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Biofuel mandating and the green paradox

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Abstract

The theory on the green paradox has focused primarily on the consumption of a clean substitute produced using a static technology. In reality, we observe the gradual accumulation of the clean substitute's capacity, suggesting that supply decisions for the clean substitute and finite carbon resource should both be treated as dynamic. This paper shows that when climate policy is preannounced, and with simultaneous consumption of a finite carbon resource and a clean substitute, myopia in the supply of the latter leads to the green paradox. When clean substitute producers can accumulate capacity and are forward looking, the green paradox may or may not arise, however. In this setting, its occurrence depends on both the size of the discount rate and the remaining stock of carbon resource. These and other drivers of the green paradox are investigated in a multi-producer game-theoretic model calibrated to real-world global oil market data. The timing of mandating policy is shown to be the single most important variable for mitigating the green paradox. Moreover, for EU-2020 and US-2022 style biofuel mandating targets, a rather robust 0.3% decline in production is observed during the premandate phase, suggesting that concerns over the green paradox may be seriously overstated.

Keywords: Green paradox, Climate change, Peak oil, Biofuel mandates, Unconventional crude oil

JEL: C61, C7, H25, H32, Q28, Q35 , Q42, Q58

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1. Introduction

Fuel mandates are a key policy in the drive to contain anthropogenic carbon emissions. Both the EU and US governments have announced mandating targets. EU targets specify a minimum share of 7% for biofuels to be used in transportation by the year 2020. US targets, on the other hand, specify 36 billion gallons of biofuel production by 2022.[1] Mandates may, however, engender unwanted phenomenon such as the green paradox[2] (Sinn, 2008, 2012) or fail to stimulate the supply of clean alternatives during the pre-mandate phase. While a substantial number of articles (see e.g., van der Meijden et al., 2015; Winter, 2014; Michielsen, 2014; van der Ploeg and Withagen, 2012b,a; Smulders et al., 2012; Grafton et al., 2012; Gerlagh, 2011; Eichner and Pethig, 2011; Sinclair, 1992) assess, from a theory perspective, how subsidies directed towards substitute technologies or carbon taxes influence the extraction of a polluting exhaustible resource, only a few articles (e.g., Greaker et al., 2014; Fischer and Salant, 2014; Chakravorty and Hubert, 2013; De Gorter and Just, 2009; Allaire and Brown, 2015) examine mandating targets as a policy tool in the context of the green paradox. The contribution of this paper is to investigate the plausibility of the green paradox in a model where biofuel producers, like fossil producers, can anticipate future mandating policy, and thus, may adjust present day capacity in response to preannounced mandating targets.

As such, this paper provides insights into how expectations influence mandating policy. When biofuel producers are unable to anticipate and react to future mandating policy, i.e., are myopic, a double green paradox is observed. A preannounced mandating target hastens the supply of crude oil, (i.e., first green paradox) which in turn depresses the supply of biofuels (i.e., second green paradox). This is the well-known adverse effect of demand-side climate policies popularized by Sinn 2008, 2012 as the green paradox. When biofuel producers can anticipate and react to future mandating policy, however, —similarly to fossil fuel producers —only one channel for the green paradox results. That is, while the announcement of targets induces crude oil producers to hasten extraction, it also induces biofuel producers to expedite capacity accumulation thus increasing biofuel supply during the premandating phase. The surge in biofuel production may under certain conditions offset the increase in crude oil production leading to delayed carbon emissions, or in other words, a green orthodox. In the analytical model of this paper, this result is driven primarily by the size of the discount rate but also to some extent by the remaining stock of crude oil reserves.

This paper also highlights how the length of the pre-mandate phase affects biofuel

[1]The US target translates to about 9% of the EIA (2015) 2022 projected US oil consumption.

[2]The green paradox occurs when producers hasten the extraction of carbon-rich resources in anticipation of carbon mitigation policies.

supply decisions. Conventional wisdom is that mandates should have longer premandating phases so as to give stakeholders time to adjust to future policies. This analysis shows that such an approach can be detrimental for pre-mandate carbon abatement efforts, especially if preannounced mandating policies are delayed and stringent. While some adjustment period may indeed be necessary, policies with short pre-mandate phases are observed to be better at stimulating the supply of the clean alternative and in turn limiting the green paradox. This is the case even when these polices are eventually as ambitious as delayed policies.

Biofuel mandating policies are also introduced in a calibrated model of the global oil market to provide quantitative insights. Assessed against a reference path without mandating policies, the model predicts a rather robust 0.3% percent decline in global crude oil supply in several scenarios, as a result of announcing EU 2020 and US 2022 style mandating targets. Notwithstanding, it is observed that high biofuel and low crude oil discount rates, well within the range of those cited in the literature, can induce the green paradox when mandating targets are delayed.

The numerical model developed for this paper introduces many features from the real world. While some of these such as learning in biofuel technology, market power in crude oil production, and isoelastic supply and demand functions can reinforce the green paradox (Winter, 2014; Nachtigall and Rübbelke, 2016; Grafton et al., 2012; van der Ploeg and Withagen, 2012a; De Gorter and Just, 2009; Allaire and Brown, 2015), others such as geological and capacity constraints (Cairns, 2014; Okullo et al., 2015) limit its likelihood. The model has eighteen oil producing regions eleven of which are in OPEC and can supply oil as oligopolies or members of a perfectly cohesive cartel. These supply oil alongside seven competitive non-OPEC producing regions. The market structure thus, has flavors of the cartel versus fringe framework as discussed in Benchekroun et al. (2009); Salant (1976); Okullo and Reynès (2011b). Additionally, the model introduces multiple crude oil resources both conventional and unconventional. The various crude oils are assumed to be equally emission intensive while biofuels are the clean alternative.

One of the stronger arguments put forward for why demand side intervention policy might not induce the green paradox is that policy boosts the supply of the clean alternative, which in turn curbs a potential surge in carbon emissions (Gerlagh, 2011; Grafton et al., 2012).[3] While the mechanics of this argument are similar to ours, it neglects the fact that policies are typically preannounced. We show that introducing a policy imple-

[3]Grafton et al. (2012) presents another argument that is based on elasticities of supply and demand. More specifically, when supply and demand curves are isoelastic, they find that the green paradox can arise for some parameter values where the policy induced surge in biofuel production fails to offset an increase in crude oil production.

mentation lag in these models results in a green paradox. Another argument presented by Michielsen (2014) is that if a scarce and dirty resource (e.g., oil) is consumed alongside an even dirtier and abundant resource (e.g., coal); then, under sufficient substitutability, preannounced policies can decrease carbon emissions as oil extraction is expedited, which cuts carbon emissions from coal until the carbon policy eventually kicks in. While Michielsen's analytical model points to this possibility, his numerical analysis indicates only positive leakage rates (see also van der Meijden et al., 2015).[4] Our analysis can therefore be seen as the first to introduce a theoretically, structurally, and empirically consistent channel for why fears over the green paradox may be overstated.

The rest of the article is organized as follows. Using a simplified global oil market model, the next section provides analytical insights into the occurrence of the green paradox. Section 3 describes the computational global oil market model at the heart of our simulations, whereas 4 describes its calibration and sets up the policy simulation scenarios. Section 5 presents the baseline and sensitivity results whereas 6 concludes.

2. Mandating in a stylistic oil model

To gain analytical insights into the occurrence of the green paradox and its drivers, this section sets up two models of fuel mandating: one with myopic behavior, as captured through a static biofuel supply function, and the other with forward looking behavior, captured using a dynamic biofuel supply function. In the static case, the biofuel producer is unable to react directly to preannounced mandating targets but is still affected by them through the reactions of crude oil producers. In the dynamic case, biofuel (like fossil fuel) producers have forward looking expectations and thus, while still indirectly influenced by the announced targets, are also directly affected through the impacts of preannounced policy on the shadow value of capacity accumulation.

For the static technology, we observe that preannounced targets give rise to a double green paradox: targets hasten crude oil production (first green paradox) and depress biofuel production (second green paradox). The dynamic supply function, on the other hand, results in one channel for the green paradox since preannounced targets stimulate pre-mandate biofuel supply. We also analyze the impact of postponing mandating targets. With a static supply function, the green paradox is mitigated whenever mandating policy

[4] Only one published paper that we are aware of explores the likelihood of the green paradox empirically. Di Maria et al. (2014) investigate whether the introduction of the Acid Rain Program in the US, resulted in a green paradox effect. They find that between announcement and implementation of the policy, coal consumption increased, and prices for high sulfur coal fell more than for low sulfur coal. But, they find no evidence that the consumption of high sulfur coal increased. They conclude that while the mechanism indicated by the green paradox theory may have been at work, market conditions and concurrent regulations prevented the green paradox.

is delayed. For the dynamic supply function, on the other hand, hastened crude oil extraction cannot be ruled out. Delaying mandates in this case can be detrimental for carbon abatement efforts.

2.1. Demand side

Consider a home country that intends to implement mandating targets. Crude oil is the source of carbon emissions, while biofuels are the clean or at least a carbon neutral alternative. We assume that crude oil and biofuels are perfect substitutes and that there is (always) a niche market for biofuels. It follows that as long crude oil resources are not depleted, both fuels will be consumed simultaneously. The regulator in the home country seeks to maximize discounted net utility, $\mathcal{W}$, from fuel consumption, net of purchasing costs. That is,

$$\max_{\{y_t,b_t\}} \mathcal{W}_0 = \int_0^\infty \left(U\left(y_t + b_t\right) - P_{y,t}y_t - P_{b,t}b_t\right) e^{-\delta t} dt \tag{1}$$

where $t \in [0, \infty)$ is the time index, δ is the discount rate, y_t and b_t are the consumption of crude oil and biofuels respectively, $P_{y,t}$ and $P_{b,t}$ are the purchase price for crude oil and biofuels respectively, and $U\left(y_t + b_t\right)$ is the utility derived from oil/fuel consumption. Utility is concave in the consumption of biofuels and crude oil such that:

$$\frac{\partial U\left(y_t + b_t\right)}{\partial y_t}, \frac{\partial U\left(y_t + b_t\right)}{\partial b_t} > 0 \quad \text{and} \quad \frac{\partial^2 U\left(y_t + b_t\right)}{\partial y_t \partial y_t}, \frac{\partial^2 U\left(y_t + b_t\right)}{\partial b_t \partial b_t} < 0$$

Moreover, we assume that crude oil and biofuels are perfect substitutes, implying that:

$$\frac{\partial U\left(y_t + b_t\right)}{\partial y_t} = \frac{\partial U\left(y_t + b_t\right)}{\partial b_t} = P_t$$

whenever there is positive consumption of both fuels.

Mandates may target the volume of biofuel consumption (i.e., volume mandates) or the consumption share of biofuels vis-à-vis crude oil (i.e., share mandates). Volume and share mandates can be represented using the following constraints, respectively:

$$b_t \geq \bar{b}_t \tag{2}$$

$$b_t \geq \bar{s}_t\left(y_t + b_t\right) \tag{3}$$

where (2) requires that as of date t, the volume of biofuels consumed is at least as as large as $\bar{b}_t$ units, whereas (3) requires the share of biofuels in fuel consumption to be no less than $\bar{s}_t \times 100$ percent. The volume and share mandating constraint can be combined to read as: $b_t \geq \bar{b}_t + \bar{s}_t\left(y_t + b_t\right)$.

The current value Lagrangian for the regulators consumption-mandating decision is $\mathcal{L}_t = U\left(y_t + b_t\right) - P_{y,t}y_t - P_{b,t}b_t + \chi_t\left(b_t - \bar{b}_t\right) + \mu_t\left(b_t - \bar{s}_t\left(y_t + b_t\right)\right)$, which gives the following first order necessary conditions:

$$\frac{\partial U\left(y_t + b_t\right)}{\partial b_t} - P_{b,t} + \chi_t + \left(1 - \bar{s}_t\right)\mu_t \leq 0 \qquad b_t \geq 0, \text{ c.s} \tag{4}$$

$$\frac{\partial U\left(y_t + b_t\right)}{\partial y_t} - P_{y,t} - \mu_t\bar{s}_t \leq 0 \qquad y_t \geq 0, \text{ c.s} \tag{5}$$

$$\chi_t\left(b_t - \bar{b}_t\right) = 0 \tag{6}$$

$$\mu_t\left(b_t - \bar{s}_t\left(y_t + b_t\right)\right) \tag{7}$$

where c.s refers to complementary slackness. χ_t is the shadow price on the volume mandating constraint whereas μ_t is the shadow price on the share mandating constraint. Respectively, they represent the welfare that can be had if volume or share mandating requirements are relaxed for an instant. The necessary conditions can be interpreted as follows. Equation (5) reads as: whenever biofuel consumption is positive, the marginal utility from its consumption should equal the biofuel purchase price plus subsidies introduced as a result of share and volume mandates. At the time the volume mandate comes into effect, the imposed subsidies increase biofuel consumption relative to crude oil consumption. Equation (4) says that there is no consumption of crude oil when the marginal utility from its consumption falls below the sum of the crude oil purchase price plus the tax imposed due to the share mandating requirement. Equations (6) and (7) imply that mandating constraints hold with complementary slackness. That is, if the mandating tax/subsidy is positive, then the mandating constraints is active. Otherwise, if the mandating constraints are slack, then no taxes/subsidies are imposed.

