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ABSTRACT

Effective Climate Policy Needs Non-combustion Uses for Hydrocarbons

A central issue that is discussed in climate policy is the fear of owners of stocks of fossil hydrocarbon deposits that high CO_2 taxes and bans on the combustion use of hydrocarbons will turn their stocks into stranded assets. They might react by extracting and selling their reserves today: a rush to burn results. We show how the stranded-asset problem could be avoided or strongly moderated. We analyze a simple intertemporal equilibrium with a given stock of fossil hydrocarbons. In this framework the following properties hold: For a climate-neutral solution to the rush-to-burn problem it is important to maintain existing and generate new markets for climate-neutral products from fossil hydrocarbons in the future, where we give examples for such products. Subsidies for such products (or for their innovation) reduce the rush-to-burn problem. In contrast, the creation of substitutes for fossil hydrocarbon-based climate-neutral products, or subsidies for such products reduce the market for products made from fossil hydrocarbons. This can aggravate the stranded-assets problem and thus can have a climate-damaging effect.

JEL Classification: Q54, Q35

Keywords: green paradox, rush to burn, catalytic pyrolysis, hydro-carbons, plastics

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1 Introduction

The stock of fossil hydrocarbons is a precious natural resource, but burning this stock would have significant adverse consequences for the global climate.[1] Climate economists are therefore considering arrangements to leave the resource stock in the ground (Asheim et al., 2019). The owners of fossil hydrocarbon resources are likely to see that policy measures such as high and increasing carbon-based energy taxes and future cheap and clean backstop technologies threaten their natural resource wealth, comparable to a threat of expropriation. In response they may rush to extract and sell their resources as quickly as possible. This general logic is known from the incomplete property rights literature on natural resources (Long 1975; Konrad, Olsen and Schöb 1994; Rodriguez Acosta 2018). The threat to owners that their natural resource stock becomes a stranded asset and the induced 'rush to burn', or 'green paradox' might therefore become a major climate policy obstacle, as suggested by equilibrium analysis (Sinn 2008; Ploeg and Withagen 2012, 2014; Meijden, Ploeg and Withagen 2015; Long 2015). These theoretical considerations have been confirmed by empirical evidence: announced tightening of future regulation lead to an intertemporal supply shift in the sense of a rush to burn (see Di Maria et al., 2014, for the effects of the U.S. Acid Rain Program in the U.S., and Lemoine, 2017, for the U.S. bill on CO_2 emissions in 2009).

We show in an intertemporal equilibrium analysis that a positive perspective for future markets for climate-friendly non-combustion uses of fossil hydrocarbons can reduce or even inverse the 'rush to burn'. To prevent climate change effectively, policy support for such alternative climate-friendly uses might be a necessary complement to policies that ban future hydrocarbon use for combustion energy purposes.

Furthermore, we discuss future climate friendly non-combustion uses of hydrocarbon such as technologies for CO_2-free catalytic pyrolysis of hydrocarbon (Geißler et al. 2016; Upham et al. 2017; Abanádes et al. 2016 ; Kanga et al. 2019) and markets for durable polymer products from fossil hydrocarbon. The catalytic cracking and utilization of hydrogen from hydrocarbon

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[1] For instance, the 2°C target is seen as incompatible with the combustion energy use of the remaining stock of fossil hydrocarbons (see, e.g., McGlade and Ekins 2015).

may also be relevant in the context of a future hydrogen-based energy system. But even more importantly, the invention of such climate friendly uses can be of great significance in terms of climate policy as a countermeasure to the "rush to burn".

2 A model how to fight the rush to burn

The importance of climate-friendly uses for fossil hydrocarbon in the period when its combustion use is banned can be established studying the intertemporal equilibrium for the use of fossil hydrocarbon in a framework with two periods $t = 1, 2$ and a given initial worldwide resource volume of fossil hydrocarbon of size $s > 0$ at the beginning of period $t = 1$.[2]

Each unit of hydrocarbon can be extracted in period 1 or period 2.[3] If extracted and utilized in period 1 it can be burned for energy (heat, electricity, transportation). Burning for energy can also take place in period 2. Burning hydrocarbon causes CO_2 emissions that contribute to global warming. Let the units of emissions be normalized such that burning one unit of hydrocarbon generates one (appropriately defined) unit of CO_2 emissions. Let the emitted CO_2 not degrade within the time horizon considered, such that the total amount of emissions is a suitable measure of climate-damaging emissions.

