# PARETO OPTIMALITY IN THE EXTRACTION OF FOSSIL FUELS AND THE GREENHOUSE EFFECT
## A NOTE

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## Abstract

This note generalizes the Solow-Stiglitz efficiency condition for natural resources to the problem of fossil fuel extraction with a greenhouse effect. The generalized optimality condition suggests that the greenhouse effect implies overextraction in the sense of leaving future generations a wrongly composed wealth portfolio with too few natural resources relative to man-made capital. This judgment is independent of society's ethical preferences concerning the well-being of future generations.


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*1. Introduction*

A forward-looking society has to solve two fundamental economic problems. It has to decide how much wealth it wants to transfer from the present to the future and how its wealth portfolio of natural resources and man-made capital is to be composed, given that natural resources can be extracted and transformed into capital by means of producing investment goods. While the analysis of the first decision requires assumptions about society's intertemporal preferences including difficult ethical considerations concerning the proper weight to be given to future generations, the second decision is potentially simpler insofar as technological efficiency conditions that make use of the principle of Pareto optimality may suffice.

For the case of exhaustible natural resources that have zero extraction costs, that serve as factors of production and that produce no environmental waste, Solow (1974) and Stiglitz (1974) have solved the wealth composition problem by showing that the speed of resource extraction should be chosen such that the marginal product of the natural resource grows at a rate that equals the marginal product of capital. The Solow-Stiglitz condition is a necessary condition for Pareto optimality because when this condition is satisfied, it is impossible to increase consumption of man-made goods in one period of time without decreasing it in another.

As is well known, the Solow-Stiglitz condition is the market analogue of a rule derived by Hotelling (1931) which describes the behavior of well-functioning competitive markets for natural resources with perfect foresight. According to Hotelling's rule, the price of the exhaustible resource will grow at a rate that is equal to the market rate of interest, for if not, wealth maximizing resource owners would shift extraction from periods with low to periods with high discounted prices until any differences between the discounted prices have disappeared. Hotelling's rule coincides with the Solow-Stiglitz efficiency condition when the market rate of interest equals the marginal product of capital and the price of the natural resource equals the marginal product of the resource.

The Solow-Stiglitz condition was derived a quarter of a century ago when the Meadows report (Meadows et al. 1972) had alerted the world of the problem of the exhaustibility of natural resources shortly before the 1973 oil crisis. Recently, the Stern report (Stern et al. 2006) has alerted the world of the huge costs in terms of lost GDP resulting from the greenhouse effect that the accumulation of carbon dioxide in the atmosphere is causing, arguing that this effect is "the greatest and widest-ranging market failure ever seen" (p. 1). It now appears that the greenhouse effect is not just a side aspect of the extraction of fossil fuels but of paramount importance for the economics of resource extraction. As the stock of carbon is gradually taken out of the ground, the stock of carbon dioxide accumulates in the air, and possibly the limited absorption capacity of the latter will slow down the extraction of fossil fuels more and earlier than the limited availability of the former. There is a double stock adjustment problem for natural resources, and a triple one in society's portfolio problem: Society has to decide on how much man-made capital, how many unused fossil fuels and how much waste in the form of carbon dioxide it wants to bequeath to future generations.

This note extends the Solow-Stiglitz efficiency condition to the case of counterproductive effects resulting from the accumulation of a stock of carbon dioxide in the atmosphere. In the spirit of the Stern report, global warming is seen as technological problem that creates measurable damage in terms of lost growth as well as protection and reaction costs. Think for example of the dykes, the new buildings, the air conditioning and dislocation costs that a change in the world climate would require. As the protection and reaction cost reduces the output remaining for investment and consumption, the quality of the environment in the sense of additional carbon dioxide being absent from the atmosphere can be seen as an argument of the aggregate production function. The note also incorporates stock-dependent extraction costs to take account of the fact that the resources lie in different sites with different site-specific extraction costs. Following Kemp and Long (1980) and Sinn (1981, 1984), it is assumed that the sequence of extraction is in the inverse order of the site-specific extraction costs.