2.2. Supply side with a static biofuel supply function

Mandates imposed on the demand side feed into supply side decisions. The crude oil producer faces the standard Hotelling (1931) problem of maximizing discounted revenues from the extraction of a non-renewable resource over a foreseeable future $t \in [0, \infty)$:

$$\max_{\{y_t\}} \pi\left(R_0\right) = \int_0^\infty \left(P_{y,t}y_t - C\left(y_t\right)\right)e^{-\delta t}dt \tag{8}$$

where $P_{y,t}$ the crude oil price is given as $P_{y,t} = P_t - \mu_t \bar{s}_t$. $y_t\,(\geq 0)$ is the extraction of crude oil, $C\,(y_t) = c \times y_t$ is the cost of extracting crude oil, and $R_t\,(\geq 0)$ is the resource stock.[5] The initial resource stock $R_0 > 0$ is given. For analytical convenience, we assume that the crude oil producer's discount rate is the same as that of the consuming country. Given the price path, the producer chooses an extraction sequence such that the resource constraint $\int_0^\infty y_t dt = R_0$ holds in equilibrium. In dynamic form, the resource constraint reads as:

$$\dot{R}_t = -y_t \tag{9}$$

which requires the resource base to decrease by the amount extracted.

We assume that the biofuel producer solves a static supply problem, and for analytical convenience that biofuel supply is linear in price: $b_t = a \times P_{b,t}$, where a is the responsiveness of biofuel supply to a marginal change in the biofuel price. From the specification of the demand side, we can write $P_{b,t} = P_t + \chi_t + (1 - \bar{s}_t)\,\mu_t$. In the next subsection, we shall introduce a dynamic supply function, and the simulation model will consider a nonlinear dynamic supply function. Subsidies raise the biofuel price which in turn boosts biofuel supply. To keep the analysis tractable, we assume for the rest of this analytical section that taxes and subsidies are constant over time. Moreover, if we impose that $P_{y,t} = P_{b,t} = P_t$, we can study the impact of mandating targets, using taxes and subsidies, by examining changes in a and c, where an increase in a corresponds to a subsidy on biofuel production while an increase in c corresponds to a tax on crude oil supply.

Let us define the fuel demand function to be linear in price of the form $P_t = \alpha - \beta\,(y_t + b_t)$ where α is the choke price for fuel demand, and β is responsiveness of price to a marginal change in demand. Moreover, define $a = \frac{\eta}{\beta}$. The specified model is solved to obtain crude oil supply as — see AppendixB.1 for details:

$$y_t = \frac{1}{\beta}\,(\alpha - c\,(1 + \eta))\left(1 - e^{\delta(t-T)}\right) \tag{10}$$

which shows that crude oil production is increasing in α, and decreasing in β, c, and η. Notice that for α, β, c, and η constant, crude oil production is monotonically declining and hence the fuel price rises monotonically as does biofuel supply. Crude oil demand vanishes when $P_t = P_T = \frac{\alpha}{(1+\eta)}$.

Suppose the consuming country announces a subsidy/tax that comes into effect at

[5] Note that the assumptions on cost imply that marginal extraction costs are constant in extraction. Assuming quadratic costs instead does not alter the results, but makes the model less tractable.

some future date t_1 ($t_1 < T$). Foreseeing the implementation of the policy, crude oil producers expect their resources to be rendered less attractive and therefore react by hastening extraction. This leads to a surge in crude oil production during the premandating phase, which depresses the fuel price and the supply of biofuels as well. Policy formulated with the intention of boosting the clean alternative and curbing the supply of the dirty pollutant, as consequence, leads to two unwanted impacts: a surge in crude oil production and a decline in biofuel supply over the premandate phase. A double green paradox, so to speak.

Now suppose the regulator contemplates delaying the introduction of the mandating policy, how could this affect biofuel and crude oil supply? To the crude oil producer, the delay extends the time over which crude oil demand is exercised. As such, the crude oil producer reacts by delaying production, thereby raising the fuel price and in turn boosting biofuel supply. The following proposition formalizes these observations — see AppendixB.1 for the proof:

Proposition 1. *Let T denote the final date for extraction of a polluting nonrenewable resource and $t_1(t_1 < T)$ a point in time when a mandating policy is imposed. In the competitive model with with linear demand, linear extraction costs, and a linear supply function for the perfect substitute,*
(i) an announced tax on crude oil supply or a subsidy on biofuels hastens the extraction of crude oil and depresses biofuel supply during the premandating phase.
(ii) lengthening the premandating phase, i.e. increasing t_1 increases the total amount of crude oil resource extracted by t_1, but leads to the delayed extraction of crude oil at all $t \leq t_1$.

Introducing an announcement or premandating phase, as is typical for many climate policies, reverses Gerlagh's and Grafton et al.'s results who fail to observe a green paradox under comparable model assumptions. We see that delaying the subsidy/tax policy increases the total amount of crude oil extracted as of the implementation date. In the short-run, the delay actually slows the extraction of carbon, thus mitigating the green paradox.

2.3. Supply side with a dynamic biofuel supply function

A more realistic specification for biofuel production technology is to consider producers, who like fossil producers, foresee and are capable of reacting to future mandating policy. This is accomplished by introducing a dynamic supply function for biofuel production technology. Consider the following program where the biofuel producer seeks to maximize present value revenues of supplying biofuels net of capacity expansion costs:

$$\max_{\{z_t\}} \pi\left(b_0\right) = \int_0^\infty \left\{\left(P_{b,t}b_t - W\left(z_t\right)\right)\right\} e^{-\delta t} dt \tag{11}$$

subject to the capacity accumulation constraint: $\dot{b}_t = z_t$ where z_t is the newly installed capacity and $W\left(z_t\right) = a \times z_t^2$ are costs of capacity expansion. Since the marginal productivity for installed capacity, that is, the shadow price for capacity, falls as the terminal time period is approached, investments in capacity ultimately decline towards zero. Thus, there is a phase of capacity accumulation and since costs are quadratic, this phase could last until the termination period.

In contrast to the previous static specification of the biofuel production technology, in the current specification, the biofuel producer's capacity expansion decision is impacted by future mandating policy through two channels. Directly through the impact of the mandating target on the marginal product of new capacity, and indirectly through developments on the crude oil market.[6] In anticipation of future policy, the direct effect induces the biofuel producer to expedite capacity expansion. This is in contrast to the indirect effect that suppresses the surge in biofuel production due to expedited crude oil extraction. The domineering effect of these two determines whether or not the green paradox occurs.

We can obtain an analytical characterization of the fuel supply problem under the assumption of linear crude oil production costs. The interpretation of the closed form expressions is intractable, however. As such, we introduce the simplifying assumption that crude oil extraction is cost-less. This has the appealing property that whatever the size of the subsidy on biofuels, crude oil resources always get depleted. For analytical convenience, we forego characterizing the impact of a tax, and only look at the impact of a subsidy on biofuels. We expect the subsidy and the carbon tax to have broadly similar impacts, provided that the tax is not set too high as to render crude oil resources indefinitely uneconomic to exploit.

In AppendixB.2, we show that under the assumption of linear demand as in proposition 1, the dynamic system for the fuel supply problem, can be solved to give the following expressions for the fuel price, biofuel supply, and crude oil supply:

[6]Note that the former channel was not present in the static specification of the biofuel production technology.

$$P_t = \frac{a\alpha\delta^2 e^{\delta t}}{a\delta^2 e^{\delta T} - \beta - \beta\delta T + \beta e^{\delta T}} \quad (12)$$

$$b_t = \frac{\alpha\left(-1 - \delta T + e^{\delta t} + \delta T e^{\delta t} - \delta t e^{\delta t}\right)}{a\delta^2 e^{\delta T} - \beta - \beta\delta T + \beta e^{\delta T}} \quad (13)$$

$$y_t = \frac{\alpha\left(a\delta^3 e^{\delta T} - a\delta^3 e^{\delta t} + \beta\delta^2 t e^{\delta t} - \beta\delta^2 T e^{\delta t} + \beta\delta e^{\delta T} - \beta\delta e^{\delta t}\right)}{\beta\delta\left(a\delta^2 e^{\delta T} - \beta - \beta\delta T + \beta e^{\delta T}\right)} \quad (14)$$

Note that T is endogenous and is determined by solving $\int_0^T y_t dt = R_0$. The fuel price is non-negative and we can infer that it rises monotonically. Moreover, observe that the smaller the subsidy on biofuels (the larger a is), the higher the fuel price. All else constant, the subsidy has a positive impact on biofuel supply but, can have either a positive or negative impact on crude oil supply. Since $\frac{\partial b_t}{\partial t} > 0$ and $\frac{\partial y_t}{\partial t} < 0$, we conclude that biofuel capacity is rising monotonically whereas crude oil production declines monotonically.

Consider the impact of the biofuel subsidy on the termination date. AppendixB.2 shows that $\frac{dT}{da} \gtrless 0$. $\frac{dT}{da} > 0$ when the discount rate is sufficiently low and the extraction duration is short. A high discount rate combined with a long extraction duration can give rise to $\frac{dT}{da} < 0$, however. These observations imply that a subsidy brings (pushes) the termination date closer (further away) if producers are patient (impatient) and if crude oil producers have a small (substantial) remaining resource stock. To the crude oil producer, a low discount rate means that late extraction is relatively as valuable as immediate extraction. A subsidy in this case markedly cuts into future earnings thus eliciting a stronger response to hasten extraction. If crude oil resources are abundant and the discount rate is sufficiently high, however, the exhaustibility rent, which is crucial for the green paradox result to occur, has a much smaller influence on the extraction path because of its smaller magnitude. Thus, the incentive for crude oil producers to hasten extraction is weaker and the surge in biofuel production may delay crude oil production.

Compared to proposition 1 where an announced subsidy depresses biofuel supply, in the current specification, it can actually boost it provided the direct impact of the announcement dominates the indirect impact that comes from crude oil producers expediting extraction. Moreover, delaying the implementation date of the mandate could expedite rather than delay crude oil supply. Proposition 2 (see AppendixB.2 for a formal proof) formalizes this observation:

Proposition 2. *In the model defined in Proposition 1, introduce a dynamic biofuel supply function as defined by the objective* (11) *and the capacity accumulation constraint* $\dot{b}_t = z_t$. *Then, for cost-less extraction of crude oil:*

(i) an announced subsidy can hasten the extraction of crude oil, but can also boost the

supply of biofuels in the premandate phase. The manifestation of the green paradox is, as such, contingent upon which of the two is the domineering effect.
(ii) delaying the implementation date increases the amount of crude oil extracted in the pre-mandating phase, but can also hasten the extraction of crude oil.

The predictions of proposition 2 become clear in the simulation results of section 5. The main takeaway from this section is that: when biofuel producers can be regarded as myopic as in Proposition 1, announced mandating targets give rise to a double green paradox. Delaying mandates in this case is beneficial, at least with regard delaying carbon emissions during the premandate phase. By contrast, when biofuel producers are forward-looking and have dynamic supply functions as in Proposition 2, outcomes can be very different from the static case. Announcing targets may or may not generate the green paradox. Furthermore, delaying mandates may worsen rather than mitigate the green paradox.

3. A model for the global oil market

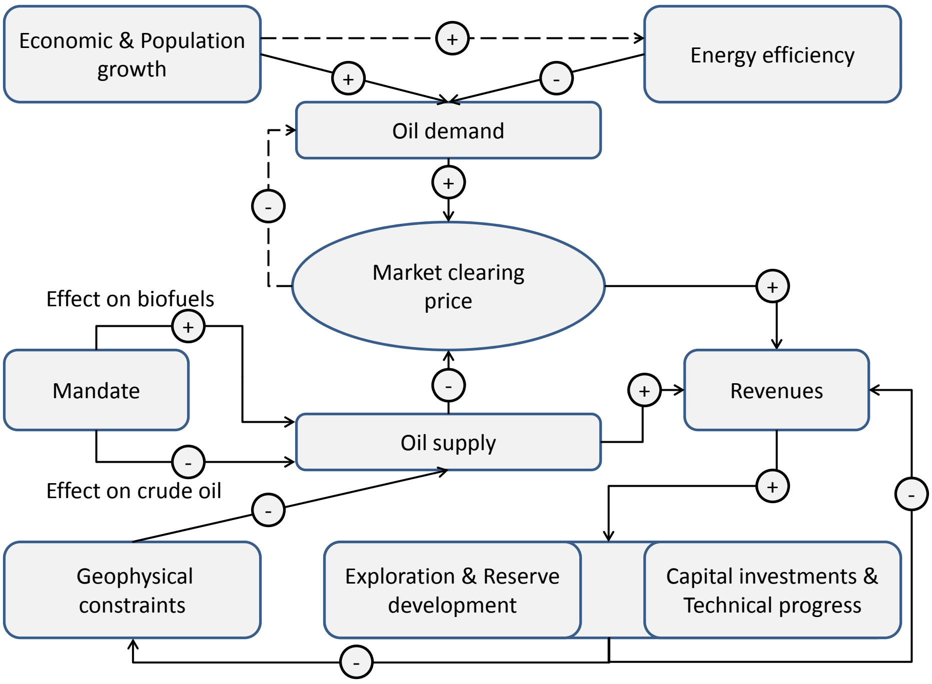

Figure 1: Overview of drivers and feedbacks in the global oil market model . The arrows point to the direction of influence, where “+” indicates a positive relationship between adjacent nodes all else constant, whereas “-” indicates a negative relationship, all else constant. The dashed lines indicate feedbacks that are captured exogenously through elasticities.