Hydrocarbon can also be used for the manufacturing of climate neutral (or, at least, more climate-friendly) products only in period 2. As a mild overstatement of the empirical situation, we assume that in period 1 this usage does not play a role at all.[4] Acknowledging that the production and the non-combustion use of such products might not completely be without

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[2] There are various types of hydrocarbons such as natural gas and natural oil, and they differ in their carbon-footprint as well as in their alternative uses. But for the sake of the argument we consider a homogenous product "hydrocarbon" in what follows.

[3] Our analsis abstains from considerations of extraction costs. Extraction costs are well-studied and have important and interesting implications for the Hotelling rule and the corresponding equilibrium extraction path. But such considerations are orthogonal to the argument here and complicate the analysis without interacting with the main intertemporal and sectoral substitution effects in hydrocarbon use.

[4] Hamilton and Feit (2019, p.24) write "According to WEF, plastic production accounts for 4–8 percent of global oil consumption annually."

carbon footprint, let $\gamma \in [0, 1]$ be the percentage of greenhouse gas emissions if one unit of hydrocarbon is transformed into these goods, compared to the emission of one unit if the unit is burned. Note that γ is a policy variable in a more general analysis. For instance, γ might be very high, if the alternative products are plastics and are simply burned at the end of the plastic consumption cycle. Evidently combustion of plastics is not the only final use for it, and burying plastics in the ground, for instance, would be a much less climate-damaging final use. Finally, let us assume a perfectly competitive market for a homogenous resource named 'hydrocarbon', with many price-taking owners of deposits (a monopoly owner or a resource owners' cartel that acts like a monopolist is discussed in the Appendix).

Overall, this description defines three markets for an exogenously given stock of hydrocarbon. In period $t = 1$, without binding climate conventions in this period, x is the aggregate amount owners sell for combustion purposes. They keep an aggregate stock of $s - x$ for uses in period 2. The aggregate demand function for the market in period 1 is assumed to have constant elasticity[5] and given by

$$p_x = \frac{\alpha_x}{x^k}, \tag{1}$$

where parameter $\alpha_x > 0$ characterizes the size of the market for hydrocarbon for combustion use in period 1 and $1/k$ is the constant price elasticity of demand. The variable p_x is the marginal willingness to pay (the demand price) in the market for energy use (combustion purposes) and is equal to the gross sales value that owners achieve in that period for selling a unit of the stock of hydrocarbon. Their gross return is $p_x x = \alpha_x x^{1-k}$, and -in the absence of extraction costs- also their net return. Owners of deposits are price takers in a perfectly competitive market. Hydrocarbon owners may also sell their resources at the markets in period 2. The demand function for hydrocarbon for combustion purposes in period 2 is

$$(1 + \tau)p_y = \frac{\alpha_y}{y^k}, \tag{2}$$

and also has constant elasticity, with $\alpha_y > 0$ the measure of the market size

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[5] The parametric form of the demand function is chosen to allow for closed-form solutions, but also because the constant-elasticity-demand case has particular prominence as a benchmark, and has a long tradition in the analysis of exhaustible natural resources. Departures from this benchmark are well-understood.

for hydrocarbon for combustion purposes in period 2. The price p_y is what the owners of hydrocarbon obtain in this market per unit in period 2. Buyers in this market pay $(1+\tau)p_y$ in period 2. The parameter τ is the environmental tax rate on combustion use of hydrocarbon, and $T \equiv 1+\tau$ is the factor that distinguishes the buyer price from the seller price and p_y is endogenously determined in the equilibrium. Finally, the market for hydrocarbon used for clean, non-combustion purposes is characterized by

$$(1-\sigma)p_z = \frac{\alpha_z}{z^k}. \tag{3}$$

Here, p_z is the price obtained by the resource owners in period 2, α_z is a parameter that is a measure of market size. Buyers in this market pay $(1-\sigma)p_z$ in period 2 per unit. The subsidy σ paid to reduce the price for hydrocarbon if used in a clean fashion in period 2 is a policy choice. For notational convenience we define $(1-\sigma) \equiv S$. We allow that $\alpha_z = \alpha_z(N, R)$ is a function of two policy variables N and R. The first is government's innovation effort N that develops further clean uses of hydrocarbon. The innovations can also be cost-reducing innovations that make it cheaper to transform hydrocarbon into such goods. Second, efforts R to develop close substitutes to clean products made from hydrocarbon, for instance, qualitatively identical materials from renewable resources, tend to reduce a_z.

