climate damages HP	-	-
NPV Climate damages LP	+	+
NPV total climate damages	-	-

When extraction costs depend on individual reserves instead of common reserves, the strategic behavior of oil producers changes. Extraction costs of future oil sales of producer i increase as other producers extract oil today in the model of Ploeg (2020), regardless of whether producer i extracts oil from its' own reserves. This means that by not selling oil, producer i will face higher extraction costs in the next period for the same unit of oil compared to when this producer would have extracted this unit today. In the case of the adjusted model where I assume extraction costs only depend on remaining individual reserves, extraction of competitors in the market do not affect individual extraction costs. The results of using this different model compared to the original Ploeg (2020) model are presented in the second column of table 2 and explained below.

In table 2 I compare how both the adjusted model and increasing market power (i.e. lowering N) affect model outcomes. Both adjustments to the situation in the model increase market power, so all the effects are the same (indicated by a green color). The adjusted model and lowering N results in a higher initial price and lower initial extraction. This result is intuitive, as in markets with more market power producers are not forced to compete on price but can maximize profits instead. Increasing market power in the oil sector (i.e. less producers in the market or using the adjusted model) leads to a longer fossil era due to a shorter Hotelling phase and longer Limit Pricing phase. As the price during the Limit Pricing phase is fixed but extraction costs increase with each unit of oil sold, profits go to zero towards the end of this phase. In a market with more market power profits are higher. Therefore, in an oil market with lower N, at the start of Limit Pricing there is more room for the extraction costs to increase before profits are zero. The demand for oil during each period of the Limit Pricing phase is the same for every N, so in less competitive markets oil producers will be able to use the Limit Pricing strategy for more periods.

The total extraction does not change, but the distribution over the Hotelling and Limit Pricing phase differs. As explained above, in less competitive oil markets producers are able to set the price higher during the Hotelling phase, thereby lowering the total extraction during Hotelling Pricing and increasing the extraction during Limit Pricing.

Furthermore, I analyze the climate damages from GHG emissions as a result of burning the oil being sold in each period. Both making extraction costs dependent on individual reserves and increasing market power result in lower total climate damages, as extraction is transferred to future periods and becoming worth less today by discounting to calculate the Net Present Value (NPV). The well-known phrase "the monopolist is the environmentalist's best friend" is thus confirmed by this analysis. As discussed in section 2.3., the design of the price path of the SCC and the discount rate are an important factor in the outcome of this analysis. If the growth rate of the SCC is set marginally higher (lower) than 5%, total climate damages in the case of more market power and using the adjusted model become larger (smaller), as now future climate damages become more worth per unit. When the price path of the SCC is fixed but the discount rate used increases (decreases), the NPV of future damages decrease (increase). Increasing the growth rate of the SCC or decreasing the discount factor being used results in higher total climate damages for the case of using the adjusted model or for a low N (i.e. an oligopolistic or monopolistic oil market).

3.2. Renewables subsidies

The main purpose of this paper is to analyze the effect of different climate policies on oil markets and how this might induce a Green Paradox or Orthodox. In this section, the effect of a green subsidy is analyzed for different market structures in the two models. The Green Paradox effect is a situation in which oil producers start dumping their oil on the market as a result of suboptimal designed climate policies. The most important outcome of the model when analyzing renewables subsidies and the Green Paradox thus is the initial price of oil, P_0, and initial extraction, $\dot{S}_0$. In the case of a Green Paradox, P_0 will decrease and $\dot{S}_0$ will increase as oil is dumped on the market. In figure 1, the results of this analysis are presented for both the cost function assumptions made by Ploeg (2020) and the adjustment to this; extraction costs dependent on individual reserves (adjusted model). Increasing the subsidy decreases the length of the Hotelling phase, up to the point where producers immediately shift to Limit Pricing. For $N = 2$ for instance, this point is at a subsidy of 98.2, so therefore there are no bars visible for subsidies higher than 50 for $N = 2$ as beyond that subsidy level the initial price will reach the limit price and is not able to rise further.