To obtain quantitative insights into the impacts of global biofuel mandating policies, we develop and simulate a calibrated model of the global oil market. Figure 1 summarizes the various drivers and feedbacks present in the model. The equilibrium price is market clearing in that it equates demand to supply. As such, oil is not inter-temporally arbitraged after it has been produced. A higher crude oil price implies higher revenues, which has a positive impact on reserve augmentation, and expansion of capacity. New reserve additions ease geophysical constraints which in turn boosts crude oil production. We assume that in the long run, costs can decline through learning by doing. In the short run, however, exploration, reserve augmentation, capacity expansion, and extraction are costly and therefore profit reducing.

At the time that a mandate comes into effect, biofuel supply is boosted while crude oil supply is suppressed. The ultimate impact on total oil supply depends on the type of mandate that is imposed. Share mandates reduce the total amount of oil consumed because the surge in biofuel supply typically fails to offset the policy induced reduction in crude oil supply. Conversely, a volume mandate increases total oil supply since it boosts biofuel supply while introducing no explicit policy on crude oil supply. On the demand side, economic growth, population growth, and the oil price are driving forces for changes in demand. The first two have positive impact on demand while the last has a negative impact. We assume that energy efficiency increases with economic growth (Medlock and Soligo, 2001). As such, while demand generally increases over time due to economic growth, it does so at a falling rate. When oil prices increase, through the price elasticity of demand, demand for crude oil falls.

The demand side is subdivided into two oil consuming regions: OECD and non-OECD. The supply side by contrast has eighteen crude oil producing regions, each extracting from either of six resources, and four biofuel producing regions. The eighteen crude oil producing regions include eleven OPEC regions: Algeria, Angola, Iran, Iraq, Libya, Kuwait, Nigeria, Qatar, Saudi Arabia, U.A.E, Venezuela (also includes Ecuador), and seven non-OPEC regions: Asia and the Pacific, Brazil, Europe, Former Soviet Union, North America, South and Central America, and Rest of the World. Each of these regions is capable of supplying (i) conventional crude oil, (ii) natural gas liquids, (iii) tar and bituminous sands, (iv) gas to liquids, (v) coal to liquids, and (vi) oil shales, provided it is economic to do so. The four biofuel supplying regions are: the United States (US), the European Union (EU) (mainly Germany and France), Brazil, and Rest of the world. We do not distinguish first from second generation biofuels but, model bioethanol and biodiesel supply separately. Next, we elaborate on the optimization program for the suppliers, those for the traders that link demand markets, and demanders are relegated to AppendixD.

3.1. Crude oil production

Let h denote the different types of crude oil, i be the index that identifies a crude oil producer, and j the index that identifies a demand market. At the evaluation period, k, the crude oil producer's objective is to choose a time path for oil shipments, y_{ijt}, extraction q_{iht}, reserve development x_{iht} and investments in new production capacity z_{iht}, such that discounted net present value profits are maximized:

$$\max_{\{y_{ijt},q_{iht},z_{iht},x_{iht},\}}\pi_{ik} = \int\limits_{t=k}^{t=T} \sum_{h}\left(\sum_{j} P_{jt}^{c}\left(\bullet\right) y_{ijt} - C^{q}\left(\bullet\right) - C^{z}\left(\bullet\right) - C^{x}\left(\bullet\right)\right) e^{-\delta^{c}(t-k)}dt \tag{15}$$

s.t.

$$\dot{R}_{iht} = x_{iht} - q_{iht} \tag{16}$$

$$\dot{K}_{iht} = z_{iht} - \varrho_{ih}K_{iht} \tag{17}$$

$$\dot{S}_{iht} = -x_{iht} \tag{18}$$

$$\sum_{h} q_{iht} = \sum_{j} y_{ijt},\ K_{iht} \geq q_{iht},\ \gamma_{ih}R_{iht} \geq q_{iht} \tag{19}$$

$$R_{ihk},\ S_{ihk},\ K_{ihk} > 0,\ R_{iht},\ S_{iht},\ z_{iht},\ K_{iht},\ z_{iht},\ q_{iht}\ \geq 0 \tag{20}$$

where $P_{jt}^{c}\left(\bullet\right)$is crude oil price in consumption region j, $C^{q}\left(\bullet\right)$ the cost of extraction, $C^{z}\left(\bullet\right)$ the cost of reserve development, and $C^{x}\left(\bullet\right)$ the cost of installing new capacity. Later, we explicate the functional forms for the demand and cost, but for now "•" symbolizes the set of variates that cause demand or costs to change. R_{iht} is the stock of developed reserves, K_{iht} the installed production capacity, and S_{iht} represents undeveloped reserves. δ^{c} is the discount rate used by crude oil producers, ϱ_{ih} the depreciation rate of installed production capacity such that $1/\varrho_{ih}$ gives the lifetime for a unit of capacity, and γ_{ih} is the intensity of geological constraints such that $1/\gamma_{ih}$ is the reserve to production ratio whenever the geological constraint binds.

Equation (15) is the objective function. Equation (16), (17), and (18), give the transition equations for developed reserves, capacity, and undeveloped resources, respectively. Reserves are augmented through additions, but are depleted through extraction. Capacity increases due to investments, but declines as a result of depreciation. Resources, on the other hand, monotonically decline by the amount that is developed and added to reserves. Provided in Equation (19) are the constraints ensuring that: (i) all extracted crude oil is shipped to demand markets, (ii) capacity is weakly greater than production, and (iii) geological constraints limit extraction to a fraction of the reserves base. Restrictions on initial values for reserves, resources, and capacity, and the non-negativity constraints on selected variables in the model are given in Equation (20).

The geological constraint warrants further explanation. As pointed in Okullo et al.

(2015), when the developed reserve base is initially small and reserve developments costs strictly convex, the geological constraint binds. That is, the geological constraint holds under mild regularity conditions. Production can then be shown to trace a hump shape, and price and the extraction rents an inverted hump shape even when both demand and technology are stationary. Our model as such can be calibrated to reproduce the long-run stylized facts about fossil fuel extraction under minimal assumptions. Stated differently, the geological constraints allows us to calibrate the model such that production responds more to geological constraints than to prices as reported in the empirical literature (Thompson, 2001; Adelman, 1990; Anderson et al., 2014; Cairns and Davis, 2001; Okullo and Reynès, 2011a; Black and LaFrance, 1998).

The cost function is strictly convex in extraction. It is specified such that the degree of convexity costs falls overtime as a result of (induced) technological progress. The intercept on marginal extraction costs is, however, specified so as to rise in the degree of resource depletion: $C^q\left(q_{iht}, \Phi_{iht}, K_{iht}\right) = \alpha_{0ih}\alpha_{1ih} \cdot q_{iht}^2 \cdot \left({K_{iht}}/{K_{iho}}\right)^{\beta_{1ih}} + \alpha_{0ih}\alpha_{2ih} \cdot q_{iht} \cdot \Phi_{iht} \cdot \left(1-\Phi_{iht}\right)^{-1/\beta_{2ih}}$ where $\alpha_{0ih}, \alpha_{1ih}$, α_{2ih}, $\beta_{2ih} > 0$, $\beta_{1ih} \leq 0$ are calibrated parameters and $\Phi_{iht} = \frac{R_{iho}+S_{iho}-(R_{iht}+S_{iht})}{R_{iho}+S_{iho}}$ tracks the state of depletion of the resource base[7]. The cost function says that whereas it gets more expensive to extract over time due to depletion of low cost reserves, it also gets cheaper to ramp-up extraction due to technological progress. Since conventional crude extraction is a relatively mature industry, however, $\beta_{1ih} = 0$ to reflect a maturation in learning opportunities. Conversely, we let $\beta_{1ih} < 0$ for unconventional crude oil, reflecting the potential for technologies such as hydraulic fracturing and horizontal drilling to enhance accessibility to such resources, above a cost threshold implied by the intercept on marginal extraction costs.

We choose cost functions for reserve development and capacity expansion to be of the same structure. $C^x\left(x_{iht}\right) = \alpha_{5ih} \cdot x_{iht} + \alpha_{6ih} \cdot x_{iht}^2$; α_{5ih}, $\alpha_{6ih} > 0$, is the cost function for reserve development, and $C^z\left(z_{iht}\right) = \alpha_{3ih} \cdot z_{iht} + \alpha_{4ih} \cdot z_{iht}^2$; α_{3ih}, $\alpha_{4ih} > 0$, is the investment cost function. We specify these costs as strictly increasing to capture the notion that revenue expenditures have an opportunity cost, so that reserve development or capacity expansion must be directed to the most productive sites first. Depletion and technological progress are not introduced in these specifications, because of the limited empirical information on how such aspects might affect these costs over time.

We model OPEC and non-OPEC behavior differently. A cartel versus fringe framework, similar to that of Salant (1976) is adopted. That is, non-OPEC producers act competitively. They take the price path as given when choosing their activity levels. Conversely, OPEC producers are assumed to act as price setters in that they know the

[7]The state of depletion captures the fact that extraction progresses from low to high costs reserves.

form of the demand function, and therefore choose extraction with the knowledge that their supply decision affects the global crude oil price. The model is setup to be flexible so that OPEC producers can either be represented as a monopoly or Cournot-Nash oligopolies[8]. Because OPEC producers are strategic, we must choose an information structure. We restrict the analysis to open-loop strategies (Long, 2010; Dockner et al., 2000). These assume that producers' choices can be recovered as function of time and the initial state alone. Such strategies are know for their computational convenience relative to subgame strategies that assume actions are function of observed states each point in time.

3.2. Biofuel production

Bioethanol and biodiesel production are both modeled. Since biofuel production is likely to be spread across multiple countries, the exercise of market power by any single producer is not probable. Thus, we assume that biofuels are marketed competitively. Let g be the index for biofuel type, the i'th biofuel producer's problem is to choose the optimal time path for shipments, b_{ijt}, production, q_{igt}, and the expansion of processing capacity, z_{igt}, so as to maximize net profits over t, $t \in [k, \infty)$:

$$max_{\{b_{ijt},q_{igt},z_{igt}\}}\pi_{ik} = \int_{t=k}^{t=\infty} \sum_g \left(\sum_j P^b_{jt}(\bullet)\, b_{ijt} - W^q(\bullet) - W^z(\bullet) \right) e^{-\delta^b(t-k)} dt \tag{21}$$

s.t.

$$\dot{K}_{igt} = z_{igt} - \varrho_{ig} K_{igt} \tag{22}$$

$$\sum_g q_{igt} = \sum_j b_{ijt},\ K_{igt} \geq q_{igt} \tag{23}$$

$$K_{igk} > 0,\ I_{igt},\ K_{igt},\ q_{igt} \geq 0 \tag{24}$$

where $P^b_{jt}(\bullet)$ is the biofuel price per barrel of oil equivalent (boe) in region j, $W^q_{igt}(\bullet)$ is the cost of biofuel production, and $W^z_{igt}(\bullet)$ is the cost of biofuel capacity expansion. δ^b is the discount rate for biofuel production, which can be different than that for crude oil extraction. Equation (21) is the objective function and (22) is the transition equation for biofuel capacity. Equation (23) gives the restriction that all produced biofuels are shipped to market, and that capacity is weakly greater than production. By contrast, (23) gives the standard periodical constraints governing capacity and production.

[8]Please refer toOkullo and Reynès (2011b) for details on this specification

$W^q\left(q_{igt}, K_{igt}\right) = \alpha_{7ig}\left(\alpha_{8ig} \cdot q_{igt} + \alpha_{9ig} \cdot q_{igt}^2\right)\left(\frac{K_{igt}}{K_{ig0}}\right)^{\beta_{3ig}}$ where α_{7ig}, α_{8ig}, $\alpha_{9ig} > 0, \beta_{3ig} < 0$ is the functional form for the cost of producing biofuels. The parameter α_{7ig} is used to calibrate the cost function such that base year production matches observed base year production. Costs are quadratic in the level of extraction implying that marginal costs are higher at higher levels of production. We specify that costs decline with technological progress, which lowers both the intercept and slope of the marginal cost function. Such an aggressive assumption for costs declines is in line with predictions that the biofuel industry is likely to experience dramatic declines in both average as well as marginal costs over the coming years (Mandil and Shihab-Eldin, 2010; IEA, 2008; Kahouli-Brahmi, 2008). For the same learning rates as in the unconventional crude oil case, where the learning rate is given by$1 - 2^{\beta}$ for β the learning exponent, marginal costs for biofuel production fall much faster. We therefore expect biofuels to steal an increasingly larger share of the market vis-à-vis unconventional crude oil.