s	exogenous total stock of hydrocarbon resources
x	quantity used for combustion in period 1
y	quantity used for combustion in period 2
z	quantity used for non-combustion purposes in period 2
p_x, p_y, p_z	producer prices for the three different uses of hydrocarbon
α_x, α_y, α_z	parameters measuring the size of the markets
τ	tax rate on combustion use in period 2
T	defined as $1+\tau$
σ	subsidy rate on non-combustion uses in period 2
S	defined as $1-\sigma$
δ	intertemporal discount factor
$1/k$	elasticity of demand (constant, same in all three markets)

Table 1: definitions of main variables and parameters

For the market equilibrium analysis we remain unspecific about the who makes or funds these innovations, but it is important to note that these policy measures are not chosen or paid for by the resource owners - they take α_z and its determinants N and R as given. We discuss some such measures that are currently still in the stage of basic research in section 3. Table 1 summarizes the notation chosen for main variables and parameters. An interior competitive market equilibrium must make price-taking owners indifferent about when to sell their hydrocarbon, and to whom, and this implies $p_x = \delta p_y = \delta p_z$, or, inserting (1), (2) and (3),

$$\frac{\alpha_x}{x^k} = \delta \frac{\alpha_y}{T y^k} = \delta \frac{\alpha_z}{S z^k}. \tag{4}$$

Here, $\delta \in (0, 1]$ is the common intertemporal discount factor that might be caused by a positive interest rate in the capital market, for instance, and/or by other reasons for discounting. The equations in (4) describe the well-known Hotelling rule of use of a stock of natural resources: the present value of returns net of taxes need to be the same for the different uses of hydrocarbon from the perspective of their owners. If $\delta \in (0, 1)$, then the net prices received by the resource owners need to increase over time such that the owners are compensated for the discounting of future returns if they delay extraction. Making use of this Hotelling rule and the aggregate resource constraint $s \geq x + y + z$ that binds in equilibrium, equilibrium quantities are

$$\begin{aligned} x &= s \frac{(\alpha_x S T)^{\frac{1}{k}}}{(\alpha_x S T)^{\frac{1}{k}} + (\delta \alpha_y S)^{\frac{1}{k}} + (\delta \alpha_z T)^{\frac{1}{k}}} \\ y &= s \frac{(\delta \alpha_y S)^{\frac{1}{k}}}{(\alpha_x S T)^{\frac{1}{k}} + (\delta \alpha_y S)^{\frac{1}{k}} + (\delta \alpha_z T)^{\frac{1}{k}}} \\ z &= s \frac{(\delta \alpha_z T)^{\frac{1}{k}}}{(\alpha_x S T)^{\frac{1}{k}} + (\delta \alpha_y S)^{\frac{1}{k}} + (\delta \alpha_z T)^{\frac{1}{k}}}. \end{aligned} \tag{5}$$

From the equilibrium values in (5) we can directly recover the central consumption of hydrocarbon for combustion purposes is increasing in the environmental tax τ. This holds because the partial derivative of current hydrocarbon consumption in (5) with respect to τ using $T = 1 + \tau$ is

$$\frac{\partial x}{\partial T} = s \frac{(\alpha_x S T)^{\frac{1}{k}} (\delta \alpha_y S)^{\frac{1}{k}}}{\left((\alpha_x S T)^{\frac{1}{k}} + (\delta \alpha_y S)^{\frac{1}{k}} + (\delta \alpha_z T)^{\frac{1}{k}} \right)^2 k T} > 0. \tag{6}$$

A future tax on combustion use shifts some of the use of hydrocarbon for combustion from period 2 to period 1. This result recovers the green paradox. A careful look at (6) also shows that, for $\alpha_z = 0$, a prohibitively high tax $\tau \to \infty$ (which would be equivalent in its effect to a ban on the use for combustion purposes in period 2) causes a maximum rush to burn: $x = s$.