The problem of economic growth with depletable resources and the accumulation of waste in the atmosphere has been studied by a number of authors in rich intertemporal optimization models. See, in particular, Krautkraemer (1985, 1998), Kolstad and Krautkraemer (1993) and Withagen (1995). While this literature thoroughly analysed the implications of environmental variables on the growth process and derived interesting conclusions, it has not explicitly addressed the question of intertemporal Pareto optimality. Moreover, it typically assumed waste to be an argument of the utility rather than the production function, to capture the role of environmental amenities. The model used here comes closer to a special variant of a more general intertemporal setting that Kamien and Schwartz (1982, p. 58) once described. Kamien and Schwartz treat resource extraction as a factor of production and include the stock of the accumulated waste as an argument in the production function. However they do not derive the conditions for Pareto optimality.

## *2. The Model*

Let *S* be the stock of (reduced, oxidizable) carbon underground, *R* the current flow of carbon extraction and *P* the accumulated stock of carbon dioxide in the atmosphere. To keep things simple, assume a given mix of fossil fuels and hence a given energy output per unit of carbon or carbon dioxide.[1] Assume moreover that a given fraction of the produced carbon dioxide is absorbed by the oceans and the biomasses on land.[2] Then, $P = a + b(S_0 - S)$ where *a* is some initial stock of *P*, *b* is a technological parameter following from the laws of organic

[1] Produced energy (including energy waste) relative to carbon burned is higher the higher the hydrogen content of fossil fuels. However, the emissions of carbon dioxide are in strict proportion to the reduced carbon actually burned (and not wasted because of insufficient combustion).

[2] This fraction is about 55%. The remainder, 45% of the emitted carbon, accumulates in the air with hardly any natural decay. See, e.g., Houghton (2004, p. 32). If anything, with a continuation of global warming, the fraction of carbon dioxide emissions that stays in the air will be gradually increasing. The approach of this paper could

chemistry, geology and meteorology, and $S_0$ is the initial stock of *S*. Thus, without loss of generality, the economy's output *Y* net of the damage caused by the stock of carbon dioxide in the atmosphere can be taken to be given by a neo-classical production function

(1) $$Y_t = F(K_t, R_t, S_t, t)$$

where *K* is the stock of capital and *t* indicates the time period. It is assumed that $F_K, F_R, F_S > 0$ and $F_{KK}, F_{RR}, F_{SS} < 0$. Note that the resource in situ, *S*, can be treated like a production factor since the damage from carbon dioxide is smaller the larger the stock of carbon that is not extracted. In fact, *S* can be interpreted as a measure of environmental quality so that (1) is basically the production function proposed in the Stern report (p. 124). Accordingly, $F_S$ denotes both the marginal benefit of an enhanced environmental quality and the marginal damage of the stock of carbon dioxide in the atmosphere. $F_{SS} < 0$ implies that the marginal damage is larger, the more carbon dioxide has already been emitted.

Output is used for consumption of final goods *C*, investment goods *I*, and resource extraction *X*, where the extraction cost function is $X(S,R)$ with $X_S < 0$ and $X_R > 0$. $X_S < 0$ reflects the assumption that the extraction of different sites is in the inverse order of extraction costs.

(2) $$Y_t = C_t + I_t + X(S_t, R_t).$$

While the flow controls *C*, *I* and *R* can freely be chosen in line with (2), the state variables *K* and *S* evolve according to

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easily be reinterpreted for the more general case where $P = \varphi(S_0 - S)$ where $\varphi' > 0$ and the curvature of $\varphi$

(3) $$K_{t+1} - K_t = I_t$$

and

(4) $$S_{t+1} - S_t = -R_t \,.$$

Equations (1) through (4) hold for all *t*.

Let us now assume that the economy evolves in a Pareto efficient way and see what this implies. Pareto efficiency means that a technically feasible perturbation of the time paths of the economy's variables is unable to increase consumption in one period without decreasing it in another. To be specific, consider a perturbation that keeps all time paths unchanged until time $t^*-1$ and again from $t^*+2$ onwards, while $C_{t^*+1}, I_{t^*}, I_{t^*+1}, R_{t^*}, R_{t^*+1}, K_{t^*+1}$ and $S_{t^*+1}$ are variable. Note that because of (3) an (4) this assumption implies that $K_{t^*}$ and $S_{t^*}$ are fixed. In addition, keep $C_{t^*}$ unchanged to see whether the perturbation is able to change $C_{t^*+1}$; if it is not, the time path is efficient.