The costs of expanding biofuel production capacity is: $W^z\left(z_{igt}, K_{igt}\right) = \alpha_{10ig} z_{igt} + \alpha_{11ig} \cdot z_{igt}^2 \cdot \left({K_{igt}}/{K_{ig0}}\right)^{\beta_{4ig}}$ where α_{10ig}, α_{11ig}, $\beta_{4ig} > 0$. Observe that it becomes more costly to expand capacity as the industry matures. This specification is based on the premise that marginal lands on which to grow and obtain biomass will become increasingly scarce as the industry grows. Moreover, if first generation biofuels continue to remain a substantial part of the supply profile, biofuels will compete with food for biomass inputs. At the same time, even if the future production profile shifts towards second generation biofuels, relatively more expensive and sophisticated technologies will need to deployed. The specified cost function as such attempts to capture these dynamics.

4. Calibration and scenarios

This section presents the data used to calibrate the model and sets out the simulation scenarios. First we describe the data and then give a description of the scenarios deployed in the model.

4.1. Calibration data

Conventional crude oil, natural gas liquids, tar and bituminous sands, gas to liquids, and coal to liquids resource data is obtained from USGS (2000), IEA (2010), and WEC (2010) where the p5 estimates — see Table C.4 — are used in the main simulations. Oil shale resource estimates are obtained from Dyni (2006), IEA (2010), WEC (2007), and WEC (2010). Crude oil production data, proven reserves data[9], and biofuel production

[9]To capture the impacts of geological constraints as explained in Okullo et al. (2015), we calibrate initial developed reserves, R_{ihk}, such that producers with a proven reserves to production ratio of less than or equal to 10, as of 2005, have 100% of their 2005 proven reserves in their initial developed reserves.

data are from BP (2009) and EIA (2012). Conventional crude oil production costs are obtained from Rogner (1997), WEC (2007), and Aguilera et al. (2009), while unconventional crude oil production costs are from WEC (2007) and IEA (2010), and biofuel production cost data from IEA (2007, 2008, 2011) and Mandil and Shihab-Eldin (2010). Investment cost, and exploration and reserve development cost data is obtained from IEA (2010), EIA (2011), and Brandt (2011). Base year capacities are set at 2% higher than the base year production level, while depreciation rates for crude oil (biofuels) are set at 5% (2%). In the baseline simulations, the depletion rate, γ, is set to 10%, and a uniform discount rate of 5% is used for all producers, transporters, and consumers.

Every doubling of capacity reduces costs by 2^{β}, where β is the learning elasticity defined in section 3. The Learning Rate (LR) is obtained as: LR $= 1 - 2^{\beta}$, where LR defines the percentage reduction in costs for every doubling in capacity.[10] McDonald and Schrattenholzer (2001) and Kahouli-Brahmi (2008) are the source for our learning rates. They state learning rates for ethanol of 20% to 22% , and learning rates for unconventional crude oil of 21%. For simplicity, we use one learning rate of 20% for both resources. Recall, however, that costs for biofuel production fall much faster since learning reduces both the level and slope of the marginal cost curve, as opposed to only the slope in the case of unconventional crude oil. Since we specify that costs of expanding biofuel capacity increase in capacity and without a measure of this value available from the literature, we make use of an ad hoc procedure to find the appreciation exponent, β_{4ig}. We set β_{4ig} such that the model's reference simulations match the IEA (2014) prediction of approximately 3.4 million barrels daily of oil equivalent (mbdoe) in the year 2035.

The demand function takes the form $Q_{jt} = A_j \mathcal{P}_{jt}^{\varepsilon_j} Y_{jt}^{\eta_{j,1}+\eta_{j,2}\cdot logY_{jt}}$ where, Q_{jt} is the sum total of crude oil and biofuel consumption in region j at time t, A_j is autonomous demand and Y_{jt} is regional Gross Gomestic Product (GDP). ε_j (< 0) is the price elasticity of demand for oil, $\eta_{j,1}$ (> 0) is the income income elasticity, and $\eta_{j,2}$ (< 0) calibrates energy efficiency. Economic growth accentuates energy efficiency, such that crude oil demand per unit of output is falling overtime all else constant. Data used to parameterize the demand

Those with a proven reserves to production ratio of greater than 10 but less than or equal to 20, we specify that these have 70% of their 2005 proven reserves in their initial developed reserves. Finally, for those with a proven reserves to production ratio of greater than 20, these are assumed to have 40% of their 2005 proven reserves in their initial developed reserves. The remaining proven reserves are added back to initial resources, S_{ihk}. These adjustment are made in order to capture the fact that not all proven reserves are developed reserves. Moreover, we adopt these simplified assumptions because coherent data for a country by country assessment on the share of developed reserves in proven reserves are nonexistent and are often confidential.

[10]The LR allows us to compute the learning exponents, β_{1ih}, β_{3ih}, (i.e. the elasticities of learning by doing) based on the formula $\beta_{1ih}, \beta_{3ih} = \frac{\ln(1-\text{LR})}{\ln(2)}$. Recall that for the case of conventional crude oil, we assume that no learning takes place (lr=0%); this is equivalent to having $\beta_{1ih} = 0$.

function are as follows. GDP data is obtained from IIASA (2009) where we use their medium growth projections. Income and demand elasticity estimates are from Dahl and Yücel (1991) and Griffin and Schulman (2005), whereas energy efficiency coefficients are from Medlock and Soligo (2001). Income elasticity, energy efficiency, and price elasticity coefficients are specified as: $\eta_1 = \{0.56, 0.53\}$, $\eta_2 = \{-0.2, -0.1\}$, $\varepsilon = \{-0.7, -0.4\}$, with the elements in each curly bracket representing OECD and nonOECD coefficients, respectively.

The model is simulated over the period 2005 to 2150 in 5 year time steps. However, policy simulations are performed from 2015 on wards with the period 2005 to 2015 being used to evaluate the model's performance in reproducing observed supply trends. The model matches global production closely, but has trouble reproducing producer specific patterns. Regions whose production the model under predicts in the year 2015 include: North America (by 5 mbd), Brazil (by 1.8mbd), Iraq (by 1.6 mbd), and Qatar (by 0.8 mbd). Those regions whose production the model over predicts include: Western Europe (by 2 mbd), Venezuela (by 0.8mbd), Saudi Arabia (by 1.2mbd), Iran (by 1mbd), Former Soviet Union (by 1 mbd), UAE (by 0.8 mbd), and Libya (by 1.2 mbd). One of the reasons for these divergences is that the model is not designed and calibrated to match the impact of geopolitical shocks[11] that have led to wild swings in the oil price and can incentivize reserve development in ways that the model in its current form does not capture. The other is that the current calibration is static, based only on the requirement that model match 2005 observed production. Future extensions will focus on calibrating the model to match impacts from geopolitical shocks, introducing a short-run demand specification to better capture the impact of geopolitical shocks, and calibrating the production cost function dynamically to match production at two different observation points. Our current results should therefore be interpreted in a model-specific context.

4.2. Simulation scenarios

Nine policy scenarios are setup to explore how different mandating designs may influence the likelihood and size of the green paradox. Additional simulations are performed as a sensitivity analysis to investigate how alternative parametric and structural assumptions change the baseline outcome. Next, we describe the seven policy simulations. The supplementary simulations are discussed in the simulation results of section 5.

Table 1 presents the nine policy scenarios. While EU targets have been set for 2020 and US targets for 2022, in the model we assume that targets do not come into effect until 2025. This gives producers in the model a reaction period of ten years, which more

[11]During 2010 to 2014 the oil price averaged nominal US $100, due strong oil demand from China before 2011, the Libyan civil war since 2011, and sanctions on Iran since 2012.

Table 1: Policy simulations in each scenario set.

Policy scenario	OECD mandate		
	2025	2035	2045
REF	N/A	N/A	N/A
OECD I SHR	10%	10%	N/A
OECD II SHR	10%	20%	N/A
OECD III SHR	N/A	20%	N/A
OECD IV SHR	10%	20%	40%
OECD I VOL	based on **OECD I SHR** biofuel volumes in 2025		
OECD II VOL	based on **OECD II SHR** biofuel volumes in 2025 and 2035		
OECD III VOL	based on **OECD III SHR** biofuel volumes in 2035		
OECD IV VOL	based on **OECD IV SHR** biofuel volumes in 2025, 2035 and 2045		

or less matches the time length from when US mandates (2007) and EU mandates (2009) were first announced to when they are due to come into effect. For REF, no mandating target is imposed. In this case, the penetration of biofuels on to the global oil market is determined solely by demand and supply. The REF policy is the benchmark against which we evaluate the impacts of biofuel mandating. By comparing crude oil production in the REF simulation to that in the mandating policy simulations during the pre-mandate phase, we can examine the likelihood and magnitude of the green paradox. The eight mandating policy simulations are labeled "OECD I SHR/VOL," "OECD II SHR/VOL," "OECD III SHR/VOL" and "OECD IV SHR/VOL." SHaRe (SHR) mandates target the fraction of biofuels in total oil supply, whereas VOLume (VOL) mandates target the volume/quantity of biofuels produced. Since the model is specified with only two demand regions, we assume that targets are imposed in all OECD countries as opposed to the US and EU alone. Future versions of the model will consider further disaggregating the demand side.

"OECD I SHR," is inspired by the EU 2020 mandating strategy that imposes a 7% minimum share for biofuels in transportation by 2020. Considering that our model implements the mandating requirement five years later, i.e., in 2025, we set the target in our model to 10%, instead. "OECD II SHR," assumes that in supplement to the "OECD I SHR" target, a new target of 20% biofuel share is set for 2035. This specification explores the impacts of announcing a series of progressively stringent mandating targets. "OECD III SHR," on the other hand, explores the consequences of delayed mandating as it excludes the 2025 mandating requirement and only considers the 2035 requirement. Finally, "OECD IV SHR" investigates the impacts from stringent and delayed mandating targets. More specifically, in addition to OECD II mandating targets, biofuels are targeted for a 40% share in OECD oil consumption by 2045. By comparing OECD IV to OECD II, we can isolate the impact of delayed but stringent mandating targets.

The volume mandating approach follows the US strategy. US targets specify 36 billion gallons of biofuel supply by 2022. Instead of ad hocly imposing a volume target, we set volume mandates to the levels achieved in the corresponding share mandating representations. This makes the SHR and VOL volume mandating requirements comparable, at least in terms of the attainable supply for biofuels. In both SHR and VOL mandating, we specify that once a target comes into effect, it remains in place for the indefinite future. This, however, does not mean that the target needs to be supported with a subsidy or tax forever. Indeed, we observe in our simulations that targets become self-sustaining on average within 20 years of the mandating requirements coming into effect.

5. Simulation results

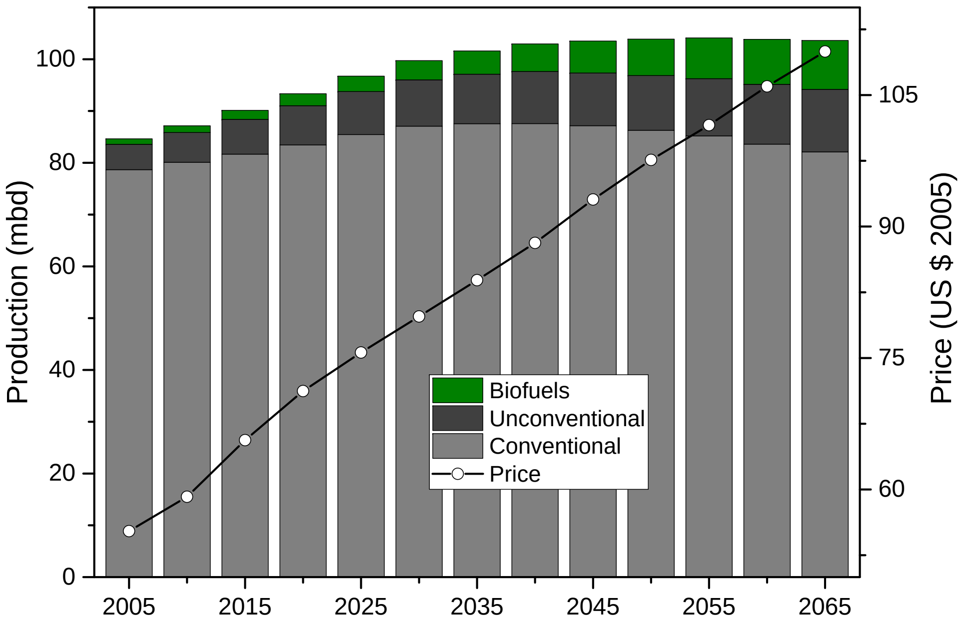

Figure 2: Global oil production and global oil price in the REF scenario.