The novel result emerges, however, if a market of positive size for uses of hydrocarbon for non-combustion purposes exists in period 2 (i.e. for $\alpha_z > 0$):

Proposition 1 *If a market for non-combustion uses of hydrocarbon has a positive size in period 2 ($\alpha_z > 0$), then a tax τ on CO_2 emissions from combustion uses imposed in period 2 reduces the total combustion use for hydrocarbon and the sum of emissions.*

Proof. Note that $d\tau = dT$, and

$$\frac{\partial(x+y)}{\partial T} = -s\frac{(\delta\alpha_z T)^{\frac{1}{k}}(\delta\alpha_y S)^{\frac{1}{k}}}{\left((\alpha_x ST)^{\frac{1}{k}} + (\delta\alpha_y S)^{\frac{1}{k}} + (\delta\alpha_z T)^{\frac{1}{k}}\right)^2 kT} < 0. \tag{7}$$

Now recall that the total emission impact is proportional to

$$x + y + \gamma z = s - (1-\gamma)z. \tag{8}$$

Hence, the change in the emission impact has the opposite sign of $\frac{\partial z}{\partial \tau}$. Using again that $d\tau = dT$, and z as given in (5), we find

$$\frac{\partial(x+y+\gamma z)}{\partial \tau} = -(1-\gamma)\, s\frac{(\delta\alpha_z T)^{\frac{1}{k}}(\delta\alpha_y S)^{\frac{1}{k}}}{\left((\alpha_x ST)^{\frac{1}{k}} + (\delta\alpha_y S)^{\frac{1}{k}} + (\delta\alpha_z T)^{\frac{1}{k}}\right)^2 kT} < 0. \tag{9}$$

■

These effects are illustrated in Figure 1. The figure plots demand functions (1), (2) and (3) with p on the vertical axis, for a particular numerical example with $\alpha_x = 1, \alpha_y = 0.8, \delta = 0, k = 1$. The lower left corner is the origin of a quadrant that is used to draw the (downward sloping) demands (1) and (2) for x and for y, with larger x and larger y plotted horizontally from this origin to the right. These are the slim black and dashed downward sloping curves for $\tau = \sigma = 0$. The bold black downward sloping curve is obtained by horizontally aggregating these dashed curves, with the distance from the left vertical price axis the sum of x and y that correspond to a given p. The lower right corner is the origin of the quadrant used to draw the demand function (3). Here, quantity is plotted horizontally from the right to the left, larger value of z is plotted as the distance further left from this origin. Seen from this origin, this demand function is also downward sloping. The distance between the two vertical price axes is equal to the total stock s of hydrocarbon. Equilibrium is reached at a price at which the three demands x, y and z add up to s. It is characterized by the intersection of the two solid black curves, determining the equilibrium price for $\tau = 0$, and quantities z and $x + y$ for this price. The individual values of x and y at this price can then be recovered from the value of the dashed demand functions for this price. For the above numerical values, these are $x \approx 0.71$ and $y \approx 0.57$, and $z \approx 0.71$. Let us now turn to the introduction of a carbon tax of size $\tau = 0.5$ in this figure. The length of the box remains equal to the total initial stock of hydrocarbon. The carbon tax shifts the demand curve for y to the left (slim red dashed curve) and also the aggregate demand $(x + y)$ for combustion use over the periods (bold red dot-dashed curve). The function (3) remains unchanged. The new equilibrium intersection of the red dot-dashed curve with (3) has a lower price, lower $x + y$ and a higher amount of non-combustion use. Numerically, for the parameter values underlying the demand functions in Figure 1, the sum of y and x reduce from approximately 1.29 to approximately 1.21 and the non-combustion use of hydrocarbon increases accordingly.