To carry out the perturbation differentiate equations (1) and (2) totally for $t = t^*$ and $t = t^*+1$ setting the derivatives of those variables that are assumed to be unchanged equal to zero. This yields

(5) $$\mathrm{d}\, I_{t^*} = (F_{R_{t^*}} - X_{R_{t^*}})\,\mathrm{d}\, R_{t^*}$$

and

(6) $$\mathrm{d}\, C_{t^*+1} = -\mathrm{d}\, I_{t^*+1} + F_{K_{t^*+1}}\,\mathrm{d}\, K_{t^*+1} + (F_{R_{t^*+1}} - X_{R_{t^*+1}})\,\mathrm{d}\, R_{t^*+1} + (F_{S_{t^*+1}} - X_{S_{t^*+1}})\,\mathrm{d}\, S_{t^*+1} \,.$$

As the perturbation is limited to periods *t** and *t**+1,

captures the endogenous change in the oceanic and land-biological absorption processes.

(7) $$\mathrm{d}\,I_{t^*} = -\mathrm{d}\,I_{t^*+1}$$

and

(8) $$\mathrm{d}\,R_{t^*} = -\mathrm{d}\,R_{t^*+1},$$

and because of (3) and (4) it holds that

(9) $$\mathrm{d}\,K_{t^*+1} = \mathrm{d}\,I_{t^*}$$

and

(10) $$\mathrm{d}\,S_{t^*+1} = -\mathrm{d}\,R_{t^*}.$$

Using (7) - (10), equation (6) can be converted to

(11) $$\mathrm{d}\,C_{t^*+1} = (1 + F_{K_{t^*+1}})\,\mathrm{d}\,I_{t^*} - (F_{R_{t^*+1}} - X_{R_{t^*+1}})\,\mathrm{d}\,R_{t^*} - (F_{S_{t^*+1}} - X_{S_{t^*+1}})\,\mathrm{d}\,R_{t^*}.$$

If equation (5) is used to eliminate $\mathrm{d}\,I_{t^*}$, (11) becomes

(12) $$\mathrm{d}\,C_{t^*+1} =$$

$$(1 + F_{K_{t^*+1}})(F_{R_{t^*}} - X_{R_{t^*}})\,\mathrm{d}\,R_{t^*} - (F_{R_{t^*+1}} - X_{R_{t^*+1}})\,\mathrm{d}\,R_{t^*} - (F_{S_{t^*+1}} - X_{S_{t^*+1}})\,\mathrm{d}\,R_{t^*}.$$

This equation shows that, in general, consumption in period $t^*+1$ will change after the perturbation in the time paths of the model's variables, indicating the possibility of Pareto improvements. However, if the time paths around which the perturbations are carried out are Pareto optimal, then $\mathrm{d}\,C_{t^*+1} = 0$. Obviously, this is the case if

(13) $$1+F_{K_{t^*+1}}=\frac{F_{R_{t^*+1}}-X_{R_{t^*+1}}+F_{S_{t^*+1}}-X_{S_{t^*+1}}}{F_{R_{t^*}}-X_{R_{t^*}}}.$$

Equation (13) gives the marginal condition for a Pareto optimal resource extraction policy with global warming and stock dependent extraction costs.

*3. Interpretation*

To interpret the optimality condition consider first the Solow-Stiglitz case where $X_R = X_S = F_R = F_S = 0$. Equation (13) becomes

(14) $$F_{K_{t^*+1}}=\frac{F_{R_{t^*+1}}}{F_{R_{t^*}}}-1\ ,$$

confirming the rule that the rate of increase in the marginal product of the natural resource equals the marginal product of capital. Choosing among two means of transferring wealth to the future, man-made capital and the resource in situ, society should compose its portfolio such that both means have the same marginal rate of return. Giving up a unit of consumption today and investing it for one period, makes it possible to consume $F_{K_{t^*+1}}$ more than this unit one period ahead. Postponing the extraction of $1/F_{R_{t^*}}$ units of the natural resource by one period also means giving up a unit of consumption of man-made goods today. The reward of doing so is that, after the period, output and hence consumption will increase by $F_{R_{t^*+1}}/F_{R_{t^*}}-1$ units above the one unit of consumption given up. There is such a reward to postponing extraction because the resource is more scarce in the future and is therefore making higher marginal contributions to aggregate output.