Figure 2 presents the baseline REF scenario. Demand and the exhaustion of cheap oil reserves together explain the change in the oil price which rises from US dollars 55.21 in 2005 to US dollars 110.18 in 2065.[12] Because the model is designed to represent long run

[12]Running the model with median (50p) rather than the optimistic (5p) USGS (2000) estimates for endowments of conventional crude oil resources results in a higher price of US$ 135 in 2065. Additionally assuming a monopoly OPEC further jacks up the price to US$ 162 in 2065.

drivers and does not include uncertainty, price does not exhibit jumps that are observed in practice.

Rising demand explains the increase in global oil supply from 82.9 million barrels daily (mbd) in 2005 to a peak level of 104 (mbd) in 2055. Global production declines thereafter due to increasing efficiency in oil use and increased depletion in Europe, Asia and the Pacific, South and Central America, Algeria, and Angola. Because of vast holdings of tar sand resources, crude oil production in North America increases gently as tar sands are brought on board to replace declining production of North American conventional crude oil. This nearly doubles the share of unconventional crude oil in global crude oil production from 5.8% in 2005 to 11.7% in 2065.

Biofuel production also rises overtime, and by 2040 when global crude oil supply peaks, biofuels meet 6.07% of global oil consumption needs, as compared to just 1% in 2005. By 2065, the biofuel share further rises to 9.5% of global oil consumption. The significant expansion in biofuel production is brought about by declining marginal production costs that are experienced as result of technological progress. The policy scenarios which we shall discuss next reveal that mandating targets moderately increase the 2065 share of biofuels in global oil production. They, however, substantially accentuate the composition of biofuels in the global oil supply in the early years.

5.1. Main results

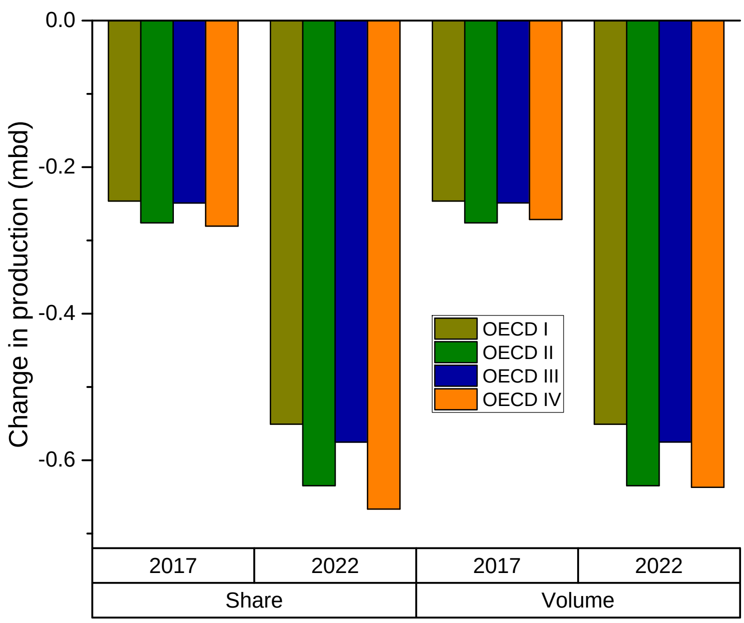

Figure 3: Crude oil production in the baseline policy scenarios differenced from that in the baseline REF scenario. Since the model is run every five years, each indicated year should be interpreted as an average for the periods, 2015 to 2019, and 2020 to 2024.

The main simulations results are as follows:

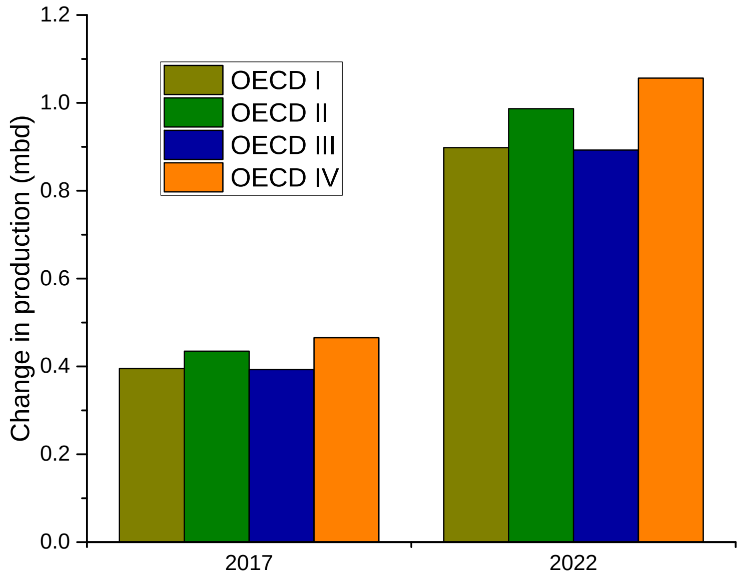

Figure 4: Biofuel production in the baseline policy scenarios differenced from that in the baseline REF scenario.

1. Figure 3 shows the change in crude oil production, obtained by subtracting production in the policy scenarios from that of the REF scenario. Notice that there is no green paradox as the announced mandating targets lead to a reduction in premandate crude oil extraction. From proposition 1 and 2, we know that crude oil producers are incentivized to accentuate extraction in response to preannounced mandating targets. When biofuel producers are forward looking, Proposition 2 states that they too are incentivized to hasten capacity build up. This increases premandate biofuel supply, which for our calibrated model is shown in Figure 4. The increase in this calibrated case manages to offset a would be increase in premandate crude oil supply thus explaining the green orthodox result. We see that during the first decade, the average reduction in crude oil production is 0.4 mbd, which is about 0.62 gigatonnes of carbon, while the surge in biofuel production amounts to about 0.6 (mbd).
2. We carry out a sensitivity analysis (details below) and observe that the green paradox can arise under two conditions: a low discount rate for crude oil production and a high discount for biofuel production. Figure 5 and 6 show the outcome from setting the crude oil discount rate at 1.5% and the biofuel discount rate at 10%.[13] Notice that the likelihood of a green paradox increases, and in fact the green paradox arises in the OECD IV SHR simulation where crude oil production increases by

[13]We also adjust the learning rate for biofuel production, β_{3ig}, such that the global share of biofuels in the REF simulation of this scenario matches that in the baseline REF at all t.

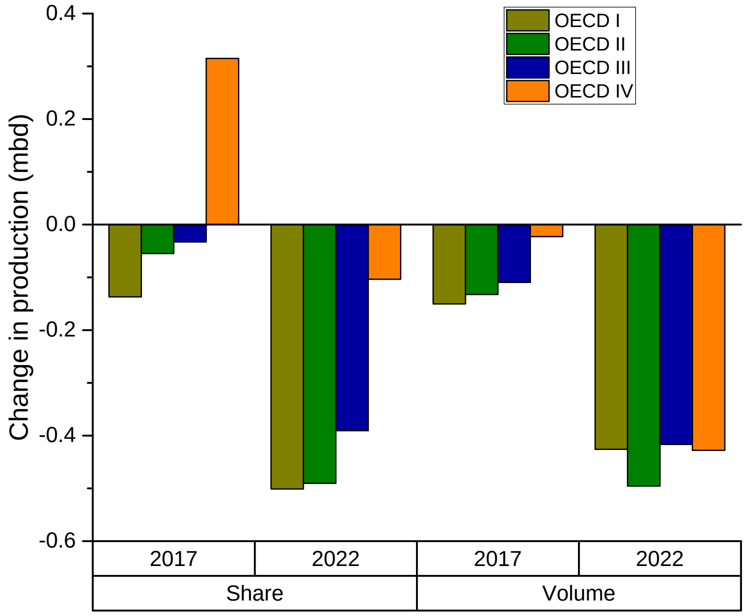

Figure 5: Crude oil production in policy scenarios with the crude oil and biofuel discount rate set at 1.5% and 10%, respectively, differenced from the corresponding REF scenario production.

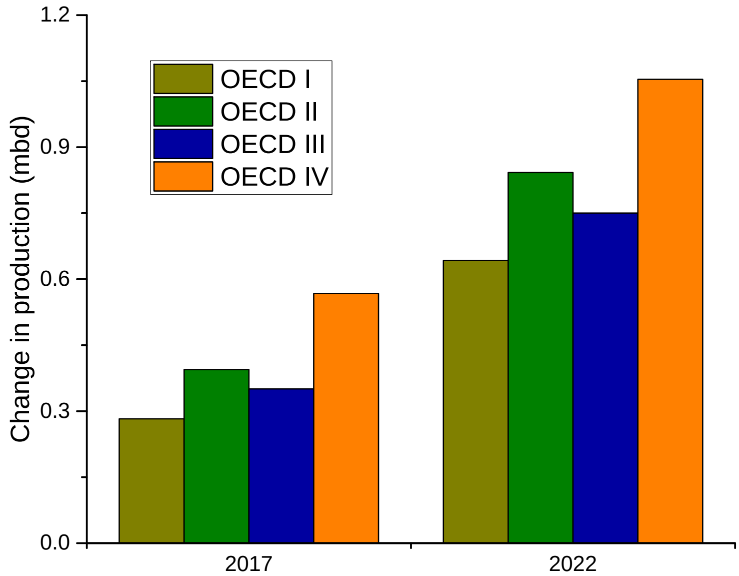

Figure 6: Biofuel production in policy scenarios with the crude oil and biofuel discount rate set at 1.5% and 10%, respectively, differenced from the corresponding REF scenario production.

0.3 mbd. Three observations emerge.

(a) Share mandates are more likely to lead to a green paradox than volume mandates. This is based on the fact that share mandates impose a tax on crude oil production which directly cutbacks on fossil production during the mandate phase. Such a tax provides a stronger incentive for crude oil producers to expedite extraction relative to volume mandating that only relies on subsidies.

(b) Comparing OECD II to OECD III, we see that longer pre-implementation phases increase the likelihood of the green paradox and at the same time weaken the incentive for biofuel producers to boost capacity. This indicates that the key to an effective mandating strategy is to ensure that biofuel production is boosted early rather than late.

(c) Commitment to a timely series of mandating targets, rather than single ambitious mandating target, boosts investments in biofuel capacity. Yet, these commitments have little impact on increasing the likelihood of the green paradox. Instead, the likelihood of the green paradox is driven by the first two factors above: the perceived stringency of the mandating target on crude oil producers and the length of the premandating phase.

The mechanisms that lead to the green paradox above are as follows. Firstly, a lower crude oil discount rate induces crude oil producers to place a non-trivial weight on future extraction. More specifically, it tilts the shadow value of the resource stock in the initial years upwards while tilting it downwards in later years. This creates a flatter time path for the shadow value of the resource stock which leads to a more conservationist extraction schedule. In this setting, mandating targets have stronger negative impact on late extraction which strengthens the incentive for crude oil producers to expedite extraction.

Secondly, the discount rate affects the biofuel and crude oil producers differently because of the exhaustibility of crude oil reserves in the latter. Increasing the biofuel discount rate increases the user cost of capacity. This makes investments in biofuel capacity more costly which strengthens the incentive to delay capacity expansion. As such, more substantive taxes on crude oil production and subsidies on biofuel production must be introduced in order stimulate the latter's supply. Unfortunately this induces crude oil producers to expedite extraction leading to the green paradox.

5.2. Sensitivity analysis

Table 2 and 3 gives the percentage change in crude oil production for selected sensitivity runs. Results for OECD III and IV are presented as these are the only policy scenarios for which we observe a green paradox in at least one of the sensitivity simulations. The indicated change in production is calculated by differencing crude oil production obtained in the mandating simulation run from that in the corresponding REF simulation. We observe that pre-mandate production declines in all but two cases, both indicated in bold. These are the case with a low (1.5%) discount rate for crude oil production and that with a high discount rate (10%) for biofuel production. Next we elucidate each outcome.

The case "No Bio. technical progress" specifies there to be no learning by doing in biofuel production. As such, biofuel producers do not enjoy the benefits of falling

Table 2: Change in crude oil production for OECD III policy scenario relative to the corresponding REF scenario.

	Share		Volume	
	2017	2022	2017	2022
baseline	-0.273	-0.667	-0.273	-0.635
No Bio. technical progress	-0.273	-0.670	-0.273	-0.638
1.5% crude discounting	-0.042	-0.542	-0.132	-0.586
10% biofuel discounting	**0.034**	-0.090	**0.017**	-0.054
2×baseline price elasticity	-0.190	-0.471	-0.179	-0.414
No fuel efficiency	-0.186	-0.458	-0.184	-0.433
1.5×income elasticity	-0.137	-0.343	-0.137	-0.326
Monopoly OPEC	-0.201	-0.488	-0.197	-0.451
Tighter geological constraints	-0.331	-0.788	-0.301	-0.680
Hotelling depletion	-0.245	-0.638	-0.271	-0.668
No economic depletion	-0.301	-0.728	-0.300	-0.693
USGS p50 reserves	-0.096	-0.260	-0.102	-0.256

*Global biofuel share in the SHR mandating scenario. That in the VOL mandating scenarios is typically a few percentages lower.

