FONDAZIONE ENI ENRICO MATTEI

NOTA DI LAVORO

14.2010

Too Much Oil

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SUSTAINABLE DEVELOPMENT Series
Editor: Carlo Carraro

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Summary
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Keywords: Green Paradox, Climate Change, Exhaustible Resources, Fossil Fuels

JEL Classification: Q31, Q54

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TOO MUCH OIL

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ABSTRACT

Fear for oil exhaustion and its consequences on economic growth has been a driver of a rich literature on exhaustible resources from the 1970s onwards. But our view on oil has remarkably changed and we now worry how we should constrain climate change damages associated with oil and other fossil fuel use. In this climate change debate, economists have pointed to a green paradox: when policy makers stimulate the development of non-carbon energy sources to (partly) replace fossil fuels in the future, oil markets may anticipate a future reduction in demand and increase current supply. The availability of 'green' technologies may increase damages. The insight comes from the basic exhaustible resource model. We reproduce the green paradox and to facilitate discussion differentiate between a weak and a strong version, related to short-term and long-term effects, respectively. Then we analyze the green paradox in 2 standard modifications of the exhaustible resource model. We find that increasing fossil fuel extraction costs counteracts the strong green paradox, while with imperfect energy substitutes both the weak and strong green paradox may vanish.

Keywords: green paradox, climate change, exhaustible resources, fossil fuels

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1. INTRODUCTION

In the 21st century, mankind has to solve two problems closely intertwined and both fundamental to economic prosperity for centuries to come. The first problem concerns the secure supply of energy when the era of cheap oil will come to an end. The 1973 oil crisis, which was a prolonged interruption in the otherwise reliable and growing supply of cheap oil, exposed world's dependence. The interruption was temporary, though, and overall cheap oil has been a corner stone for worldwide economic growth during the second half of the 20th century. But the oil crisis had put exhaustible resources on the map of economic theory and a rich literature has developed. The second problem concerns the containment of global climate change, a phenomenon that is already observed in rapidly melting glaciers and the Greenland, Antarctic and polar ice-cap. Climate change threatens to destroy vast eco-systems, raise sea levels substantially and alter our world in yet unknown directions.

Economists have noted an unexpected interaction between the two problems. When with good intentions policy makers set up green policies to develop energy sources that may substitute for oil in the long run, they may enhance climate change problems, rather than mitigate them (Strand 2008 and Hoel 2008). The argument is intuitive. Oil suppliers, when anticipating the development of an alternative competitive energy source, will bring forward the sales of their resource, and thus increase current emissions, to protect their revenues. This phenomenon is called the green paradox (Sinn 2008).[2]

This paper discusses the typical resource model that underlies the green paradox, and analyzes some common extensions and studies whether the green paradox remains robust. The need for an extension of the simple model is based on two observations. First, there is too much oil plus other fossil fuels, in the sense that we cannot allow the exploitation of all non-conventional oil and coal reserves to progress unchecked. That is, if we want to maintain a safe climate threshold. Second, there are no ideal non-carbon energy sources that can substitute for oil and other fossil fuels at unlimited supply and constant marginal costs. Instead, many non-carbon energy sources have decreasing returns to scale and are imperfect substitutes. The implication of both observations is that substantial market interventions are needed to prevent the use of too much oil and other fossil fuels. The silver lining, though, is that the same features make the appearance of a green paradox less likely.

The basic model that combines the dynamics of exhaustible resource markets with climate change damages was analyzed by Sinclair (1992) who noted that carbon taxes as such would not necessarily lead to the decrease of emissions associated with fossil fuel use: "the key decision of those lucky enough to own oil-wells is not so much how much to produce as when to extract it." Thus, he reasoned, as climate policy should aim to delay the extraction of oil, the main target for a tax on fossil fuels should be to shift supply from the present to the future. That is, the price wedge of a climate tax, when measured relative to the rent that the oil-well owners receive, should decrease over time. Under the optimal carbon tax, owners could increase their net present value rent by delaying supply.

Ulph and Ulph (1994) added to the above model the notion that the marginal damages associated with carbon dioxide emissions, that is, the use of fossil fuels, is not constant over time, but can be expected to follow a hump-shaped curve. The higher the atmospheric CO_2 concentrations, the higher the additional damages associated with an extra unit emitted. Based on

[2] The green paradox can also occur for other climate change policies such as announced carbon pricing. Anticipation of future reductions in demand for oil and other fossil fuels will drive the resource owners to bring forward their supply (Sinn 2008, Di Maria et al. 2008, Eichner and Pethig 2009, Smulders et al. 2009). In this paper, though, we will focus on the development of cheaper energy substitutes for oil and fossil fuels.

this argument, Ulph and Ulph showed that as the resource stock of fossil fuels is exploited and builds up the atmospheric stock of CO_2, marginal damages would increase and carbon taxes should increase in parallel, to be reduced at the later stage when the climate system would slowly return to the natural state.

Hoel and Kverndokk (1996) further developed the analysis by including rising extraction costs for fossil fuels and the existence of a substitute energy source, a so-called backstop available at constant marginal costs and at infinite supply. The backstop is important to the analysis as it ensures that economic production is possible without use of the exhaustible resource. It offers an outside option to the buyer, and thereby prevents the seller from setting prices too high. The extraction costs are important because they capture the understanding that the cumulative supply of fossil fuels, and thereby cumulative CO_2 emissions, is not only determined by the geography of the resource, but also depends on the price that the fossil fuel owners receive for their resource. Nonetheless, Hoel and Kverndokk (1996) conclude that optimal climate policy will not affect cumulative fossil fuel use, but will mainly shift part of current fossil fuel use to the very long term, when the atmospheric CO2 concentrations have passed their peak.

The above literature thus established some of the basic mechanisms that have to be taken into account when one thinks about optimal carbon pricing jointly with the working of the oil market. The analytical model typically considers one global resource market with cooperation between countries for climate policy. The assumption is a far cry from practice, where countries are accepted to have different responsibilities for climate policy, and where climate policy is feared to interfere with countries' competitiveness. Policy makers worry that carbon pricing will push out energy-intensive firms as these will move to countries without high carbon prices or strict regulations. The reduction in domestic CO_2 emissions may then partly be offset by an increase in foreign emissions. This phenomenon, dubbed carbon leakage, has been studied widely both in the theoretical setting (Copeland and Taylor 2005, Di Maria and van der Werf, 2008) and through applied numerical simulations (see Gerlagh and Kuik 2008 for an overview).