Next, allow for damages resulting from the accumulated stock of carbon dioxide in the atmosphere, while continuing to neglect extraction costs. Equation (13) becomes

(15) $$F_{K_{t^*+1}} = \frac{F_{R_{t^*+1}}}{F_{R_{t^*}}} - 1 + \frac{F_{S_{t^*+1}}}{F_{R_{t^*}}} \ .$$

The new term in this formula on the right measures the marginal environmental benefit from keeping the carbon underground. The $1/F_{R_{t^*}}$ additional units of the natural resource that temporarily stay underground when society gives up one unit of consumption not only make it possible to generate more output and man-made consumption after one period because the growing resource scarcity will then generate a higher marginal product of resource consumption. They also generate a further $F_{S_{t^*+1}}/F_{R_{t^*}}$ units of output and man-made consumption as fewer protective measures have to be taken. The labor, capital and oil needed to build the additional dikes, buildings and air conditioning devices protecting mankind against global warming can be used to produce consumption goods instead. If society pursues a Pareto efficient development path, these two future advantages of curtailing consumption by way of extracting a bit less in the present must be equal to the future advantage in terms of higher output and consumption that would result from giving up a bit of present consumption for the purpose of additional investment.

Another interpretation can be given to equation (15) if it is written as

(16) $$F_{R_{t^*}}(1 + F_{K_{t^*+1}}) - F_{S_{t^*+1}} = F_{R_{t^*+1}} \ .$$

Suppose, society chooses between two strategies of generating additional consumption in period $t^*+1$ by way of extracting one additional unit of carbon. The first is the capitalist strategy: The additional unit of carbon is extracted for productive purposes right away in period $t^*$ , and the additional output is invested so as to produce more consumption goods in $t^*+1$. The other is the green strategy: The additional unit of carbon is extracted later, in period $t^*+1$, and is then used to generate more consumption goods directly, without the detour via investment. The additional consumption goods generated by the capitalist strategy are measured by the left-hand side of the equation. Their quantity is diminished by the environmental damage $F_{S_{t^*+1}}$ that this strategy causes. The additional consumption goods generated with the green strategy, $F_{R_{t^*+1}}$, are measured by the right-hand side of the equation. The equation shows that Pareto efficiency prevails if both, the capitalist and the green strategies, are equally successful at the margin.

Unfortunately, of course, Pareto efficiency does not prevail in reality, as market forces do not take account of the environmental damage. As markets at best pursue the Hotelling rule $F_{R_{t^*}}(1+F_{K_{t^*+1}})=F_{R_{t^*+1}}$ it follows that

(17) $$F_{R_{t^*}}(1+F_{K_{t^*+1}})-F_{S_{t^*+1}}<F_{R_{t^*+1}} \qquad \text{(market solution).}$$

Thus, without government intervention, the green strategy is clearly better at the margin.

Condition (17) implies that the marginal product of the resource rises too quickly relative to what the marginal product of capital and the marginal environmental benefit of the resource in situ demand. This means that the extraction path is too steep, with too much extraction in the present and a too rapid decline over time. Because of “the greatest and widest-ranging market failure ever seen”, to repeat the words of the Stern report, society chooses a suboptimal composition of the wealth portfolio that it transfers to future generations with too little natural capital relative to man-made capital.[3]

Consider now the case where stock dependent extraction costs are added. This is the case captured by equation (13) which can also be written as

$$(18) \qquad F_{K_{t^*+1}} = \left( \frac{F_{R_{t^*+1}} - X_{R_{t^*+1}}}{F_{R_{t^*}} - X_{R_{t^*}}} - 1 \right) + \frac{F_{S_{t^*+1}}}{F_{R_{t^*}} - X_{R_{t^*}}} - \frac{X_{S_{t^*+1}}}{F_{R_{t^*}} - X_{R_{t^*}}} .$$