Table 3: Percentage change in crude oil production for OECD IV policy scenario relative to the corresponding REF scenario.

	Share		Volume	
	2017	2022	2017	2022
baseline	-0.273	-0.711	-0.310	-0.741
No Bio. technical progress	-0.276	-0.727	-0.315	-0.754
1.5% crude discounting	**0.513**	-0.047	**0.020**	-0.536
10% biofuel discounting	-0.073	-0.982	-0.061	-0.738
2×baseline price elasticity	-0.216	-0.576	-0.233	-0.542
No fuel efficiency	-0.185	-0.491	-0.211	-0.512
1.5×income elasticity	-0.130	-0.366	-0.157	-0.393
Monopoly OPEC	-0.165	-0.460	-0.211	-0.505
Tighter geological constraints	-0.338	-0.841	-0.352	-0.808
Hotelling depletion	-0.242	-0.734	-0.324	-0.831
No economic depletion	-0.281	-0.735	-0.329	-0.783
USGS p50 reserves	-0.074	-0.269	-0.112	-0.307

*Global biofuel share in the SHR mandating scenario. That in the VOL mandating scenarios is typically a few percentages lower.

production costs whereas unconventional crude oil producers still do. Nachtigall and Rübbelke (2016) have shown in a two period model that the anticipated benefits of learning by doing may induce biofuel producers to increase production and thus crowd out crude oil production. Less learning would therefore accentuate the green paradox. We observe in Tables 2 and 3, that learning by doing makes little difference if any in changing the baseline results. Expectation formation in biofuel production thus appears to be the more critical factor in mitigating the green paradox.

"1.5% crude discounting" sets the crude oil discount rate to 1.5% from 5%. As explained before, lower discount rates cause crude oil producers to place a larger weight on future crude oil production, thus increasing their incentive to hasten extraction in event of a preannounced policy. We see in the Tables that the green paradox arises under the OECD IV specification and, its likelihood to occur increases under the OECD III specification. These results indicate that when crude oil producers are patient, the occurrence of green paradox increases in both the stringency of the mandating target and the length of time between announcement and when the stringent target first comes into effect. Over the long-run, stringent policies may boost the share of clean energy in the market — in our simulations, biofuels reach a 15% global fuel share in 2065 under the OECD IV mandating scenario, as compared to 10% in the OECD I/II/III scenarios — but when these targets are delayed, they carry the risk of causing the green paradox.[14]

"10% biofuel discounting" can be compared to a situation where investing in biofuel capacity is perceived as risky and therefore producers demand an appreciably high rate of return. Subsidies as well as taxes need to be set at much higher levels in order to incentivize biofuel production. What is interesting to note from the sensitivity simulations is that the green paradox occurs in Table 2, but not in Table 3 although the likelihood of the green paradox is observed to increase. Unlike the case of low crude oil discounting where strict but delayed mandates can undo the benefits of early mandating, here, the mere act of delaying mandates induces the green paradox. We can deduce, therefore, that the centerpiece for an effective mandating strategy is early rather than delayed mandating, especially if regulators will need to deploy stringent targets.

Changing the price elasticity of demand results in only a marginal change in the results when evaluated against the baseline outcome. An elastic demand curve means that a small change in price results in a more than proportionate change in quantity demanded. As such, crude oil producers are more willing to hasten extraction since future mandating requirements lead to pronounced changes in prices and hence profits. As Tables 2 and 3

[14]In the literature, it has been argued that OPEC countries extract with low discount rates (Adelman, 1986). Our results therefore advise that regulators give more weight to prompt mandating (no matter how small the targets) and move away from delayed and ambitious policy designs.

show, however, doubling the price elasticity of demand negligibly increases the likelihood of the green paradox. In more simplified models, Grafton et al. (2012); van der Ploeg (2016) observe that a more elastic demand leads to the green paradox. While their results do share directional impacts with ours, our model calibrated to global data and with expectation formation on the part of biofuel producers, suggests little evidence for concern over the green paradox.

"No fuel efficiency" and "1.5×income elasticity" can be explained together. In both cases, future fuel demand is more persistent compared to the baseline scenario. In the "No fuel efficiency" case, we assume that growth in GDP does not result in energy efficiency. That is, in the demand function $\eta_{j,2} = 0$. Conversely, in the "1.5×income elasticity" case, we increase the baseline income elasticities by fifty percent meaning that fuel demand becomes more or less perfectly correlated with GDP. We see from Tables 2 and 3, that in both cases, crude oil producers are less willing to make cuts when compared against the baseline. The outcomes are not sufficient to cause concern about the green paradox arising, however. The intuition for this result is that resilience in future demand makes biofuels more competitive as the fuel price is higher than in the baseline. Any intervention to support biofuels would thus give crude oil producers a stronger incentive to hasten extraction.

"Monopoly OPEC" pricing has OPEC act as if it were a single producer with multiple deposits (in different nations) from which to extract. This change in structure drives the oil price higher as OPEC imposes a larger mark-up when setting the crude oil price. Higher prices, similarly to the "No fuel efficiency" and "1.5×income elasticity" case above, makes biofuels more competitive in the long run thus, giving OPEC and non-OPEC producers a stronger incentive to hasten extraction in event of preannounced mandating requirements. This outcome is evident in Tables 2 and 3 where less pronounced reductions in production than in the baseline are evident. In spite of the directional impacts, the model does not predict a green paradox. This is in contrast to van der Ploeg and Withagen (2012a) who find a green paradox for this case. Their model considers a perfect backstop and does take into account strategic interactions between dirty and clean energy producers, however. As such there specification will amplify the likelihood or occurrence of the green paradox, relative to ours.

"Tighter geological constraints" and "Hotelling depletion" can be explained together, as well. With the former the geological parameter γ_{ih} is changed from its baseline value of 0.1, which corresponds to a reserve to production (R/P) ratio of ten, to a value of 0.05 which corresponds to an R/P ratio of twenty. With an R/P ratio of twenty, producers must maintain reserves of at least twenty years, when measured against current production, in order to sustain extraction. By contrast, the "Hotelling depletion" specification is at the other extreme as it imposes no such geological constraint although producers still have to engage in reserve development. Clearly, crude oil exploitation will be more costly in the former since since crude oil producers must maintain a much larger reserve base and thus explore more actively. Since present reserve development depends on the future earnings stream, an announced policy that decreases the stream of earnings will reducing exploration and reserve development activity, thus reducing the likelihood of the green paradox. The opposite explanation applies for the "Hotelling depletion" path. Although there is no equivalent of this result in literature, we can draw similarities with Österle (2016) who finds that introducing exploration to the classical Hotelling model decreases the likelihood of the green paradox.

Excluding economic depletion, i.e., costs that rise with depletion of reservations, from the crude oil production function results in only marginal changes differences with the baseline outcome. Indeed, we would not expect this feature to change the likelihood of the green paradox since its effects are felt mostly on the total amount of crude oil that is eventually extracted than the the amount that is hastened (see e.g., Gerlagh, 2011; van der Ploeg and Withagen, 2012a; Grafton et al., 2012).

Finally, the impact of a smaller reserve base, which we investigate by setting the ultimately recoverable reserves to USGS p50 reserves — see Table C.4 — is that it increases the likelihood of the green paradox. A smaller crude oil reserve base raises the in situ value the resource, leading to a higher oil price that also rises faster over time. Similarly to the "OPEC monopoly," "No fuel efficiency," and "1.5×income elasticity" cases, the higher price makes biofuels more competitive. As such, a mandating policy that will make biofuels even more competitive, will inducescrude oil producers to hasten extraction, thus increasing the likelihood that the green paradox occurs. For our specification, however, the green paradox does not arise, despite the likelihood of its occurrence increasing when evaluated against the baseline results.

6. Conclusion

Sinn (2008, 2012) puts forth an argument that carbon producers may hasten extraction in response to (pre)announced demand-side carbon management policies, such as, subsidies for renewables, efficiency standards, carbon taxation, or mandating targets. Considering the paucity of data to empirically evaluate the quantitative significance of the green paradox, this paper has developed a detailed numerical model of the global oil market to provide insights on the issue. The policy instrument of choice for our analysis has been the recently announced EU and US biofuel mandates. Several key aspects that may facilitate or impede the green paradox have been investigated: the design of the mandate, learning-by-doing in biofuel technology, the discount rate, the elasticities of demand for oil, fuel efficiency, future energy demand prospects, OPEC behavior, the intensity of geological constraints, and the crude oil resource endowment.

In contrast to the previous literature, this paper has introduced forward looking behavior through capacity accumulation on the biofuel side of the market. It has been shown that in this environment, the green paradox can be mitigated. And, in many of the empirically relevant cases, preannounced carbon policies result in a green orthodox rather than a green paradox. While forward looking behavior is in itself sufficient to mitigate to the green paradox, the analysis points to early, rather than delayed mandating as being the key mechanism through which the green paradox can be curbed or mitigated. We find that the mere act of delaying mandating can result in a green paradox if biofuel producers' discount rates are high enough. Furthermore, stringent and delayed preannounced mandating targets can result in a green paradox if crude oil producers have sufficiently low discount rates, and this may undo the benefits of earlier mandating targets.

For preannounced EU 2020 and US 2022 style mandating targets, we find that oil production falls by 0.3 percent in the ten years before the mandating targets come into effect. This is in contrast to positive leakage rates that are simulated in the literature. The critical difference between our model and those in literature investigating the green paradox is that we accommodate for forward looking behavior on the clean side of the market. While the model has been applied only to the oil market, the results have wider implications for other sectors of the energy industry. We also find only marginal differences between share and volume mandating targets. Major and moderate differences arise only when mandates are delayed and strict, in which case share mandates are more likely than volume mandates to lead to a green paradox. In the long run, mandates irrespective of type of mandating strategy have a positive impact on the share of biofuels in global oil production. We find that mandates increase the 2065 global biofuels share to between 10 to 15 percent, compared with the 5 percent obtained in the reference simulation without mandating policy.

Future extensions to this work might consider the impacts of biofuel mandates when biofuels and crude oil are imperfect substitutes. Moreover, incorporating land use emissions from biofuels and modeling different emissions intensities for crude oil could place the research in a wider context. Whereas welfare effects have not been investigated in our analysis, Greaker et al. (2014) offers a perspective on the issue. We expect the following. First, total welfare is higher under share mandating than under volume mandating. Second, the crude oil producer surplus is higher under volume mandating than under share mandating. Third, biofuel producers' surplus is higher under share mandating policy. Finally, consumer surplus is higher under volume than under share mandating. Future work could verify these conjectures. Whether these policies are welfare enhancing is another issue that can be investigated in future research.

AppendixA. References

Adelman, M.A., 1986. Oil producing countries' discount rates. Resources and Energy 8, 309 – 329.

Adelman, M.A., 1990. Mineral depletion, with special reference to petroleum. The Review of Economics and Statistics 72, 1–10.

Aguilera, R.F., Eggert, R., C.C., G.L., Tilton, J., 2009. Depletion and the future availability of petroleum resources. The Energy Journal 30, 141–174.

Allaire, M., Brown, S.P., 2015. The green paradox of us biofuel subsidies: Impact on greenhouse gas emissions. Economics of Energy & Environmental Policy 4.

Anderson, S.T., Kellogg, R., Salant, S.W., 2014. Hotelling under pressure. Technical Report. National Bureau of Economic Research.

Benchekroun, H., Halsema, A., Withagen, C., 2009. On nonrenewable resource oligopolies: The asymmetric case. Journal of Economic Dynamics and Control 33, 1867–1879.

Black, G., LaFrance, J.T., 1998. Is hotelling's rule relevant to domestic oil production? Journal of Environmental Economics and Management 36, 149 – 169.

BP, 2009. BP statistical review of world energy of world energy 2009. Technical Report. British Petroluem.

BP, 2012. Bp statistical review of world energy of world energy 2012.

Brandt, A.R., 2011. ROMEO model documentation: The Regional Optimization Model for Environmental impacts from Oil Substitutes. Technical Report. Department of Energy Resources Engineering, Stanford University.

Cairns, R.D., 2014. The green paradox of the economics of exhaustible resources. Energy Policy 65, 78 – 85.

Cairns, R.D., Davis, G.A., 2001. Adelman's rule and the petroleum firm. The Energy Journal 22, 31–54.

Chakravorty, U., Hubert, M.H., 2013. Global impacts of the biofuel mandate under a carbon tax. American Journal of Agricultural Economics 95, 282–288.

Dahl, C., Yücel, M., 1991. What motivates oil producers?: testing alternative hypotheses. Research Paper 9106. Federal Reserve Bank of Dallas.

De Gorter, H., Just, D.R., 2009. The economics of a blend mandate for biofuels. American Journal of Agricultural Economics 91, 738–750.