Depending on technology development, but also depending on regulatory interventions and industrial policy the demand for hydrocarbon for climate-neutral non-combustion uses can be very small or very large in the future (see section 3 for a discussion). The carbon footprint for such non-combustion uses is lower - a percentage of the emissions from combustion uses. It might even be close to zero is some non-combustion uses. The proposition shows that the development of such climate-neutral uses of hydrocarbon can have an important climate impact. Diagrammatically, an increase in the demand for non-combustion uses causes an upward shift of $\delta a_z/z^k$, forcing an increase in the equilibrium price, an increase in the equilibrium quantity of z and a decrease in the equilibrium quantity of $x + y$. Larger demand can counter the existing fear of resource owners that their remaining stock becomes a

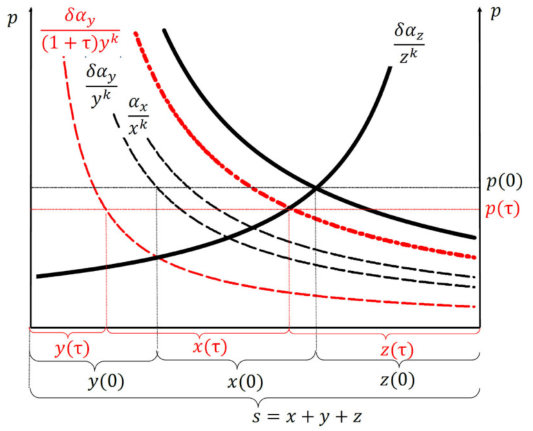

Figure 1: a future tax on combustion use

stranded asset. This reduces the negative and paradoxical effects of an environmental tax on the use of hydrocarbon for CO_2-emitting processes. The effect depends on the size of the market for non-combustion uses. As can be seen straightforwardly from (5), the carbon footprint approaches γs if the demand for non-carbon uses becomes very large in comparison to the demand for combustion uses.

We can now discuss the comparative static results on several parameters of the formal framework:

Proposition 2 *Higher subsidies on hydrocarbon products with a low climate impact* ($\gamma < 1$) *or a larger market for such non-combustion uses and higher technological investment in developing such products all reduce period-1 combustion use of hydrocarbon and total emissions. Technological investment in replacement products for such products from fossil hydrocarbon increase combustion use of hydrocarbon and the aggregate sum of* CO_2 *emissions from fossil hydrocarbon.*

Proof. By $S = 1 - \sigma$ it holds that $\frac{\partial S}{\partial \sigma} = -1$. Using (5) we find that

$$\frac{\partial x}{\partial \sigma} = -\frac{\partial x}{\partial S} = -s\frac{(\alpha_x ST)^{\frac{1}{k}}(\delta\alpha_z T)^{\frac{1}{k}}}{\left((\alpha_x ST)^{\frac{1}{k}} + (\delta\alpha_y S)^{\frac{1}{k}} + (\delta\alpha_z T)^{\frac{1}{k}}\right)^2 kS} < 0. \qquad (10)$$

Similarly,

$$\frac{\partial x}{\partial \alpha_z} = -s\frac{(\alpha_x ST)^{\frac{1}{k}}(\delta \alpha_z T)^{\frac{1}{k}}}{k\alpha_z\left((\alpha_x ST)^{\frac{1}{k}} + (\delta \alpha_y S)^{\frac{1}{k}} + (\delta \alpha_z T)^{\frac{1}{k}}\right)^2} < 0. \tag{11}$$

Note further that higher N directly increases α_z, and a lower R directly decreases α_z by definition.

Total emissions are proportional to $s-(1-\gamma)z$. Using that $dS = -d\sigma$, the equilibrium value of z from (5) and taking the first derivative yields

$$\frac{\partial(x+y+\gamma z)}{\partial \sigma} = -s\frac{(\delta \alpha_z T)^{\frac{1}{k}}(1-\gamma)\left((\alpha_x TS)^{\frac{1}{k}} + (\delta \alpha_y S)^{\frac{1}{k}}\right)}{\left((\alpha_x TS)^{\frac{1}{k}} + (\delta \alpha_y S)^{\frac{1}{k}} + (\delta \alpha_z T)^{\frac{1}{k}}\right)^2 kS} < 0 \tag{12}$$