Policy makers interpret carbon leakage as a signal that domestic carbon pricing will be an expensive and ineffective climate policy. They look for an alternative green policy without the competitiveness costs: the development of an energy substitute that would in the long term be cheap enough to drive out oil and other fossil fuels as main energy sources. The prospect is a double dividend in which a new clean energy source reduces dependency on oil and other fossil fuels, and at the same time decreases climate change damages. The double benefits would come without the fear of firm relocation and associated job losses. It is this perspective that we will analyze in this paper. We will abstract from carbon pricing policy, and focus on the development of a non-carbon energy substitute and its effect on energy markets and climate change.

Specifically, we ask when the green paradox arises. Under which conditions will cheaper non-carbon energy sources increase current emissions and climate change damages, or alternatively, when will it mitigate the damages. To be more precise, we distinguish between a weak and a strong green paradox. A *weak* green paradox arises when (the anticipation of) a cheaper clean energy technology increases current emissions, as in Smulders et al. (2009). A weak green paradox need not be the main concern though. Current emissions may increase, but if future emissions sufficiently decrease, in the long term, climate change may be less severe. A *strong* green paradox arises when the cheaper clean energy technology increases cumulative damages associated with emissions as well, evaluated at the net present value. The weak green paradox refers to an immediate effect. The strong green paradox refers to an aggregate welfare effect. One cannot directly derive from the analysis whether a cheaper non-carbon energy source increases or decreases welfare. But for a feel of the welfare effects, let us assume that there are generic policies in place that correct the innovation market in such way that the development of new technologies is at an efficient level, insofar the effects on production and income are concerned. In such a context, we may say that if a cheaper non-carbon energy source decreases climate change damages, the innovation has a positive externality and it deserves some extra stimulus. If, however, climate change damages increase as in the strong green paradox, then the energy innovation has a negative externality and an extra stimulus is unwarranted.

The analysis presented in this paper is complementary to Hoel (2009), who studies a similar question in a two-period model, whereas we will employ an infinite horizon model. The two-period timeframe allows Hoel (2009) to find a full analytical solution and a complete characterization of how different assumptions on parameters affect the green paradox. Our infinite horizon model more naturally fits the very long-term nature of the problem. The price we pay for our long horizon is that we put more restrictions on various parameters.

The set up of the paper is as follows. Below we start with a basic check on the scientific understanding of how much oil and fossil fuels we can use without risking dangerous climate change. That is, we relate climate change to global fossil fuel economic reserves and resources. Thereafter, we analyze and compare three base models of fossil fuel extraction and climate change damages. The first model has a fixed resource, constant extraction costs, and a backstop technology. This model is closest to most of the other models used in the green paradox literature. The second model has increasing extraction costs, and in this model the end of the fossil fuel era is determined by economic exhaustion, rather than physical exhaustion. The third model replaces the assumption of a backstop energy source, which is a perfect substitute at constant marginal costs, with an imperfect substitute with decreasing returns to scale. From the first to the last model, the green paradox step by step erodes. The final section discusses our results and policy implications.

2. ATMOSHPERIC CO_2 ABSORPTION VS RESERVES AND RESOURCES

By 2000, cumulative emissions of CO2 had reached about 440 GtC (1600 GtCO2), and atmospheric CO2 concentrations were at about 370 ppmv (Allen et al 2009). Annual emissions related to fossil fuel use were approximately 7 GtC/yr, while CO2 concentrations increased by 1.7 ppmv/yr. We abstract here from deforestation and other greenhouse gases, which also provide a substantial contribution to global warming. Allen et al suggest that, in order to maintain a high probability that global mean temperatures will not increase by more than 2 degrees Celsius, compared to 1900, we should keep atmospheric concentrations well below 500 ppmv (excl. other greenhouse gases), and cumulative emissions below 1000 GtC. The implication of this target is that cumulative emissions from 2010 onwards should stay well below 500 GtC. Similar conclusions have been derived by Kharecha and Hansen (2008).

We now confront the absorption capacity with global oil and fossil fuel reserves and resources. As fossil fuel combustion is not the only source of emissions, we should exploit strictly less then 500 GtC of our global oil and fossil fuel resources. Kharecha and Hansen report that proven conventional oil reserves slightly exceed cumulative historic emissions, and with expected resources to be discovered, they amount to between 120 and 250 GtC. For gas, proven plus expected reserves exceed cumulative historic use by more, amounting to between 70 and 140 GtC. Thus, in the optimistic case, when oil and gas location and extraction techniques further improve, as they did in the 20th century, conventional oil plus gas alone may take up the largest share of the atmospheric absorption capacity. This optimistic oil and gas recovery scenario is considered most likely by some experts (Maugeri 2009). Coal reserves are estimated between about 500 and 1,000 GtC. Finally, there is a highly uncertain but potentially very large resource of unconventional oil such as tar sands and shale oil, between 150 and 1,000 GtC. The picture that emerges sketches a problem rather different from the usual worry for scarce oil. The reserves of oil plus other fossil fuels is probably too much, more than is good for climate change.

We should not exploit all fossil fuel resources that the earth provides, unless we find ways to capture and store the carbon dioxide, safely and very much at a large-scale. Though the carbon capture and storage (CCS) lobby is optimistic, it seems still too early to accept CCS as a proven solution to the climate change problem. We must therefore ask ourselves which fossil fuel resources we best leave unused. Gas provides relative high amounts of energy per unit of emissions, does not contribute to local air pollution as much as the other fuels, and is thus the most likely candidate to be fully exploited. Oil has always been the currency of fossil fuels. The combined storage and energy density qualities of petrol, its main product, make it the prime fuel for transport. It therefore seems logical to exploit most of the conventional oil resources as well.