Di Maria, C., Lange, I., Van der Werf, E., 2014. Should we be worried about the green paradox? announcement effects of the acid rain program. European Economic Review 69, 143–162.

Dockner, E.J., Jorgensen, S., Long, N.V., Sorger, G., 2000. Differential Games in Economics and Management Science. Cambridge University Press.

Dyni, J.R., 2006. Geology and Resources of Some World Oil-Shale Deposits. Technical Report. United States Geological Survey (USGS).

EIA, 2011. Performace Profiles of Major Energy Producers 2009. Technical Report. United States Energy Information Administration.

EIA, 2012. International energy statistics.

EIA, 2015. Annual Energy Outlook. Technical Report. U. S. Energy Information Administration. http://www.eia.gov/forecasts/aeo/.

Eichner, T., Pethig, R., 2011. Carbon leakage, the green paradox, and perfect future markets. International Economic Review 52, 767–805.

Fischer, C., Salant, S., 2014. Climate policy and nonrenewable resources: The Green Paradox and beyond. MIT Press. chapter Quantifying Intertemporal Emissions Leakage. p. 255.

Gerlagh, R., 2011. Too much oil. CESifo Economic Studies 57, 79–102. http://cesifo.oxfordjournals.org/content/57/1/79.full.pdf+html.

Grafton, R.Q., Kompas, T., Long, N.V., 2012. Substitution between biofuels and fossil fuels: Is there a green paradox? Journal of Environmental Economics and Management , –In Press.

Greaker, M., Hoel, M., Rosendahl, K.E., 2014. Does a renewable fuel standard for biofuels reduce climate costs? Journal of the Association of Environmental and Resource Economists 1, 337–363. http://dx.doi.org/10.1086/678189.

Griffin, J.M., Schulman, C.T., 2005. Price asymmetry in energy demand models: A proxy for energy-saving technical change? The Energy Journal 26, 1–22.

Hotelling, H., 1931. The economics of exhaustible resources. Journal of Political Economy 39, pp. 137–175.

IEA, 2007. IEA Energy Technology Essentials: Biofuel Production. Technical Report. International Energy Agency.

IEA, 2008. From 1st to 2nd generation biofuel technologies: an overview of current industry and R&D activities. Technical Report. International Energy Agency.

IEA, 2010. World Energy Outlook. Technical Report. Organisation for Economic and Cooperatice Development.

IEA, 2011. World Energy Outlook. Technical Report. Organisation for Economic and Cooperatice Development.

IEA, 2014. World Energy Outlook. Technical Report. Organisation for Economic and Cooperatice Development.

IIASA, 2009. The ggi scenario database ver 2.0. available at: http://www.iiasa.ac.at/research/ggi/db/.

Kahouli-Brahmi, S., 2008. Technological learning in energy-environment-economy modelling: A survey. Energy Policy 36, 138 – 162.

Long, N.V., 2010. A Survey Of Dynamic Games In Economics:. volume 1 of *World Scientific Books*. World Scientific Publishing Co. Pte. Ltd.

Mandil, C., Shihab-Eldin, A., 2010. Assessment of Biofuels Potential and Limitations. Technical Report. International Energy Forum.

McDonald, A., Schrattenholzer, L., 2001. Learning rates for energy technologies. Energy Policy 29, 255 – 261.

Medlock, K.B., Soligo, R., 2001. Economic development and end-use energy demand. The Energy Journal 22, 77–106.

van der Meijden, G., van der Ploeg, F., Withagen, C., 2015. International capital markets, oil producers and the green paradox. European Economic Review 76, 275 – 297.

Metzler, C., Hobbs, B.F., Pang, J.S., 2003. Nash-cournot equilibria in power markets on a linearized dc network with arbitrage: Formulations and properties. Networks and Spatial Economics 3, 123–150.

Michielsen, T.O., 2014. Brown backstops versus the green paradox. Journal of Environmental Economics and Management 68, 87 – 110.

Nachtigall, D., Rübbelke, D., 2016. The green paradox and learning-by-doing in the renewable energy sector. Resource and Energy Economics 43, 74–92.

Okullo, S.J., Reynès, F., 2011a. Can reserve additions in mature crude oil provinces attenuate peak oil? Energy 36, 5755 – 5764.

Okullo, S.J., Reynès, F., 2011b. Imperfect Cartelization in OPEC. Technical Report. Institute for Environmental Studies.

Okullo, S.J., Reynès, F., Hofkes, M., 2015. Modeling peak oil and the geological constraints on oil production. Resource and Energy Economics 40, 36 – 56.

OPEC, 2012. The annual statistical bulletin.

van der Ploeg, F., 2016. Second-best carbon taxation in the global economy: The green paradox and carbon leakage revisited. Journal of Environmental Economics and Management 78, 85 – 105.

van der Ploeg, F., Withagen, C., 2012a. Is there really a green paradox? Journal of Environmental Economics and Management 64, 342 – 363. <ce:title>2010 Monte Verita Conference on Sustainable Resource Use and Economic Dynamics(SURED)</ce:title>.

van der Ploeg, F., Withagen, C., 2012b. Too much coal, too little oil. Journal of Public Economics 96, 62 – 77.

Rogner, H., 1997. An assessment of world hydrocarbon resources. Annual Review of Energy and the Environment 22, 217–262.

Salant, S.W., 1976. Exhaustible resources and industrial structure: A nash-cournot approach to the world oil market. Journal of Political Economy 84, 1079–93.

Sinclair, P.J.N., 1992. High does nothing and rising is worse: Carbon taxes should keep declining to cut harmful emissions. The Manchester School of Economic & Social Studies 60, 41–52.

Sinn, H.W., 2008. Public policies against global warming: a supply side approach. International Tax and Public Finance 15, 360–394.

Sinn, H.W., 2012. The green paradox: a supply-side approach to global warming. MIT Press.

Smulders, S., Tsur, Y., Zemel, A., 2012. Announcing climate policy: Can a green paradox arise without scarcity? Journal of Environmental Economics and Management 64, 364 – 376. 2010 Monte Verita Conference on Sustainable Resource Use and Economic Dynamics(SURED).

Österle, I., 2016. The green paradox and the importance of endogenous resource exploration. Australian Journal of Agricultural and Resource Economics 60, 60–78.

Thompson, A.C., 2001. The hotelling principle, backwardation of futures prices and the values of developed petroleum reserves — the production constraint hypothesis. Resource and Energy Economics 23, 133 – 156.

USGS, W.E.A.T., 2000. World Petroleum Assessment 2000 — description and results. Technical Report U.S. Geological Survey Digital Data Series - DDS-60. United States Geological Survey. https://pubs.usgs.gov/dds/dds-060/.

WEC, 2007. 2007 Survey of World Energy Resources. Technical Report. World Energy Council.

WEC, 2010. 2010 Survey of World Energy Resources. Technical Report. World Energy Council.

Winter, R.A., 2014. Innovation and the dynamics of global warming. Journal of Environmental Economics and Management 68, 124 – 140.

AppendixB. Proofs

AppendixB.1. Proof of proposition 1

Let T denote the final date for extraction of a polluting nonrenewable resource and $t_1(t_1 < T)$ a point in time when a mandating policy is imposed. For the model defined in the text, we have the Hamiltonian $\mathcal{H} = P_{y,t}y_t - C(y_t) - \lambda_t y_t$, which gives the following first order necessary conditions:

$$P_t = c + \lambda_t$$
$$\dot{\lambda}_t = \delta \lambda_t$$
$$\lim_{T\to\infty} \{\exp(-\delta(T-k)) R_T \lambda_T\} = 0$$

where λ_t is the shadow price for the resource stock. On the equilibrium path, the optimal solution satisfies: $R_k := \int_k^{t_1} y_t dt + \int_{t_1}^{T} y_t dt$. Too prove whether taxes and subsidies lead to a green paradox, it suffices to sign $\frac{\partial S_{t1}}{\partial c}$, and $\frac{\partial S_{t1}}{\partial \eta}$ where S_{t1} is cumulative crude oil extraction as of date t_1. Signing $\frac{\partial S_{t1}}{\partial t_1}$ proves whether there is an increase in the total amount of resource extracted when the mandate is delayed.

From $P_t = \alpha - \beta (y_t + b_t)$, $b_t = vP_t$ where $v = \frac{\eta}{\beta}$, and the first order necessary conditions, we can show that in the case of a linear extraction costs, production is given by:

$$y_t = \frac{1}{\beta} (\alpha - c(1+\eta)) (1 - \exp(-\delta (T - t)))$$

Cumulative extraction as of the implementation date t_1 is defined as: $S_{t_1} = R_k - \int_{t_1}^{T} y_t dt$ which after substituting for $y_t = \frac{1}{\beta} (\alpha - c(1+\eta)) (1 - \exp(-\delta (T - t)))$ and integrating gives:

$$H(\bullet) = S_{t_1} - R_0 - \left(\frac{(\alpha - c\eta - c) (1 - \exp(\delta(t_1 - T)) + \delta (t_1 - T))}{\beta\delta} \right)$$

where $G(\bullet) = 0$. $G(\bullet)$ is an implicit function since T depends on parameters in the model. We therefore proceed as follows: $\frac{dS_{t_1}}{dc} = -\frac{\partial H(\bullet)}{\partial c} / \frac{\partial H(\bullet)}{\partial S_{t_1}}$

Derivatives can now be straightforwardly obtained:

$$\begin{aligned}
\frac{dS_{t_1}}{dc} &= \left(\frac{-(1+\eta) (1 - \exp(\delta(t_1 - T)) + \delta (t_1 - T))}{\beta\delta} \right) \\
\frac{dS_{t_1}}{d\beta} &= \left(\frac{-(\alpha - c\eta - c) (1 - \exp(\delta(t_1 - T)) + \delta (t_1 - T))}{\beta^2\delta} \right) \\
\frac{dS_{t_1}}{d\eta} &= \left(\frac{-c (1 - \exp(\delta(t_1 - T)) + \delta (t_1 - T))}{\beta\delta} \right) \\
\frac{dS_{t_1}}{dt_1} &= \left(\frac{(\alpha - c\eta - c) (1 - \exp(\delta(t_1 - T)))}{\beta} \right) \\
\frac{dS_{t_1}}{dT} &= -\frac{(\alpha - c\eta - c) (1 - \exp(\delta(t_1 - T)))}{\beta} \\
\frac{dS_{t_1}}{d(T - t_1)} &= -\left(\frac{(\alpha - c\eta - c) (1 - \exp(\delta(t_1 - T)))}{\beta} \right)
\end{aligned}$$

We can sign the necessary relations as $\frac{dS_{t1}}{dc} > 0$, $\frac{dS_{t_1}}{d\beta}$, $\frac{dS_{t1}}{d\eta} > 0$ and $\frac{dS_{t1}}{dt_1} > 0$, $\frac{dS_{t_1}}{d(T-t_1)} < 0$. Taxes and subsidies increase the amount of resource extracted in the pre-implementation phase. Lengthening the pre-implementation, as deduced from $\frac{dS_{t1}}{dt_1} > 0$ or $\frac{dS_{t1}}{d(T-t_1)} < 0$ increases the amount of crude oil resources extracted in the pre-implementation phase.

To prove that extraction is delayed and hence lower at all points in the pre-implementation phase, when mandating policy is delayed, we proceed as follows. First, define a point t_2 such that $t_2 < t_1$ corresponds to any point in the pre-implementation phase. For S_{t_2} the corresponding cumulative extraction by ,t_2, defined as:

$$S_{t_2} = R_k - \int_{t_2}^{t_1} y_t dt - \int_{t_1}^{T} y_t dt$$

The task is to show that cumulative extraction as of date t_2 is lower when the pre-mandating phase is extended. We take derivatives of S_{t_2} with respect to t_1, to get:

$$\frac{dS_{t_2}}{dt_1} = \frac{\partial S_{t_2}}{\partial t_1} + \frac{\partial S_{t_2}}{\partial T}\frac{dT}{dt_1}$$

$$\frac{\partial S_{t_2}}{\partial t_1} = -\frac{(\alpha - c\eta - c)\left(1 - \exp\left(\delta(t_1 - T)\right)\right)}{\beta} + \frac{(\tilde{\alpha} - \tilde{c}\tilde{\eta} - \tilde{c})\left(1 - \exp\left(\delta(t_1 - T)\right)\right)}{\tilde{\beta}}$$

$$\frac{\partial S_{t_2}}{\partial T} = -\frac{e^{-\delta T}(\alpha - c\eta - c)\left(e^{\delta t_1} - e^{\delta t_2}\right)}{\beta} - \frac{(\tilde{\alpha} - \tilde{c}\tilde{\eta} - \tilde{c})\left(1 - e^{\delta(t_1 - T)}\right)}{\tilde{\beta}}$$

$$\frac{dT}{dt_1} == -\frac{\partial G(\bullet)}{\partial t_1} / \frac{\partial G(\bullet)}{\partial T} = \frac{-e^{\delta T}\left(1 - e^{\delta(t_1 - T)}\right)}{e^{\delta t_1} - e^{\delta k}}$$

where those without (with) tildes denote the pre-mandating (mandating) phase parameters. Since $(\alpha - c\eta - c) > (\tilde{\alpha} - \tilde{c}\tilde{\eta} - \tilde{c})$, we conclude that $\frac{\partial S_{t_2}}{\partial t_1} < 0$. And since $\frac{\partial S_{t_2}}{\partial T} < 0$ and $\frac{dT}{dt_1} < 0$ we conclude that $\frac{dS_{t_2}}{dt_1} < 0$, which means delaying the implementation date slows pre-mandating cumulative extraction, and therefore the extraction path is more conservative when the mandates is delayed. Q.E.D

AppendixB.1.1.

