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The Green Paradox and Learning-by-doing in the Renewable Energy Sector

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The Green Paradox and Learning-by-doing in the Renewable Energy Sector

Daniel Nachtigall* and Dirk Rübbelke**

We investigate the effect of climate policies on fossil fuel use in the presence of a clean alternative technology that exhibits learning-by-doing. In a two-period framework, the costs of clean and regenerative energy in the second period are decreasing with the amount of this energy produced in the first one. While a carbon tax on present fossil fuels always reduces the use of the conventional energy source, the effect of a subsidy for regenerative energy is ambiguous and depends on the size of the learning effect. For small learning effects, a subsidy reduces the present use of fossil fuels since their substitute becomes comparatively cheap. However, for larger learning effects, a subsidy leads to the green paradox as the cost reduction in the clean energy sector reduces the future demand for conventional energy and brings forward extraction. We conclude that the best way to reduce present CO_2 *emissions is the implementation of a carbon tax. If the learning effect is small, the carbon-tax revenues should additionally finance the subsidy for the renewable energy.*

Keywords: climate change, exhaustible resources, regenerative energy, green paradox

JEL Classification: Q38, Q54, Q28, H23

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1 Introduction

Climate change may be the biggest challenge of humanity in the 21^{st} century and is directly related to the emissions of greenhouse gases (GHG) such as carbon dioxide (CO_2). As the latest report of the Intergovernmental Panel of Climate Change (IPCC, 2007) suggests, avoiding the largest risk from climate change could require GHG emissions to peak within the next 20 years. Several policies have been proposed that aim either at reducing the emissions that arise from the combustion of fossil fuels, such as a carbon tax, or at promoting substitutes of polluting energy sources such as subsidies for renewable energies. However, there is growing concern that those policies may have opposed effects and actually would accelerate climate change because they may incentivize the owners of fossil fuels to bring forward the extraction. This concern is known as green paradox and was first coined by Sinn (2008).

In this paper, we examine the effect of climate policies on the use of fossil fuels in the presence of learning-by-doing (LBD) in the renewable energy sector. Carbon taxes or subsidies for renewable energy favor the use of clean energies. However, LBD causes future costs of clean energy to decrease which will reduce future demand for fossil fuels and may yield an increase of the supply of non-renewable energy sources in the present. Since the combustion of fossil fuels is directly related to the emission of CO_2 and other GHG, we ask whether the green paradox can arise as a consequence of present climate policies.

We find the standard result of the green paradox, meaning that a carbon tax that will be implemented in the future brings forward fossil fuel extraction while a carbon tax on present fossil fuels reduces its use. However, the effect of a subsidy for renewable energy on the present demand for fossil fuels is ambiguous and depends on the size of the LBD effect. For small LBD, the subsidy leads to a reduced use of the polluting energy because the substitute becomes comparatively cheap. With larger LBD the future costs of renewable energy are decreasing so much, that comparatively less fossil fuels are employed in the future which, in turn, leads to higher extraction today. If the tax revenues from the carbon tax are used for the subsidy, the unambiguous result from the taxation vanishes and we come to the same conclusion as in the subsidy case.

The literature of the green paradox relates the theory of exhaustible resources (Hotelling (1931), Dasgupta and Heal (1979) and Long and Sinn (1985)) with climate policy. Sinclair (1992) was the first economist who analyzed climate policies taking into account the reaction of profit maximizing resource owners while other authors such as Ulph and Ulph (1994) and Withagen (1994) extended his approach.

Most papers assume the existence of a perfect substitute in form of a non-polluting backstop technology[1]. A common assumption is that the clean substitute supplies an unlimited amount of energy at constant marginal costs which are higher than the (constant) extraction costs of the fossil fuels. In such a setting, the equilibrium that arises from profit maximization of the resource owner is determined by two phases. In the first phase, only the fossil fuels are used up to the (economic) exhaustion of the resource, while in the second phase only the backstop technology delivers energy.

In this paper, we assume the clean energy to be also a perfect substitute for fossil fuels, but to exhibit increasing marginal costs, following Chakravorty et al. (2012). This can be justified by the fact that at any time the most appropriate locations for the installation of renewable facilities are used first and the productivity of additional facilities is therefore decreasing. Under this assumption, both the dirty and the clean energy are employed simultaneously as shows Tahvonen and Salo (2001). Furthermore, Gerlagh (2011) and Grafton et al. (2012) show that the stock of fossil fuels will be exhausted completely as long as the fossil fuels exhibit constant extraction costs.