The choice in favour of conventional oil and gas puts the burden on coal and unconventional oil. Coal has a very high emission level per energy use, but nonetheless is the main fuel for power plants world wide. It is a cheap resource, partly because the market understands that it is not scarce in the same way as oil and gas. The basic calculations above suggest that we will have to phase out the use of coal during the 21st century, or fully complement it with CCS, to prevent climate change slipping out of hand. The main driving force for the required transition cannot be physical exhaustion of coal, but must either be a price wedge attached to its use, the development of a competitive non-carbon energy substitute, or a combination of both. Unconventional oil, finally, has stacked the odds against it, if we take climate change seriously. The processing of tar sands and other non-conventional oil types, to make petrol and other end-use fuel, is in itself very energy-intensive. The emissions per final energy supply are thus far above those for gas and conventional oil. Unless complemented with CCS, unconventional oil seems best left aside.

The above discussion on fossil fuel resources and the atmospheric absorption capacity leaves out the geopolitical dimension. A coordinated global effort to constrain climate change may leave almost unchanged the economic value of conventional oil and gas resources, while coal and unconventional oil owners will see the value of their assets substantially reduced (Persson et al 2007, Johansson et al 2009). Countries such as Canada, which possesses huge tar sands deposits, may oppose international measures that suppress the value of their resources.[3] The international distribution of costs and benefits of climate change policy is possibly the core problem to be resolved before effective global action can be expected, and hence this problem cannot be dismissed. Yet it is outside the realm of this paper. The main point that we want to bring from the above discussion to our economic analysis below is that if we want to constrain climate change to remain below levels that most scientists consider dangerous, we cannot allow fossil fuel resources to be physically fully exhausted. The reasons for the economy to move from fossil fuels to other energy sources must lie with profit incentives, and not with physical exhaustion.

3. GREEN PARADOX MODELS

Model 1. Fixed resource, perfect backstop

The base model in which the green paradox arises is fairly simple. Consider an exhaustible resource, competitively supplied with initial stock S_0, flow extraction q_t, and constant extraction costs ζ. Resource owners maximize the net present value (NPV) of supply,

$$\Pi = \int_0^\infty e^{-rt}(p_t - \zeta)q_t dt\,, \tag{1}$$

where p_t is the real price of the resource and r is the real interest rate, subject to the resource stock constraint

[3] In energy content, Canadian tar sands may rival the Saudi Arabian oil reserves.

$$\int_0^\infty q_t dt \le S_0 . \qquad (2)$$

Each point in time, the resource market is in equilibrium so that supply is equal to demand specified through a continuous demand function $q_t=D(p_t)$, decreasing in real prices p_t. Maximum demand is labeled $\alpha=D(0)$, while the choke price is labeled β: $D(\beta)=0$. Furthermore, there is a perfect substitute for the resource, available at infinite supply at constant marginal costs ψ, with $\zeta<\psi<\beta$. A substitute with these characteristics is typically called a backstop. It is well known from theory that in this competitive resource economy, the resource price consists of two elements, the extraction costs and the rent λ_t. The latter increases exponentially with the real interest rate:

$$p_t = \zeta + e^{rt}\lambda_0 . \qquad (3)$$

Notice that the net present value resource rent is given by $\Pi=\lambda_0 S_0$. Supply is strictly positive as long as the resource is cheaper than the backstop. As prices increase exponentially, at some future termination data $t=T$, prices will equal the backstop price, $p_t=\psi$, and demand will drop to zero. The equilibrium is thus fully determined by the NPV rent variable λ_0 through

$$\int_0^T D(\zeta + e^{rt}\lambda_0)dt = S_0 , \qquad (4)$$

with the termination date T given by

$$rT = \ln(\psi-\zeta) - \ln(\lambda_0). \qquad (5)$$

Before we will analyze the effects of a cheaper backstop (lower ψ), we will define climate change damages and the green paradox. Climate change damages are captured through a shadow price on emissions, θ_t. The net present value of damages is given by

$$\Gamma = \int_0^\infty e^{-rt}\theta_t q_t dt \qquad (6)$$

In the context of the green paradox, an important assumption we make here is that early emissions cause more damages than delayed emissions, thus $e^{-rt}\theta_t$ decreases over time. Restated, we assume that the marginal damage per emissions increases with less than the interest rate. This assumption can be shown to be consistent with typical climate and damage dynamics (Hoel and Kverndokk 1996).

We now have all tools to define the weak and strong green paradox. The *weak green paradox* occurs when an improvement in the backstop technology ($\mathrm{d}\psi<0$) raises current emissions: $\mathrm{d}q_0/\mathrm{d}\psi<0$. The *strong green paradox* occurs when net present value damages increase, $\mathrm{d}\Gamma/\mathrm{d}\psi<0$.

Notably, we do not consider the effects on overall welfare. In general, a cheaper energy source, whether it is fossil fuel or an alternative, will increase the consumer's surplus and reduce the resource owner's surplus, but the former will outweigh the latter. However, here we are interested in a situation where there is an externality, climate change associated with the use of the resource, that is not internalized in the market through appropriate Pigouvian taxes. We could assume that the market in combination with the standard research policies ensures that innovations are sufficiently stimulated to implement an efficient level of technology, apart from the effect of the technology on climate change. The green policy under consideration stimulates the innovations in clean energy sources, and the belief is that this innovation may provide an environmental payoff. If this is the case, the development of clean energy sources needs support above the typical support for generic innovations. A strong green paradox then means that such support is not warranted. The green paradox thus does not suggest that innovations do not increase welfare, but only that there is no added environmental dividend.

For this simple model, we can easily show that both the weak and strong green paradox occur.

PROPOSITION 1. *In the competitive resource model with constant extraction costs and a backstop,* (4)-(5)-(6)*, both the weak and strong green paradox arise.*

We outline the proof here, provide intuition, and refer to the appendix for the details. We first observe that when the rent λ_0 increases, demand decreases at every point in time, and as total cumulative demand must match the stock S_0 (4), it follows that the termination date T must increase. Thus $\mathrm{d}T/\mathrm{d}\lambda_0>0$. Combining this insight with the termination date equation (5), we can see a more competitive backstop technology (lower ψ) to lead to lower resource rents and an earlier termination date. The lower rent implies lower prices and higher demand so that the weak green paradox immediately follows.