This shows that a larger subsidy on non-combustion uses of hydrocarbon reduces overall emissions. Similarly,

$$\frac{\partial(s-(1-\gamma)z)}{\partial \alpha_z} = -s\frac{(1-\gamma)(\delta \alpha_z T)^{\frac{1}{k}}\left((\alpha_x TS)^{\frac{1}{k}} + (\delta \alpha_y S)^{\frac{1}{k}}\right)}{\left((\alpha_x TS)^{\frac{1}{k}} + (\delta \alpha_y S)^{\frac{1}{k}} + (\delta \alpha_z T)^{\frac{1}{k}}\right)^2 k\alpha_z} < 0. \tag{13}$$

Hence, a larger market for hydrocarbon for non-combustion use reduces emissions. Again, note further that higher N and lower R both directly increase α_z by definition of α_z. ■

Proposition 2 shows that the rush to burn can be slowed down by policies that increase the demand for climate-neutral products from hydrocarbon, and that the opposite effect emerges from policies that support substitutes to such products. Moreover, We should also note that hydrocarbon has a high energy content. The CO_2-neutral separation of hydrogen can contribute to the hydrogen-based energy supply of the future. Furthermore, hydrocarbons are valuable raw materials in many possible petrochemical applications. It might therefore be useful to distinguish between policy recommendations that suggest to ban hydrocarbons altogether, and policy recommendations that suggest to make use of them in a CO_2 -neutral or CO_2 emission friendly fashion. The latter might be valuable on its own, but as we show, it has the benefit of making a potentially strong contribution to climate policy.

Figure 2 uses the same demand and discount parameters for plotting the black demand curves as in Figure 1. It considers a future subsidy on

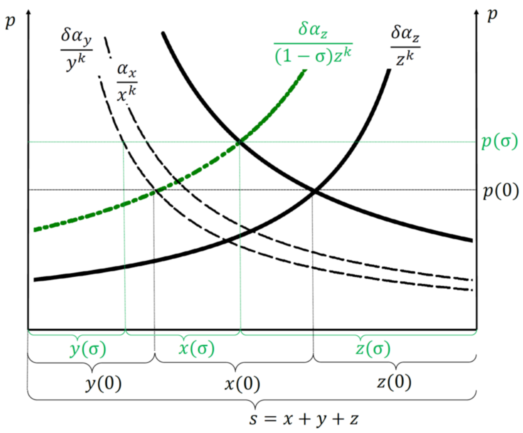

Figure 2: A subsidy on future non-combustion use

non-combustion use of hydrocarbon of $\sigma = 0.5$. This subsidy shifts the demand curve (3) for hydrocarbon for non-combustion use out to the left (to the green bold, dot-dashed line). The new equilibrium price is where the aggregate demand for combustion uses intersects this shifted curve. The new equilibrium has a higher price and higher non-combustion use. This increased demand also absorbs a larger share of the overall stock s of hydrocarbon. Hence, it reduces both the use of hydrocarbon for combustion use in period 1 and in period 2. Using the parameters used for the plots in Figure 2, x reduces to about 0.53, y reduces to about 0.42, and their sum from about 1.28 to about 0.95.

Proposition 2 considers exogenous changes in α_z, N, R, and σ. Innovations that lead to an increase in α_z (i.e., a larger N), or a decrease in innovations that lead to a decrease in α_z (i.e., a larger R) are taken as exogenous here. In particular, these innovations are not, or not necessarily, made by the owners of the natural resource stock, and might be understood as innovations that are decided in a different sector of the economy. These innovations might have a cost, but this cost does not affect the hydrocarbon market itself, other than via the change in α_z.[6]

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[6] The results in propositions 1 and 2 were derived under typical benchmark conditions for the analysis of markets for a non-renewable stock of natural resource. A large literature the green-paradox results for various modifications of the model assumptions, showing that its underlying intuition is qualitatively robust to many model modifications. We cannot

As we discuss later in section 3, the research on such technological innovations appears to be currently undertaken and making progress. Our analysis, hence, reveals that there is an unpleasant relationship between the development of substitute products to non-combustion products from fossil hydrocarbon and the extent of the green paradox. Much like CO_2 taxes that apply only in the future, the development of cheap substitutes for fossil hydrocarbon products or their subsidization triggers substitution processes in the use of hydrocarbon, similar to a kind of indirect green paradox. The indirect substitution effects emanating from such products or their subsidization accelerate the use of fossil hydrocarbon in the present. They can reinforce the rush to burn.