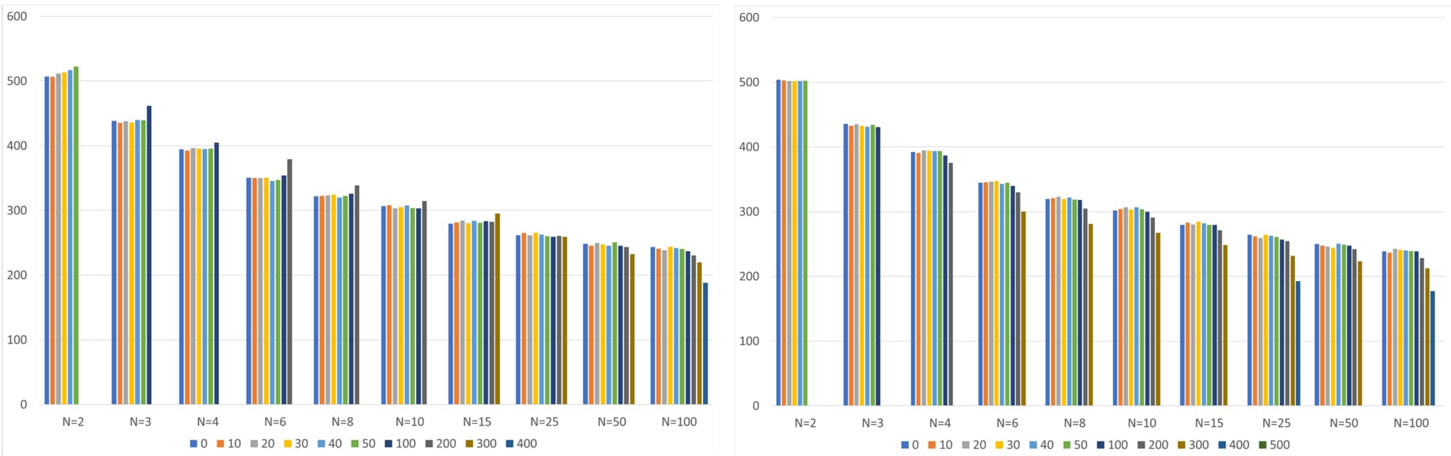

Figure 1: The effect of different subsidy levels on the initial oil price in different market structures (i.e. different N) for the adjusted model (left panel) and the original model (right panel)

For both models, we see slightly different results when comparing marginal differences in the subsidy to large differences. For large increases in the level of the subsidy, we see that in a market with in between 15 and 25 producers there is a switch point from a Green Orthodox to a Green Paradox for the adjusted model (left panel). For every integer between 15 and 25 I analyzed how initial extraction and initial price changed to an increase of the subsidy level from 200 to 300. For $N \leq 21$ I find a Green Orthodox, and for $N \geq 22$ I find a Green Paradox.

Table 3: Effects of an increase in the subsidy level for N = 21 and N=22

	$N = 21$		$N = 22$	
SUBSIDY LEVEL	200	300	200	300
P_0	263.13	263.15	264.38	263.86
$\dot{S}_0$	7.6782	7.6781	7.6672	7.6718

With less (more) producers in the market, the initial price of oil increases (decreases) as a result of significant subsidy increases. When analyzing initial oil price changes in markets with less than 22 producers I thus find a

Green Orthodox for large subsidy changes. For marginal changes in the level of the subsidy (e.g. from 10 to 20) I only find a clear Green Orthodox for $N = 2$ (cf. Benchekroun et al., 2022). For all the other market structures analyzed, there is no clear price pattern for marginal changes in the level of the subsidy.

In the original model, I find the same lack of a clear price pattern for marginal changes in the level of the subsidy. For larger increases in the level of the subsidy, with this model no Green Orthodox is found as for every type of market structure the initial price decreases when the level of the subsidy increases; a Green Paradox is found. Due to the strategic design of this model, there is too little market power in every type of market to induce a Green Orthodox.