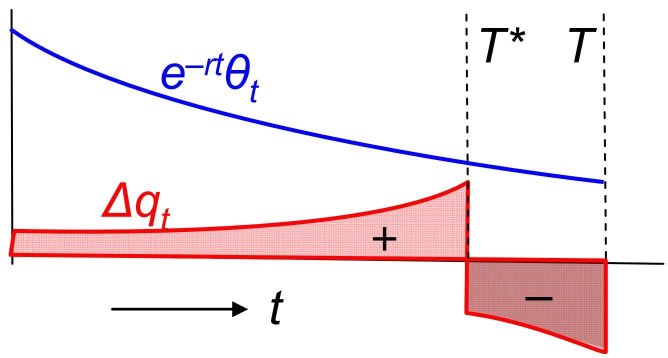

FIGURE 1. *Strong green paradox in the base climate-resource model*

Let us use variables without asterisk for the benchmark equilibrium, and variables with an asterisk for an equilibrium with a cheaper backstop. The above analysis informs us that $q_t^* > q_t$, for $t<T^*<T$. We define the change in supply brought about by the cheaper backstop by $\Delta q_t = q_t^* - q_t$, over $[0,T]$, so that $\Delta q_t>0$ on $[0,T^*]$, and $\Delta q_t<0$ on $[T^*,T]$. That is, the cheaper backstop increases emissions until T^*, and decreases emissions afterwards. Figure 1 shows a typical path for Δq_t. Since future emissions are valued less then present emissions, the net present value of Δq_t is positive, thus damages increase. Lemma 1 in the appendix provides the technical proof.

Model 2. Resource with increasing extraction costs, perfect backstop

We argued in the previous section that for climate change to be contained in a safe window we cannot let all fossil fuels be physically exhausted. That is, we need to either support the transition to the alternative energy source through a tax on the carbon-emitting resource, or we need to bring down the costs of the backstop to such levels that it successfully competes with the fossil fuels. But not only costs of the alternative energy may come down, we may also expect resource extraction costs to go up when we start to squeeze more oil from existing wells and when non-conventional oils become developed. In our simple model, we will now focus on the occurrence of the green paradox when extraction costs increase with cumulative resource extraction. We assume that marginal costs are linear in cumulative supply:

$$\zeta_t = \eta s_t \,, \tag{7}$$

where the state variable s_t is cumulative extraction:

$$s_t = \int_0^t q_\tau d\tau \,. \tag{8}$$

The competitive resource owners maximize the net present value of revenues, for given prices, subject to the above marginal costs equations. The present-value Hamiltonian for this problem is[4]

$$H = (p_t - \eta s_t) q_t - \lambda_t q_t \tag{9}$$

The first-order condition for supply q_t provides the same condition as above: prices are decomposed in extraction costs and a rent component $p_t = \zeta_t + \lambda_t$. The first-order condition for the state variable defines the shadow price dynamics:

$$\dot{\lambda}_t = r\lambda_t - \eta q_t \tag{10}$$

The equilibrium is defined by the initial value λ_0 such that at some terminal date T, the resource price equals the backstop price while the rent is zero: $\lambda_T = 0$ and $\eta s_T = \psi$. For convenience of the analysis, we assume linear demand $q_t = \alpha(1 - p_t/\beta)$. The equilibrium is now characterized as a two-dimensional linear dynamic system

$$\dot{s}_t = \alpha\left(1 - \frac{\eta s_t + \lambda_t}{\beta}\right) \tag{11}$$

$$\dot{\lambda}_t = r\lambda_t - \eta\alpha\left(1 - \frac{\eta s_t + \lambda_t}{\beta}\right) \tag{12}$$

In the appendix, we show that the dynamic differential system has steady state $(s^*, \lambda^*) = (\beta/\eta, 0)$, one stable eigenvector that is downward sloping, and one unstable eigenvector that is also downwards sloping but steeper. In Figure 2, point A is the initial state (s_0, λ_0) with $s_0 = 0$, $\lambda_0 > 0$. Point B is the steady state, and vector AB is the stable eigenvector of system (11)-(12). Vector BC is the unstable eigenvector. Arrow AC is a solution to the dynamic system, but it is not an equilibrium as it doesn't satisfy the termination date condition. Arrow AD is a solution to the dynamic system and it describes an equilibrium path with at the termination date $\eta s_T = \psi < \beta$.[5]

[4] We take the negative dual variable for the stock to have $\lambda_t > 0$.

[5] The general pattern of the dynamic system (11)-(12) is a series of paths that for $t \to \infty$ asymptotically converge to the unstable eigenvector BC or –BC, while for $t \to -\infty$ the paths asymptotically come from the stable eigenvector AB or –AB.

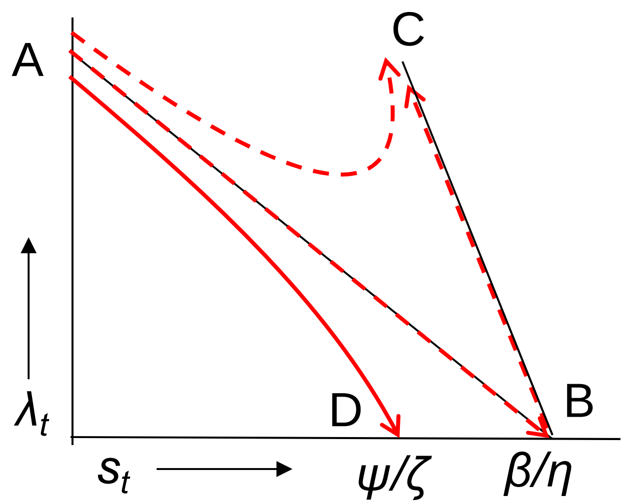

FIGURE 2. *Equilibrium with backstop and increasing extraction costs*

What we see in the figure (and formally prove in the appendix) is that when ψ decreases, D moves to the left and A moves down. That is, the rent λ_0 decreases with a cheaper backstop, so that initial supply q_0 increases. The weak green paradox occurs. While the advancement of emissions increases the net present value damages, cumulative supply is equal to ψ/β, and thus decreases with a cheaper backstop. The balance of the two effects determines whether the strong green paradox applies as well. We prove in the appendix and state here:

PROPOSITION 2. *In the competitive resource model with linear demand, extraction costs linearly increasing in cumulative supply and a backstop, the weak green paradox arises, but the strong green paradox does not arise.*

The proposition marks an important difference with the basic model. When fossil fuel extraction costs increase with cumulative output, a cheaper backstop will shorten the life-time of fossil fuels sufficiently to decrease the net present value of damages associated with their use. For the case of a cheap backstop, the result is obvious. When the backstop becomes very cheap, ψ converges to zero, and cumulative fossil fuel use becomes very small. As cumulative fossil fuel use sets an upper bound on climate change damages, these must become small as well. The proposition states that this mechanism is strong enough to neutralize the strong green paradox, even for a costly backstop.