3 What non-combustion uses?

The equilibrium results illustrate the beneficial effects of future demand for hydrocarbon for climate-neutral non-combustion purposes. But what uses can this be and how can they be encouraged? Two candidates for non-combustion use are prominent.

hydrocarbon may play a major role in a future hydrogen-based energy world. The conventional technical processes used to generate hydrogen from hydrocarbon cause large amounts of CO_2. However, progress is made on the development of catalytic pyrolysis that reduces hydrocarbon into hydrogen and pure carbon – without emissions of CO_2. Methane, for instance, can already be transformed into hydrogen and pure carbon in a climate-neutral way. Zhang et al. (2018, 827) describe the catalytic processes that transform $CH_4 \rightarrow C + 2H_2$ in an endothermal reaction that requires 74.52 kJ/mol. Various catalysts can be used. The choice of catalysts also has implications for the allotropic modifications of carbon that emerge. Some metal-based catalysts may lead to valuable nanomaterials as a by-product, such as multi-walled carbon nanotubes. The physical separation of the catalysts from the reduced carbon remains an issue and further technological progress is seemingly needed. But even an uncertain perspective of such markets can trigger positive anticipation effects and has the potential to reduce current

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carry out all possible variants here. The abstract establishes that the results are valid also if the natural resource owner has market power.

use of hydrocarbon for combustion purposes.

Hydrocarbons are also used for the production of plastics, textiles, and insulating materials in the construction sector. The market for plastics might quadruple in the next 80 years (Hamilton and Feit 2019) and demand for hydrocarbons as the major input could play a growing role. A possible trade-off exists for the current plastics consumption cycle. In particular, if plastics were burned in the end, this contributed to greenhouse gas emissions (Hamilton and Feit 2019). But changes are already discussed (Zheng and Suh 2019). A ban on plastics as it is discussed or implemented in some contexts (see Xanthos and Walker 2017), the reorganizations in the use of plastics in Africa (Adebiyi-Abiola 2019) and recommendations towards recycling (MacArthur 2017) reduce the expected future demand for hydrocarbons for plastics.

We also observe innovations of plastics from renewable resources (Zhu, Romain, and Williams 2016; Hillmyer, 2017): such a backstop has the potential to reduce the demand for fossil hydrocarbons. The development of such sustainable technologies might be desirable for other reasons. However, Proposition 2 shows that the innovation of renewable substitutes that reduce the demand for fossil hydrocarbons for non-combustion purposes might be undesirable in the context of the climate problem.

4 Conclusions

Success or failure of a global climate policy will, in large parts, depend on whether the burning of the stock of hydrocarbons can be stopped. Harstad (2012) suggests that a climate coalition might buy and conserve foreign deposits. Asheim et al. (2019) advocate a combination of supply side and demand side policies. The stakes of resource owners are enormous, however. To illustrate, BP (2019, p.14) states an estimate of proven world reserves at the end of 2018 of 1729,7 thousand million barrel. With a conservative price estimate of 50 USD per barrel, this amounts to a gross value of about 86.45 trillion USD, about 4 times the US Gross Domestic Product in 2019.

The qualitative findings from a generic intertemporal model with perfect competition and a depletable stock of hydrocarbon, as well as for a modified model with monopoly supply are as follows:

- An energy policy that only relies on pure bans but can only be enforced with a time-lag can fail, because of the ‘green paradox’. Current consumption of hydrocarbon for combustion purposes is increasing in the future CO_2 tax, confirming a ’green paradox’ in our framework.

- A future anticipated tax on CO_2 emissions can reduce total CO_2 emissions if green non-combustion uses of fossile hydrocarbon exist.
- A higher exogenous demand for clean non-combustion uses, an increase in the subsidy to such uses, and higher technological investment in developing such products can all reduce total emissions.
- Product innovations or process innovations that increase the set of clean products that are substitutes to non-combustion uses of fossil hydrocarbon can speed up the rush to burn and can increase CO_2 emissions from fossil hydrocarbon.