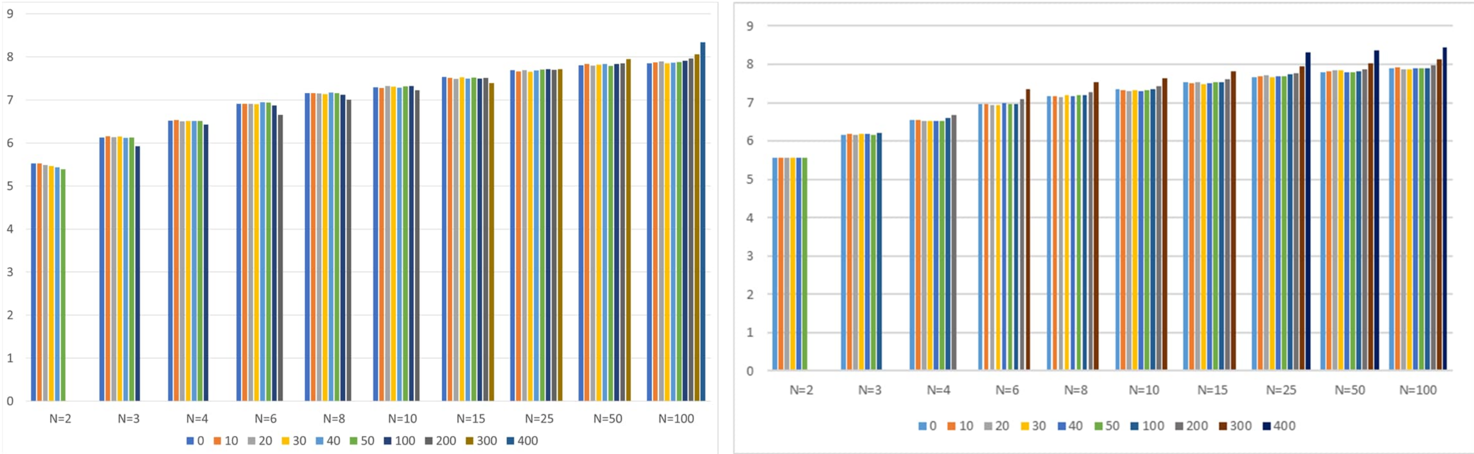

Figure 2: The effect of different subsidy levels on initial oil extraction rates in different market structures (i.e. different N) for the adjusted model (left panel) and the original model (right panel)

When analyzing the change in initial extraction as a result of subsidies, I find exactly the same Green Paradox and Orthodox related effects as for the initial price. The threshold for the adjusted model of a Green Paradox versus a Green Orthodox lays around 21 to 22 producers in the market for large subsidy increases. For marginal subsidy changes, I find the same result as Benchekroun et al. (2022); only a duopoly leads to a Green Orthodox. In the original model, I find the same lack of a clear price pattern for marginal changes in the level of the subsidy. For larger increases in the level of the subsidy, with this model for every type of market structure the initial extraction increases when the level of the subsidy increases.

In both models, with increasing subsidy levels the duration of the fossil era decreases, and cumulative emissions and total climate damages decrease. So the renewables subsidy lowers total climate damages in the long run, but increases emissions in the short run if the number of oil producers in the market is smaller than 22 for the adjusted model. There is evidence for a Green Paradox (Orthodox), but not for a strong Green Paradox (Orthodox).

3.3. Carbon tax

In this section, the effect of a carbon tax is analyzed for different market structures. In both models, introducing a carbon tax results in less initial extraction for every market structure. No Green Paradox is found, which confirms the reputation of the carbon tax as a first-best policy. There are no differences between the two models.

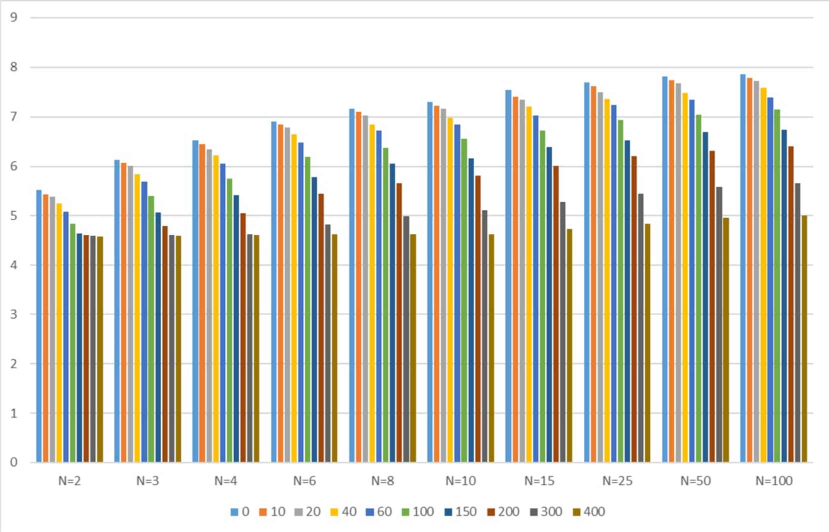

Figure 3: The effect of different carbon tax rates on initial oil extraction rates in different market structures for both models

From figure 3 it becomes clear that every increasing level of the tax lowers initial extraction rates for every market structure; no Green Paradox is found. In table 3, we can see that marginal increases in the carbon tax have a relatively larger effect on initial extraction rates for market structures with less competitors. A carbon tax thus is more effective in less competitive oil markets. This result is in line with the results of the analysis of the subsidy, where I also found that for lower N the same subsidy level lead to a relatively larger extraction decrease. For some less competitive market structures (i.e. higher N), increasing carbon taxes after a certain level of the tax has no additional effect as all the oil is already left in the ground. This issue will be discussed further in this section.