It is natural to ask whether the strong green paradox occurs in intermediate cases between the standard model with constant extraction costs and the model with linearly increasing extraction costs. We do not provide the full formal analysis but graphically discuss the case through Figure 3. It shows the NPV damages as a function of the costs of the backstop. The top solid line A presents the base model with constant extraction costs. Damages are strictly increasing with a cheaper backstop (decreasing ψ). The central solid line C presents the second model with linearly increasing extraction costs. Damages are decreasing with a cheaper backstop.

When extraction costs are convex in cumulative supply, we will have an intermediate case as portrayed in the dashed line B.. Such a scenario may be considered realistic when we assume that there is no good energy alternative to fossil fuels and extraction costs will rapidly increase during the transition phase towards substitute energy sources. The idea is that the transition phase is characterized by quickly deteriorating quality of oil wells and other fossil fuels. Damages are increasing with a cheaper backstop when the backstop is just competitive (ψ close to β, high energy prices during the transition), and decreasing when the backstop becomes cheap (ψ close to zero, moderate energy prices during the transition).

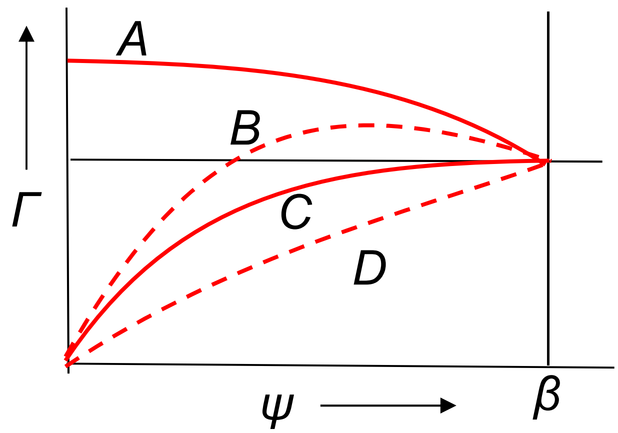

FIGURE 3. *NPV damages dependence on costs of backstop. Solid line for linear extraction costs. Dashed line A for convex, line B for concave extraction costs.*

The more optimistic line *D* represents the case when extraction costs are concave. This assumption describes a scenario where we assume that the transition phase is characterized by a switch from coal (with relatively flat extraction costs) to non-carbon energy sources. Damages are then strictly decreasing with a better backstop.

Model 3. Fixed resource, imperfect substitute

The second model relaxed Model 1's assumption of a fixed resource stock that would be fully exhausted, describing economic exhaustion rather than physical exhaustion as the main feature of the transition. We now address another aspect, the perfect backstop. As Pacala and Socolow (2004) nicely portrayed, there is not one energy source that can easily replace oil and the other fossil fuels. To support its need for energy, human kind will require a whole range of renewable energy sources based on wind, solar, geo-thermal heat, waves, tides, and nuclear. The renewable energy sources require specific geographic conditions, and a limited number of good sites will cause a large-scale employment to bring decreasing returns to scales. Therefore, it is not realistic to assume an energy supply with constant marginal costs at infinite supply, as modelled through the backstop. A stylized more realistic model would consider marginal costs ψ_0 for the first unit of the substitute energy source, increasing with ψ' for every additional unit of energy.

In addition, renewable energy sources are not a perfect substitute for fossil fuels. First, wind and solar are intermittent, and when applied at large scale they need back up storage facilities. Second, most renewables are typically used to produce electricity, but need a conversion to produce a liquid energy carrier as typically used in transport. One way to model the imperfect substitution would be through distinguishing between primary and effective final energy supply. Every additional unit of primary renewable energy adds a smaller amount to the effective final energy supply. Stated the other way around, to add one effective unit of final energy requires an increased amount of primary renewable energy. Consequently, marginal costs increase. The above model with initial marginal costs ψ_0 and increasing marginal costs ψ' can thus conveniently be used to describe both decreasing returns to scale in production and imperfect substitution. In this setting, there are two different improvements possible for the substitute energy source. A better substitute can mean that either the minimum marginal costs for the substitute ψ_0 decrease, or that the slope of marginal costs ψ' decrease, and as we will see, both features have the same effect.

With decreasing returns to scale, total demand is met jointly by resource supply and substitute supply:

$$D(p_t) = q_t + \frac{p_t - \psi_0}{\psi'}, \tag{13}$$

where the second term on the right-hand side is the substitute supply function. Cumulative demand for the resource is given by

$$\int_0^T D(p_t) - \frac{p_t - \psi_0}{\psi'} dt = S_0 . \tag{14}$$

The termination date T satisfies q_T=0:

$$\psi' D(\zeta + \lambda_0 e^{rT}) = \zeta + \lambda_0 e^{rT} - \psi_0 . \tag{15}$$

The cumulative resource constraint ensures that when the substitute becomes cheaper (ψ_0 and/or ψ' falls), then the NPV rent λ_0 tends to decrease to lift demand for the resource at every time, and the sale interval period T tends to increase. The termination date equation suggests that when the substitute becomes cheaper, the NPV rent decreases, and the termination date T comes forward (that is, T falls). The common factor in both equations is that the NPV rent λ_0 drops. The cheaper substitute eats away the revenues for the resource owners, as one expects. In the appendix, we assume linear demand and then prove this feature. We furthermore show (in the appendix) that the cheaper substitute reduces resource demand throughout equilibrium and lengthens the interval period over which the resource is used. Thus, neither the weak nor the strong green paradox arises.

PROPOSITION 3. *In the competitive resource model with linear demand, constant extraction costs, a substitute energy source with minimal marginal costs below the constant resource extraction costs, and increasing marginal costs, the weak and strong green paradox do not arise*.