These results show that innovation or fostering of greenhouse-gas neutral processes that use hydrocarbons as a major input (such as catalytic methane pyrolysis or the synthesis of durable polymers) might be important as a complement to a future high tax or ban of the use of hydrocarbons for combustion purposes.

5 Appendix

This appendix shows that the results in propositions 1 and 2 remain qualitatively valid if the market for fossil hydrocarbon is characterized by a monopoly supplier (or a cartel that acts as a monopolist). A monopolist owns a stock of hydrocarbon of size s and maximizes present value of profits. Apart from market power, the structure of the problem is kept as close as possible to the competitive equilibrium analysis. The monopolist can sell hydrocarbon in the three markets. Quantities and producer prices are x, y and z and p_x, p_y and p_z, and demands in these markets are characterized by constant-elasticity demand functions (1), (2) and (3). For the monopoly case, for constant elasticity, for an interior solution we assume this elasticity to exceed 1 (i.e., $k \in (0,1)$). To make the problem non-trivial, the three markets can be served independently: there is no arbitrage opportunity among the buyers across the three markets. The monopolist’s present value of profit is

$p_x x + \delta p_y y + \delta p_z x_z$. The parameter δ is again the intertemporal discount rate. Defining $(1+\tau) \equiv T$ and $(1-\sigma) \equiv S$ and inserting the demand functions yields this profit as

$$\pi = \alpha_x (s - y - z)^{1-k} + (\delta \frac{\alpha_y}{T}) y^{1-k} + (\delta \frac{\alpha_z}{S}) z^{1-k}. \tag{14}$$

The monopolist chooses y and z and due to the assumption about demand elasticity the resource constraint binds, and $x = s - y - z$ is implicitly determined. The first-order conditions for profit maximization are

$$\frac{\partial \pi}{\partial y} = (k-1) \frac{\alpha_x (s-y-z)^{-k} T - \delta \alpha_y y^{-k}}{T} = 0 \tag{15}$$

and

$$\frac{\partial \pi}{\partial z} = (k-1) \frac{\alpha_x (s-y-z)^{-k} S - \delta \alpha_z z^{-k}}{S} = 0. \tag{16}$$

Equations (15) and (16) can be solved for y and z. Dividing (15) by (16) and solving for y yields $y = \left(\frac{S}{T} \frac{\alpha_y}{\alpha_z} \right)^{\frac{1}{k}} z$. This relationship can be used to eliminate y in (15) to obtain

$$z = s \frac{\left(\frac{\delta \alpha_z}{\alpha_x S}\right)^{\frac{1}{k}}}{1 + \left(\frac{\delta \alpha_z}{\alpha_x S}\right)^{\frac{1}{k}} \left(\frac{S}{T} \frac{\alpha_y}{\alpha_z} \right)^{\frac{1}{k}} + \left(\frac{\delta \alpha_z}{\alpha_x S}\right)^{\frac{1}{k}}}. \tag{17}$$

This function is identical to (5). Analogously, using $z = \left(\frac{T}{S} \frac{\alpha_z}{\alpha_y} \right)^{\frac{1}{k}} y$ to replace z in an equivalent representation of condition (16) or using (**??**) yields

$$y = s \frac{\left(\frac{\delta \alpha_y}{\alpha_x T}\right)^{\frac{1}{k}}}{1 + \left(\frac{\delta \alpha_y}{\alpha_x T}\right)^{\frac{1}{k}} \left(\frac{T}{S} \frac{\alpha_z}{\alpha_y} \right)^{\frac{1}{k}} + \left(\frac{\delta \alpha_y}{\alpha_x T}\right)^{\frac{1}{k}}}. \tag{18}$$

This is identical to (5). As $s = x + y + z$, all solutions for x, y and z are the same as in the case of perfect competition. The monopolist chooses quantities/prices that are the same as the equilibrium values for perfect competition. Stiglitz (1976) already alluded to this equivalence. Intuitively, given that the total amount of hydrocarbon is fixed and eventually sold, the monopolist does not have market power in the conventional sense - total intertemporal supply is given. Stiglitz also alludes to the fact that this analysis is for a benchmark case, and that changes in some of the assumptions will cause departures from this equivalence result. But here, as x, y and z are determined by the same functions, a continuation of proof follows the lines of proof of propositions 1 and 2.

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