Table 4: Relative change of initial oil extraction compared to the situation without a carbon tax, for different number of producers and levels of the carbon tax

	10	20	40	60	100	150	200	300	400
N=2	-2%	-3%	-5%	-8%	-12%	-16%	n/a	n/a	n/a
N=3	-1%	-2%	-5%	-7%	-12%	-17%	-22%	n/a	n/a
N=4	-1%	-3%	-5%	-7%	-12%	-17%	-22%	-29%	n/a
N=6	-1%	-2%	-4%	-6%	-10%	-16%	-21%	-30%	n/a
N=8	-1%	-2%	-4%	-6%	-11%	-16%	-21%	-30%	n/a
N=10	-1%	-2%	-4%	-6%	-10%	-15%	-20%	-30%	-37%
N=15	-2%	-3%	-4%	-7%	-11%	-15%	-20%	-30%	-37%
N=25	-1%	-3%	-4%	-6%	-10%	-15%	-19%	-29%	-37%
N=50	-1%	-2%	-4%	-6%	-10%	-14%	-19%	-29%	-36%
N=100	-1%	-2%	-3%	-6%	-9%	-14%	-18%	-28%	-36%

The initial producer price of oil rises with a rising carbon tax. For markets with a larger N, a larger share of the carbon tax is charged to its' customers by the producer than in markets with smaller N. This is because in more competitive markets, profits are lower and external price increases by taxes must be largely paid by the customers, as producers have little room to use part of the profits to compensate this tax.

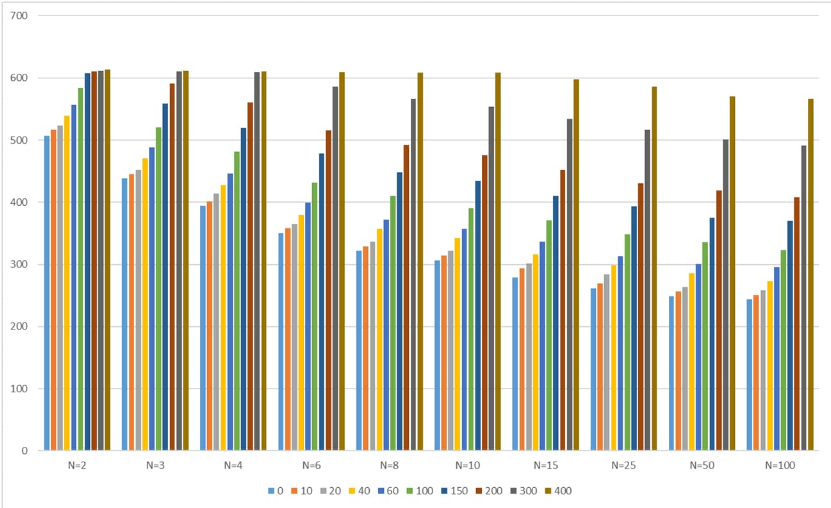

Figure 4: The effect of different carbon taxes on initial oil prices in different market structures for both models

From figure 4 it becomes clear that every increasing level of the carbon tax leads to higher initial prices, for every market structure. As can be seen in table 4, for marginal increases in the carbon tax we see the opposite pattern for initial prices as for the initial extraction; marginal increases in the carbon tax have a larger effect on initial oil prices for market structures with more competitors.