4. DISCUSSION

The coming decades will be central for the world to decide on the structures of global future energy supply. We will need to develop substitute energy sources to compensate the drop in cheap oil reserves, and at the same time we need to keep in mind the limited absorption capacity of the earth atmosphere. The challenges are big on both fronts. Economists have warned policy makers to be careful in their choices as various climate policy instruments may have unexpected consequences such as highlighted by the green paradox. In this paper, we have provided arguments for the position that, precisely because the fossil fuel reserves are too vast to be allowed to be fully exploited, one type of the green paradox is less likely to occur. Unless we accept a global carbon pricing mechanism, we will have to develop substitute energy sources that can compete with coal and non-conventional oil. Given imperfect carbon pricing policies, further development of such a substitute, leading to lower costs, will probably decrease cumulative fossil fuel use. Furthermore, as lower costs for non-carbon energy sources will also stimulate current use of these technologies, due to decreasing returns to scale and imperfect substitution between energy sources, current fossil fuel demand may also decrease. The green paradox need not arise.

To conclude, we would like to put our analysis in the context of common sense climate change policy. It is known from earlier literature that there are several mechanisms available to reduce emissions: structural change towards less energy-intensive sectors, energy savings, energy substitution from coal to gas and from fossil fuels to non-carbon energy sources, and carbon capture and sequestration.[6] The above order also more or less provides a ranking from cheap to expensive options, and from short-term to long-term. The analysis in this paper strengthens the case that we should first aim at the short-term reduction options, and not mainly focus on long-term solutions. An anticipated reduction in future oil demand may, when not accompanied measures that also reduce current demand, increase current supply. The cheaper options with both a short-term and long-term effect may ultimately also be the more effective over the entire horizon.

APPENDIX. PROOFS OF PROPOSITIONS

Notice that, for notational convenience, in this appendix we use shorthand and write θ_t for the NPV marginal damage, rather than $e^{-rt}\theta_t$. Thus, in the appendix we may write that θ_t decreases, while in the main text we say that θ_t increases with less then the interest rate.

We first prove Proposition 1, the weak and strong green paradox in case of constant extraction costs and a perfect backstop substitute.

Proof of Proposition 1

We first prove that the weak and strong green paradox arise in case of constant extraction costs and a perfect backstop substitute. The equilibrium parameters λ_0 and T are determined by equations (4) and (5). Taking full derivates for d λ_0 dT as dependent on dψ, we find

$$\left[\int_0^T e^{rt} D'(p_t)dt\right] \mathrm{d}\lambda_0 + D(p_T)\,\mathrm{d}T = 0. \tag{16}$$

$$r\,\mathrm{d}T = \mathrm{d}\psi/(\psi-\zeta) - \mathrm{d}\lambda_0/\lambda_0. \tag{17}$$

As $D'<0$, the first equation implies that $\mathrm{d}\lambda_0/\mathrm{d}T>0$. From the second equation, we can then conclude that $\mathrm{d}T/\mathrm{d}\psi>0$ and $\mathrm{d}\lambda_0/\mathrm{d}\psi>0$. Thus, consider a benchmark equilibrium, and a counterfactual denoted by an asterix where costs of the backstop have dropped, $\psi^*<\psi$. The counterfactual equilibrium has lower prices, $p_t^*<p_t$, higher demand $q_t^*>q_t$, and an earlier termination date $T^*<T$. The following lemma now proves the proposition.

LEMMA 1. Consider two continuous paths $q:[0,T]\to\mathbf{R}^+$ and $q^*:[0,T^*]\to\mathbf{R}^+$, with $\int_0^T q_t dt = \int_0^{T^*} q_t^* dt$, $q_T\geq 0$, $q^*_{T^*}\geq 0$, and a strictly decreasing weight function $\theta_t:\mathbf{R}^+\to\mathbf{R}^+$. Assume $q_t < q_t^*$ for all $t\leq\min\{T,\ T^*\}$, then $\int_0^T \theta_t q_t dt < \int_0^{T^*} \theta_t q_t^* dt$.

Proof. First, notice that $T^*<T$, because if $T^*\geq T$ then $\int_0^T q_t dt < \int_0^T q_t^* dt < \int_0^{T^*} q_t^* dt$, contradicting the assumption. Let us define the difference between the paths: $\Delta_t = q_t^* - q_t$ where we take q_t=0 for all $t>T^*$. From construction we have, $\Delta_t>0$ for $t<T^*$, and $\Delta_t<0$ for $T^*<t<T$. The lemma now

[6] If these don't suffice, we need to think about lower economic growth.

follows from the observation that $\int_0^T \theta_t \Delta_t dt = \int_0^{T^*} \theta_t \Delta_t dt + \int_{T^*}^{T} \theta_t \Delta_t dt > \theta_{T^*} \int_0^{T^*} \Delta_t dt + \theta_{T^*} \int_{T^*}^{T} \Delta_t dt = 0$. QED.

Proof of Proposition 2

To prove the second proposition, we solve the linear dynamic differential equations (11) and (12). First, we write the differential equation in vector notation as

$$\begin{pmatrix} \dot{s}_t \\ \dot{\lambda}_t \end{pmatrix} = \begin{pmatrix} -\eta\alpha/\beta & -\alpha/\beta \\ \eta^2\alpha/\beta & r+\alpha\eta/\beta \end{pmatrix} \begin{pmatrix} s_t - s^* \\ \lambda_t - \lambda^* \end{pmatrix}. \tag{18}$$

It is easy to see that $(s^*,\lambda^*)=(\beta/\eta,0)$ is a steady state. To analyze the dynamics around the steady state, we need to calculate the two eigenvalues of the 2x2 matrix, μ_1 and μ_2 that satisfy the characteristic equation

$$P(\mu_i) = \mu_i^2 - r\mu_i - \frac{r\alpha\eta}{\beta} = 0 \tag{19}$$

From the observation that $P(0)<0$ we conclude that there is one stable eigenvector with $\mu_1<0$, and one unstable eigenvector with $\mu_2>0$. The steady state thus exhibits saddle-point stability. We can also show that both eigenvectors are downwards sloping. As $P(r)<0$, $\mu_2>r$, and as $P'(0)<0$, we must have $\mu_1+\mu_2>0$. Furthermore, the eigenvectors (s_1,λ_1) and (s_2,λ_2) must satisfy

$$-\frac{\eta\alpha}{\beta}s_i - \frac{\alpha}{\beta}\lambda_i = \mu_i s_i \Rightarrow \frac{\lambda_i}{s_i} = -\frac{\beta}{\alpha r}\mu_i^2 \tag{20}$$

The condition reveals that both eigenvectors are downward sloping, and in (s,λ)-space, the unstable eigenvector has steeper slope.