AppendixB.2. Proof of proposition 2

The biofuel producers Hamiltonian is given by: $\mathcal{H} = P_t b_t - W(z_t) + \omega_t z_t$ which yields the following first order necessary conditions:

$$-W_z(z_t) + \omega_t = 0 \tag{B.1}$$

$$\dot{\omega}_t - \delta\omega_t + P_t = 0 \tag{B.2}$$

$$\lim_{T\to\infty} \{\exp\left(-\delta(T - k)\right) b_T \omega_T\} = 0 \tag{B.3}$$

where $\omega_t (\geq 0)$ is the shadow price for installed capacity. Combining B.1 and B.2 gives the following dynamic condition for evolution of newly capacity:

$$W_{zz}(z_t)\,\dot{z}_t - \delta W_z(z_t) + P_t = 0$$

We add structure using the following functional assumption for installation costs: $W(z_t) = \frac{1}{2}a \times z_t^2$ such that $W_z(I_t) = a \times z_t$ and $W_{zz}(z_t) = a$. The biofuel producers problem can be combined with the crude oil producers problem to solve the following linear system of second order ordinary differential equations:

$$\begin{aligned}
0 &= a\ddot{b}_t - \delta a\dot{b}_t + P_t \\
0 &= \dot{S}_t - \frac{1}{\beta}(\alpha - \beta b_t - P_t) \\
0 &= \dot{P}_t - \delta P_t
\end{aligned}$$

where S_t denotes cumulative extraction. Note that we assume that crude oil extraction is cost-less. Combined with four boundary conditions, we can completely solve the trajectory for biofuel capacity/supply, the cumulative extraction of crude oil, and the price path. We make use of the following boundary conditions: (i) there is be no investment in biofuel capacity in the terminal period, $I_t = \dot{b}_t = 0$, (ii) initial cumulative extraction is set to set to zero $S_0 = 0$, (iii) initial capacity is also set to zero $b_0 = 0$, and (iv) there is no supply of crude oil in the final period such that the terminal prices are given by $P_T = \alpha - \beta b_T$. Solving this system gives: $\frac{\partial b_t}{\partial a} < 0$, $\frac{\partial S_t}{\partial a} > 0$.

The following derivatives lays out the impact of an announced subsidy for biofuels, on the extraction of crude oil and supply of biofuels during the pre-implementation phase

$$P_t = \frac{a\alpha\delta^2 e^{\delta t}}{a\delta^2 e^{\delta T} - \beta - \beta\delta T + \beta e^{\delta T}}$$

$$b_t = -\frac{\alpha\left(\delta t e^{\delta t} - e^{\delta t} - \delta T e^{\delta t} + \delta T + 1\right)}{a\delta^2 e^{\delta T} - \beta - \beta\delta T + \beta e^{\delta T}}$$

$$y_t = \frac{\alpha\left(-a\delta^3 e^{\delta t} + a\delta^3 e^{\delta T} + \beta\delta^2 t e^{\delta t} - \beta\delta e^{\delta t} - \beta\delta^2 T e^{\delta t} + \beta\delta e^{\delta T}\right)}{\beta\delta\left(a\delta^2 e^{\delta T} - \beta - \beta\delta T + \beta e^{\delta T}\right)}$$

$$S_t = \frac{\alpha\left(a\delta^2 - a\delta^2 e^{\delta t} + a\delta^3 t e^{\delta T} + 2\beta + \beta\delta t e^{\delta t} - 2\beta e^{\delta t} + \beta\delta t e^{\delta T} - \beta\delta T e^{\delta t} + \beta\delta T\right)}{\beta\delta\left(a\delta^2 e^{\delta T} - \beta - \beta\delta T + \beta e^{\delta T}\right)}$$

$$G(\bullet) = R_0 - \frac{\alpha\left(a\delta^2 - a\delta^2 e^{\delta T} + a\delta^3 T e^{\delta T} + 2\beta + \beta\delta T e^{\delta T} - 2\beta e^{\delta T} + \beta\delta T\right)}{\beta\delta\left(a\delta^2 e^{\delta T} - \beta - \beta\delta T + \beta e^{\delta T}\right)}$$

$$H(\bullet) = R_0 - S_{t_1} - \int_{t_1}^{T} y_t dt$$

The impact of the subsidy on the exhaustion of crude oil is obtained by taking derives of the implicit function $G(\bullet)$

$$\frac{dT}{da} = -\frac{\partial G(\bullet)}{\partial a} \Big/ \frac{\partial G(\bullet)}{\partial T}$$

$$\frac{dT}{da} = -\frac{\beta\delta\left(\delta T + \delta T e^{\delta T}(\delta T + 1) - e^{2\delta T} + 1\right)}{-a^2\delta^4 e^{\delta T}\left(e^{\delta T} - 1\right) + a\beta\delta^2\left(e^{\delta T}\left(\delta^2 T^2 + \delta T + 3\right) - 2e^{2\delta T} - 1\right) + \beta^2\left(e^{\delta T}\left(\delta^2 T^2 + 2\right) - e^{2\delta T} - 1\right)}$$

where an evaluation of this expression reveals that $\frac{dT}{da} \gtrless 0$ as driven by the component $-e^{2\delta T}$. This means that whether a subsidy shortens or lengthens the extraction duration depends on the the length of the extraction phase and the size of the discount rate. A numerical evaluation reveals that a short extraction horizon strictly leads to $\frac{dT}{da} > 0$. A long extraction phase, by contrast, allows for the possibility that $\frac{dT}{da} < 0$ if the discount rate is large enough.

The impacts of a change in the subsidy on production choices are signed using the relations $\frac{db_t}{da} = \frac{\partial b_t}{\partial a} + \frac{\partial b_t}{\partial T}\frac{dT}{da}$ and $\frac{dS_t}{da} = \frac{\partial S_t}{\partial a} + \frac{\partial S_t}{\partial T}\frac{dT}{da}$. Since $\frac{\partial b_t}{\partial a} < 0$ $\frac{\partial b_t}{\partial T} \gtrless 0$ and $\frac{\partial S_t}{\partial a} \gtrless 0$ $\frac{\partial S_t}{\partial T} > 0$, we conclude $\frac{db_t}{da} \gtrless 0$, $\frac{dS_t}{da} \gtrless 0$.

To analyze announcement impacts we follows the same steps as those in AppendixB.1.

Q.E.D

AppendixC. Reserves

Table C.4: Break down of ultimately recoverable reserves (in gigabarrels) for conventional crude oil, natural gas liquids (NGL) and tarsands (TS) by producing region. Source is the USGS (2000), BP (2012) and OPEC (2012). Reserves have been adjusted to the year 2005 and include proven reserves.

	p50 reserves			p5 reserves		
Producer	Oil	NGL	TS	Oil	NGL	TS
ALG	21.39	17.62	0.20	35.52	22.86	0.20
ANG	22.91	2.64	5.11	37.70	5.02	5.11
ASP	70.24	35.59	15.99	143.88	58.89	15.99
BRA	61.60	9.24	0.20	119.04	20.21	0.20
EUR	24.01	30.21	19.93	66.21	53.42	19.93
FSU	341.09	104.65	794.91	527.21	171.00	846.26
IRN	245.42	29.91	0.20	324.31	46.01	0.20
IRQ	245.98	8.50	0.20	314.80	14.37	0.20
KUW	164.81	1.98	0.20	196.18	2.52	0.20
LIB	65.95	1.55	0.20	84.68	2.86	0.20
NAM	88.96	15.26	1912.58	268.47	27.88	2632.17
NIG	76.61	15.60	6.32	109.63	20.56	38.90
QAT	28.46	30.72	0.20	34.04	36.48	0.20
ROW	71.77	16.58	3.40	113.20	27.40	3.40
SAU	560.70	83.57	0.20	719.48	134.79	0.20
SCA	11.91	11.95	1.73	56.80	22.48	1.73
UAE	164.72	6.29	0.20	194.41	9.83	0.20
VEN	105.05	6.10	2303.85	150.94	12.33	2493.37
Total	**2371.59**	**427.96**	**5065.63**	**3496.51**	**688.93**	**6058.66**

*p5 indicates a 5% finding probability while p50 indicates 50% finding probability.

AppendixD. Markets

This section described the consumption and arbitragers side of the market.

AppendixD.1. Arbitragers market

We introduce a representative trader to link the two demand markets in the model. The trader arbitrages oil between the demand markets until price between them is equalized. As such, the trader ensures that OPEC producers, who are capable of charging different prices to the different demand markets, are incapable of doing so. The trader purchases oil from the high costs market and sells it to the low cost market. The approached used to represent the trader's activity is similar to that in (Metzler et al., 2003). The traders problem is:

$$min_{\{s^c_{jt}, s^b_{jt}\}} \pi_k = \int\limits_{t=k}^{t=\infty} \sum_j \left(P^b_{jt} s^b_{jt} + P^c_{jt} s^c_{jt} \right) e^{-\delta(t-k)} dt \tag{D.1}$$

s.t.

$$s^c_{jt} + \sum_i y_{ijt} = u^c_{jt},\ s^b_{jt} + \sum_i b_{ijt} = u^b_{jt} \tag{D.2}$$

$$\sum_j s^b_{jt} = 0,\ \sum_j s^c_{jt} = 0 \tag{D.3}$$

where s^c_{jt} (s^b_{jt}) are the shipments for crude oil and biofuels and P^c_{jt} $\left(P^b_{jt}\right)$ are regional prices for crude oil and biofuels, respectively. Note that shipments can be positive or negative, with the restriction the sum of shipments for a particular type of fuel sum to zero. The trader does not arbitrage oil between periods.

AppendixD.2. Consumption market

Consumers in region j maximize utility from the consumption of crude oil, u^c_{jt}, and biofuels, u^c_{jt}, net of purchasing costs. The consumers welfare maximization problem over a foreseeable future $t \in [k, \infty)$ is:

$$max_{\{u^c_{jt}, u^b_{jt}\}} \mathcal{W}_{jk} = \int\limits_{t=k}^{t=\infty} \left(U\left(u^b_{jt} + u^c_{jt}\right) - P^c_{jt} u^c_{jt} - P^b_{jt} u^b_{jt} \right) e^{-\delta(t-k)} dt \tag{D.4}$$

s.t.

$$s^c_{jt} + \sum_i y_{ijt} = u^c_{jt},\ s^b_{jt} + \sum_i b_{ijt} = u^b_{jt} \tag{D.5}$$

$$u^b_{jt} = \bar{u}^b_{jt} + \bar{s}_{jt}\left(u^c_{jt} + u^b_{jt}\right); \quad 0 \le \bar{s}_{jt} \le 1 \tag{D.6}$$

$$u^c_{jt}, u^b_{jt}, \bar{u}^b_{jt} \ge 0 \tag{D.7}$$

where δ is the discount rate,$U\left(u^b_{jt} + u^c_{jt}\right)$ is the consumers felicity function, $\bar{u}^b_{jt}$ $(\bar{s}_{jt})$ represents the volume (share) mandating requirement, and s^c_{jt} (s^b_{jt}) is the amount of crude oil (biofuels) arbitraged by traders to the point that prices between regions are equalized.

As earlier mentioned, biofuels and crude oil are perfect substitutes: $\frac{\partial U(\bullet)}{\partial u^b_{jt}} = \frac{\partial U(\bullet)}{\partial u^b_{jt}} = \mathcal{P}_{jt}$. We choose the demand function to be of the form $u^b_{jt}+u^c_{jt} = A_j \cdot \mathcal{P}_j^{\varepsilon_j} \cdot (y_j \cdot N_j)^{\eta_{j,1}+\eta_{j,2} \cdot log(y_j \cdot N_j)}$ where, A_j is autonomous demand, N_j is the regional population size, and y_j, is regional per capital income. ε_j (< 0) is the price elasticity of demand for oil, $\eta_{j,1}$ (> 0) income elasticity, and $\eta_{j,2}$ (< 0) calibrates energy efficiency. Observe that energy efficiency is linked to economic growth, implying that while demand increases with growth, the opportunities for demand savings are also higher for a larger economy (Medlock and Soligo, 2001).

Condition (D.4) is the welfare function, (D.5) ensures that the amount of crude oil consumed in a region j is exactly equal to the amount that is shipped into the region. (D.6) gives the mandating constraints while (D.7) gives selected non-negativity constraints.