Table 5: Relative change of initial oil prices compared to the situation without a carbon tax, for different number of producers and levels of the carbon tax

	10	20	40	60	100	150	200	300	400
N=2	2%	3%	6%	10%	15%	20%	n/a	n/a	n/a
N=3	2%	3%	7%	11%	19%	27%	35%	n/a	n/a
N=4	2%	5%	9%	13%	22%	32%	42%	55%	n/a
N=6	2%	4%	8%	14%	23%	36%	47%	67%	n/a
N=8	2%	5%	11%	16%	28%	39%	53%	76%	n/a
N=10	2%	5%	12%	16%	27%	42%	55%	80%	98%
N=15	5%	8%	13%	21%	33%	47%	62%	91%	114%
N=25	3%	8%	14%	20%	33%	50%	65%	97%	124%
N=50	3%	6%	15%	21%	35%	51%	68%	102%	130%
N=100	3%	6%	12%	21%	33%	52%	67%	102%	133%

In this section I discuss initial price and extraction changes as a result of carbon taxes. As mentioned, for less competitive markets after a certain carbon tax level, no change in initial extraction and price can be observed in figure 3 and 4. This is because increasing carbon taxes drives producers up on the price and extraction curve towards the switch point between the Hotelling and Limit Pricing phase. At this switch point, the price and extraction is given by the price of the backstop, the number of producers and some other parameters, and is fixed beyond this point. In table 6, we see that the higher the carbon tax level, the shorter the Hotelling Pricing phase becomes. Markets with a lower amount of producers switch earlier to Limit Pricing (see table 2), so an increase in the carbon tax level will eliminate the duration of Hotelling Pricing for lower levels of the tax for less competitive markets compared to more competitive markets.

Table 6: Duration of Hotelling Pricing Phase for different levels of the tax and market structures, for the adjusted model (left panel) and original model (right panel)

	0	10	20	40	60	100	150	200	300	400
N=2	28	26	25	22	18	11	2	0	0	0
N=3	41	40	39	36	33	27	19	10	0	0
N=4	48	47	45	43	40	34	27	18	0	0
N=6	54	53	52	50	47	42	34	27	10	0
N=8	58	57	56	53	51	45	39	31	15	0
N=10	60	59	58	55	53	48	41	34	18	0
N=15	64	62	61	59	56	51	45	38	22	5
N=25	67	66	64	62	60	55	48	42	26	9
N=50	70	69	68	65	63	58	52	45	30	14
N=100	72	71	70	68	65	61	54	48	33	16

	0	10	20	40	60	100	150	200	300	400
N=2	37	36	34	31	28	21	12	2	0	0
N=3	53	52	51	48	45	39	31	23	4	0
N=4	61	60	58	56	53	48	40	32	14	0
N=6	68	67	65	63	60	55	48	41	24	5
N=8	71	70	68	66	64	59	52	45	28	10
N=10	73	71	70	68	65	60	54	47	31	13
N=15	75	74	72	70	68	63	56	49	34	16
N=25	76	75	74	72	69	64	58	51	36	19
N=50	77	76	75	73	70	66	59	52	38	21
N=100	78	77	76	73	71	66	60	53	38	22

Furthermore, increasing tax levels leads to less cumulative extraction and less total damages in both models, so no evidence is found for a Strong Green Paradox either.

5. Conclusion

I have shown that the effects of renewables subsidies and carbon taxes depend on the market structure and the model that is been used. In the adjusted model for marginal subsidy increases I found evidence of a Green Orthodox in the case of a duopoly. For less competitive markets, up to 21 producers of oil, I only found evidence of a Green Orthodox in the case of larger subsidy increases. In the original model, no evidence for a Green Orthodox was found as every increasing subsidy level results in a Green Paradox.

For a carbon tax, no evidence of a Green Paradox was found; every tax level leads to lower initial extraction, making it an effective climate policy instrument. The carbon tax is more effective in decreasing short term extraction in less competitive markets; initial extraction decreases relatively more in markets with lower N. No evidence was found for a strong Green Paradox.

These findings build on the existing literature which emphasizes taking market structures into account when designing environmental policies. I found additional evidence that favors less competitive oil markets when fighting climate change. In that light, the dissolution of the mighty Standard Oil in 1911 could be one of the causes why climate policies are less effective than intended.

As I analyzed both marginal and larger subsidy level changes, I found a different number of oil producers for which there is a tipping point between a Green Orthodox and Green Paradox. How the exact level and the size of the steps between the subsidy levels affect model outcomes, I leave for further research. As not only the market structure, but also the level of the subsidy affects initial extraction, I recommend politicians to monitor initial extraction rates after implementing and changing renewables subsidies. Furthermore, I showed that using different models leads to very different results; as I found a Green Paradox in the adjusted model but no evidence for it in the original model. To obtain a clearer picture of what should be the model to use when analyzing Green Paradox and Orthodox effects, more empirical research could be done after the exact development of the extraction costs of oil and how profits are affected by decreasing individual and total world reserves.

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