The general solution for s_t is given by the steady state plus exponential deviations along the eigenvectors

$$s_t = \beta/\eta + Be^{\mu_1 t} + Ae^{\mu_2 t}. \tag{21}$$

From the initial condition that $s_0=0$, we have $A+B=-\beta/\eta$, so that we can derive full stock, supply, and rent paths dependent on only one parameter A:

$$s_t = \frac{\beta}{\eta}(1-(1+A)e^{\mu_1 t} + Ae^{\mu_2 t}), \tag{22}$$

$$q_t = \dot{s}_t = \frac{\beta}{\eta}(-(1+A)\mu_1 e^{\mu_1 t} + A\mu_2 e^{\mu_2 t}), \tag{23}$$

$$\lambda_t = \beta(1-\frac{q_t}{\alpha}) - \eta s_t = -(1+A)\beta(1+\frac{\beta\mu_1}{\alpha\eta})e^{\mu_1 t} - A\beta(1+\frac{\beta\mu_2}{\alpha\eta})e^{\mu_2 t}. \tag{24}$$

Termination date is determined by $\lambda_T=0$, which gives

$$\frac{(1+A)(\alpha\eta+\beta\mu_1)}{A(\alpha\eta+\beta\mu_2)} = e^{(\mu_2-\mu_1)T} \tag{25}$$

Substitution in (22) yields

$$s_T = \frac{\beta}{\eta}(1 - A^{\frac{-\mu_1}{\mu_2-\mu_1}}(1+A)^{\frac{\mu_2}{\mu_2-\mu_1}}\left(\left(\frac{\alpha\eta+\beta\mu_1}{\alpha\eta+\beta\mu_2}\right)^{\frac{\mu_1}{\mu_2-\mu_1}} + \left(\frac{\alpha\eta+\beta\mu_1}{\alpha\eta+\beta\mu_2}\right)^{\frac{\mu_2}{\mu_2-\mu_1}}\right) \tag{26}$$

It is clear that for $A \to 0$, we have $T \to \infty$, and $s_T \to \beta/\eta$, while s_T decreases in A, so that for $A>0$ we have $T<\infty$ and $s_T<\beta/\eta$. That is, the case of $A=0$ corresponds to the case that the backstop is too expensive to be ever used, $\psi>\beta$. The initial extraction rate is given by $q_0=\beta\mu_1/\eta$. The case of a competitive backstop $\psi<\beta$, $s_T=\psi/\eta$, corresponds with $A>0$, and with $q_0>\beta\mu_1/\eta$. Restated, we can interpret the parameter A (decreasing in ψ) as a proxy for technology.

To allow us to analyze NPV damages in the same fashion, we first assume that marginal damages increase at a constant rate $\theta_t=e^{\sigma t}\theta_0$ with $0<\sigma<r$. At the end we will show that if damages decrease for all values of $0<\sigma<r$, then damages will decrease for any shadow price path with decreasing NPV. For the moment, damages are given by

$$\Gamma = \int_0^T e^{(-r+\sigma)t}\theta_0 q_t dt\,, \tag{27}$$

with $\sigma<r$ so that NPV marginal damages decreases. Substitution of supply gives (where we use $\mu_2>r$)

$$\Gamma = \frac{\beta\theta_0}{\eta}\left(\frac{-(1+A)\mu_1}{r-\sigma-\mu_1}\left(1-e^{(-r+\sigma+\mu_1)T}\right) + \frac{A\mu_2}{r-\sigma-\mu_2}\left(1-e^{(-r+\sigma+\mu_2)T}\right)\right). \tag{28}$$

This damage equation can conveniently be rewriting as

$$\begin{aligned}\frac{\eta}{\beta\theta_0}\Gamma &= X + \underbrace{(X-Y)}_{negative}A \\ &\quad +(1+A)^{\overbrace{\frac{-r+\sigma+\mu_2}{\mu_2-\mu_1}}^{positive}} A^{\overbrace{\frac{r-\sigma-\mu_1}{\mu_2-\mu_1}}^{positive}}\left[\underbrace{-X\left(\frac{\alpha\eta+\beta\mu_1}{\alpha\eta+\beta\mu_2}\right)^{\frac{-r+\sigma+\mu_1}{\mu_2-\mu_1}} + Y\left(\frac{\alpha\eta+\beta\mu_1}{\alpha\eta+\beta\mu_2}\right)^{\frac{-r+\sigma+\mu_2}{\mu_2-\mu_1}}}_{negative}\right]\end{aligned} \tag{29}$$

where

$$X = \frac{-\mu_1}{r-\sigma-\mu_1} < 1 \tag{30}$$

$$Y = \frac{-\mu_2}{r-\sigma-\mu_2} > 1 \tag{31}$$

We have $0<X, Y<1$, and $X-Y<0$. We can thus conclude that the term $(X - Y)A$ is decreasing in A. Furthermore, from the characteristic equation, we can derive

$$\frac{X}{Y}=\frac{r\mu_2-\sigma\mu_2-\mu_2^2}{r\mu_1-\sigma\mu_1-\mu_1^2}\left(\frac{\mu_1}{\mu_2}\right)^2=\frac{\frac{r\alpha\eta}{\beta}+\sigma\mu_2}{\frac{r\alpha\eta}{\beta}+\sigma\mu_1}\left(\frac{\mu_1}{\mu_2}\right)^2>\left(\frac{\mu_1}{\mu_2}\right)^2=\frac{\alpha\eta+\beta\mu_1}{\alpha\eta+\beta\mu_2} \tag{32}$$

with equality when $\sigma=0$. The last term between square brackets in (29) is thus negative, and as the coefficients for the terms with A and $(1+A)$ are both positive, so that these terms are increasing in A. Thus, we have that Γ decreases in A. As A was decreasing in ψ, we have that Γ is increasing in ψ.