The common denominator of the terms on the right-hand side reflects the fact that with marginal extraction costs of size $X_{R_{t^*}}$ an additional unit of man-made consumption goods in period $t^*$ costs $1/(F_{R_{t^*}} - X_{R_{t^*}})$ units of carbon. The first term on the right-hand side again measures society's rate of return from postponing consumption by way of resource conservation, where other than in (14) and (15), the return is now measured in terms of the relative increase in the marginal product of resource input in production net of marginal extraction costs. The second term measures the rate of return from an improved environmental quality as reflected by a temporarily higher resource stock, the global warming effect. The third term measures a further rate of return from resource conservation resulting from the fact that a period ahead marginal extraction costs will be lower as more of the more easily accessible sites remain available. While the formula is significantly more complicated than before, the role of the environmental externality does not change, having the same qualitative implications for a judgment about the optimality of market processes as explained

[3]This statement would have to be modified in the case of insecure property rights.. While (15) and (16) indicate that Pareto optimality requires the marginal product of the resource to rise at a rate below the marginal product of capital, imperfect property rights in the resource ceteris paribus imply that the marginal product of the resource rises at a rate above the marginal product of capital (see Long 1975 and Konrad, Olsen and Schöb 1994). In the current setting without exploration costs imperfect property rights mean that fossil fuels are extracted faster than the Hotelling rule predicts, but global warming means that even the Hotelling rule implies too rapid extraction. As Bohn and Deacon (2000) have shown, the influence of insecure property rights is likely to be reversed, however, if there are exploration costs, for resource owners do not even dare to finance the start-up investments.

above. As the extraction cost terms entering the formula reflect private costs with no externalities involved, it remains true that market forces extract the resource faster than would be Pareto optimal.

Note finally that a simplification is possible without much loss of generality if a continuous-time formulation is chosen and marginal extraction cost is assumed to depend only on the stock in situ with unit extraction costs $g(S),\ g' < 0$, such that $X(S,R) = g(S)R$. With continuous time, equation (18) becomes

$$F_K = \frac{\dot{F}_R - \dot{X}_R + F_S - X_S}{F_R - X_R} \ .$$

Substituting $X_R = g(S)$, $X_S = g'(S)R$ and $\dot{X}_R = g'(S)\dot{S} = -g'(S)R$, as $\dot{S} = -R$, and rearranging terms gives

$$F_K = \frac{\dot{F}_R + F_S}{F_R - g(S)} .$$

*3. Concluding remarks*

This note has shown that the stock externality resulting from the increased concentration of carbon dioxide in the atmosphere plays an important role in the conditions for intertemporal Pareto externality, reducing the efficient rate of increase in the marginal product of carbon consumption below what otherwise would have been optimal. As this externality is not taken into account by market forces society hands future generations a wrongly composed wealth portfolio with a too little stock of the resource in situ relative to the stock of man-made capital.

In a general sense, this implication is not surprising. After all, it is a common political premise that the damages caused by global warming imply that carbon extraction should be reduced. The political initiatives in this regard range from the Kyoto Protocol to the United Nations Framework Convention on Climate Change in 1997 to the G8 Summit in Heiligendamn in 2007. However, not all reasons given in the public and scholarly debates can be subsumed under the argument presented here.

For example, the normative result derived does not hinge on the assumption of adjustment costs (Quiggin and Horowitz 2003) or option values (Krutilla and Fisher 1975) which might make conservation a wise strategy. Neither does it follow from intergeneration equity considerations or philosophical arguments that would legitimate the use of a lower discount rate than markets do (Anand and Sen 2000; Solow 1974, p. 9; Stern et. al. 2006, Annex to chapter 2). In fact, the result is extremely robust insofar as it simply depends on the principle of Pareto optimality which is about the weakest welfare criterion available. Rawlsians, Musgravian believers in intergeneration equity or non-discounters alike should agree to the goal of increasing consumption in one period or for one generation without reducing it for another, and this goal is enough to prove overextraction when there is a positive stock externality of the resource in situ.

Note, though, that the Pareto conditions derived do not lend themselves to defend extreme conservationist views. They do not imply that some of the carbon be permanently preserved, but only that the extraction be postponed. To make the argument for permanent preservation, much stronger assumptions about intertemporal preferences, the size of the available stock and limiting properties of the production function would be needed than were made in this note. Postponing extraction does not mean that some of the carbon available in the earth's crust should never be used. It only means that measures are appropriate to reduce the speed of extraction and global warming. It is this sense only in which this note supports the recommendations of the Stern report as well as other environmentalist concerns.

Fortunately, for the time being, that should not make a major practical difference in terms of the policy measures against the terrors of global warming that ought be taken.

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