The above analysis ensured that damages would decrease for any damage parameter path θ_t with constant growth rate less than the interest rate. As a reference we will evaluate the damages at constant current shadow prices, that is, NPV shadow prices decrease with the interest rate. The lemma below then proves that damages will also decrease if we use a damage parameter path θ_t that strictly grows but with less than the interest rate. Recall that if the backstop becomes cheaper, ψ drops to ψ^*, then cumulative supply decreases by the termination date condition $\eta s_T=\psi$.

LEMMA 2. Consider two continuous paths $q:[0,T]\rightarrow\mathbf{R}^+$ and $q^*:[0,T^*]\rightarrow\mathbf{R}^+$, $\int_0^T q_t dt>\int_0^{T^*} q_t^* dt$, $q_T\geq 0$, $q^*_{T^*}\geq 0$, and two strictly decreasing weight functions $\theta_t:\mathbf{R}^+\rightarrow\mathbf{R}^+$ and θ^*, with θ^*/θ increasing. Furthermore, assume $q_t<q_t^*$ for all $t\leq\min\{T,\ T^*\}$, and $\int_0^T\theta_t q_t dt<\int_0^{T^*}\theta_t q_t^* dt$. Then we have as well $\int_0^T\theta_t^* q_t dt<\int_0^{T^*}\theta_t^* q_t^* dt$

Proof. It is obvious that $T^*<T$. Without loss of generality, we scale θ^* such that $\theta^*_{T^*}=\theta_{T^*}$ It is now immediate that $\int_0^{T^*}\theta_t^*(q_t^*-q_t)dt-\int_{T^*}^{T}\theta_t^* q_t dt<\int_0^{T^*}\theta_t\,(q_t^*-q_t)dt-\int_{T^*}^{T}\theta_t\, q_t dt<0$

QED.

Proof of Proposition 3

For the third proposition it turns out convenient to rewrite demand as a function of the rent

$$q_t=a(1-\frac{\lambda_t}{b}), \tag{33}$$

with substituted parameters $a=\alpha(1-\frac{\zeta}{\beta})+\frac{\psi_0-\zeta}{\psi'}$ and $b=\frac{a}{\alpha/\beta+1/\psi'}$. The transformation of the demand function is allowed because $p_t>\zeta>\psi_0$. We will see that $\partial\Gamma/\partial a>0$ and $\partial\Gamma/\partial b=0$. After we have shown that how damages depend on a and b, the proposition follows from the observation that $\partial a/\partial\psi_0>0$ and $\partial a/\partial\psi'>0$. Before we can analyze $\partial\Gamma/\partial a$ and $\partial\Gamma/\partial b$, we need the following lemma that formalizes the intuition that if in a counterfactual situation supply increases faster (or decreases slower) compared to the benchmark, then initial supply must have started at a lower level, that is, supply is delayed and NPV damages decrease. We notice that an essential characteristic in this lemma is that supply continuously decreases to zero over time, without a sudden drop at the end as is characteristic of the first model. The reason is that the substitute energy source has an upward sloping, rather than a flat, supply curve.

LEMMA 3. Consider two continuously differentiable paths $q:[0,T]\to\mathbf{R}^+$ and $q^*:[0,T^*]\to\mathbf{R}^+$, with $q_T=0$, $q^*_{T^*}=0$, $\int_0^T q_t dt = \int_0^{T^*} q_t^* dt$, and a strictly decreasing weight function θ_t:$\mathbf{R}^+\to\mathbf{R}^+$. Assume $\dot{q}_t < \dot{q}_t^* < 0$ for all $t\leq\min\{T,\ T^*\}$, then $\int_0^T \theta_t q_t dt > \int_0^{T^*} \theta_t q_t^* dt$.

Proof. First, notice that $T^*>T$, because if $T^*\leq T$ then $q_{T^*} \geq 0; q_{T^*}^* = 0$, which together with $\dot{q}_t < \dot{q}_t^* < 0$ implies $q_t > q_t^*$ for all $t<T^*$, so that $\int_0^T q_t dt > \int_0^{T^*} q_t dt > \int_0^{T^*} q_t^* dt$, contradicting the assumption. Now, define the difference between the paths: $\Delta_t = q_t^* - q_t$ where we take q_t=0 for all $t>T$. From construction we have, $\Delta_T=q^*_T>0$, $\dot{\Delta}_t > 0$ for $t<T$, and $\dot{\Delta}_t = \dot{q}_t^* < 0$ for $T<t<T^*$. We have $\int_0^T \Delta_t dt = -\int_T^{T^*} q_t^* dt < 0$, which together with continuity of Δ_t and $\Delta_T>0$ implies that $\Delta_0<0$ and there is some t^* such that $\Delta_{t^*}=0$. The difference path is thus negative on $[0,t^*]$ and positive on $[t^*,T^*]$, and the lemma now follows from the observation that $\int_0^{T^*} \theta_t\Delta_t dt = \int_0^{t^*} \theta_t\Delta_t dt + \int_{t^*}^{T^*} \theta_t\Delta_t dt < \theta_{t^*}\int_0^{t^*} \Delta_t dt + \theta_{t^*}\int_{t^*}^{T^*} \Delta_t dt = 0$. QED.

We can now prove the parts of the proposition.

LEMMA 4 Given demand as function of rents (33), cumulative supply (2), and competitive pricing $\lambda_t=e^{rt}\lambda_0$, we have $\partial\Gamma/\partial a>0$ and $\partial\Gamma/\partial b=0$.

Proof. At termination date T, $\lambda_T=b$ so that $\lambda_t = be^{r(t-T)}$ and $q_t = a(1-e^{r(t-T)})$. The level of the adjusted choke price b has no effect on supply, and thus cannot have any effect on damages! Integration over time gives $s_0 = \int_0^T q_t dt = a[T - r^{-1}(1-e^{-rT})]$. Differentiation for T and a implies dT/da<0 and dT/db=0. A higher maximum demand reduces the time window in which demand is exercised. Differentiation over time of supply gives $\dot{q}_t = -rae^{r(t-T)} < 0$. It is clear that $\frac{\partial\dot{q}_t}{\partial T} > 0; \frac{\partial\dot{q}_t}{\partial a} < 0$, and thus $\frac{d\dot{q}_t}{da} < 0$. We can now apply lemma 2.

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