Since the stock of resources will be exhausted completely, we analyze the dynamic problem within a two-period framework analogously to Hoel and Jensen (2012) where the first period represents the next 20 years and the second period the remaining future up to infinity.[2] We assume the production costs of renewable energy in the second period to be negatively related to the previous production of renewable energy, reflecting the LBD effect. Arrow (1962) was the first economist who postulated that technological change may not only be induced by research and development, but also by cumulative experience. Empirically, Duke and Kammen (1999) and McDonald and Schrattenholzer (2001) report lower production costs with increasing production for solar panels and wind energy[3]. Oren and Powell (1985) and Chakravorty et al. (2012) relate LBD in the backstop technology with the extraction of fossil fuels in a completely dynamic model[4]. However, both papers focus on the evolution of resource prices rather than on the emissions in the nearer future.

The paper is organized as follows. Section 2 introduces the basic model. In Section 3,

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[1] In the literature of exhaustible resources see e.g. Heal (1976), Hoel (1978) and Hoel (1983) and for the green paradox literature see Hoel and Kverndokk (1996), Tahvonen (1997), Chakravorty et al. (1997), Strand (2007) and Fischer and Stephen (2012)

[2] Other two-period models have been employed by Hoel (2010) and Eichner and Pethig (2011).

[3] For example, McDonald and Schrattenholzer (2001) find a cost reduction in average costs of wind and solar energy between 5 and 35 % when the cumulative production is doubled.

[4] Oren and Powell (1985) assume the marginal costs of the backstop to be constant and come to the standard result where the fossil fuel is first exhausted completely and the clean energy is used afterward. Chakravorty et al. (2012) demonstrates that the resource price exhibits cycles due to environmental regulation, LBD and scarcity.

the effects of various climate policies are analyzed. In particular, we analyze a carbon tax (Section 3.1.), a subsidy (Section 3.2.) and a subsidy that is financed by a carbon tax (Section 3.3.). Finally, Section 4 concludes.

2 Basic Model

We consider a stylized model with two time periods which is based on an approach by Hoel (2010). The first period represents the near future, say the next 20 years whereas the second period represents the remaining future. Thus, we are still in a setting of an infinite time horizon. There is a single output good which is produced by using energy from fossil fuels x and renewable sources y where both are assumed to be perfect substitutes. The production functions in the first period $f(x, y)$ and in the second period $F(X, Y)$ are increasing in their arguments but exhibit decreasing marginal productivity such that $f_x(x, y) = f_y(x, y) > 0$, $f_{xx}(x, y) = f_{yy}(x, y) = f_{xy}(x, y) < 0$ as well as $F_X(X, Y) = F_Y(X, Y) > 0$ and $F_{XX}(X, Y) = F_{YY}(X, Y) = F_{XY}(X, Y) < 0$.[5] In the following, lower-case letters always refer to variables and functions in the first and capital letters to variables and functions in the second period.

The renewable energy is produced with increasing marginal costs in both periods, i.e. $c_y(y) > 0$, $c_{yy}(y) > 0$, $C_Y(y, Y) > 0$ and $C_{YY}(y, Y) > 0$. This reflects the fact that the most appropriate locations for the installation of the renewable facilities are used first and the productivity of additional facilities is therefore decreasing. Consider for example an onshore wind farm. While the first wind farm is constructed in the area where the wind blows strongest and most steadily, any further wind farm will have less favorable conditions. Furthermore, most renewable energy sources deliver energy unsteadily across the day and therefore have to be flanked by energy storages which leads to higher costs as more renewable energy is employed.

To incorporate the LBD effect, we assume the costs in the second period to fall with increasing quantity of renewable energy installed in the first period. More precisely, we suspect $C(y, Y)$ to be falling in y, but at a decreasing rate, meaning that the LBD effect becomes less strong the more renewable energy has been produced in the first period. Formally, we have $C_y(y, Y) < 0$ and $C_{yy}(y, Y) > 0$ as well as $C_{yY}(y, Y) = C_{Yy}(y, Y) < 0$ where the latter states that the marginal costs of regenerative energy in the second period decrease with experience. Figure 1 illustrates some cost curves depending on the amount of renewable energy produced in the first period.

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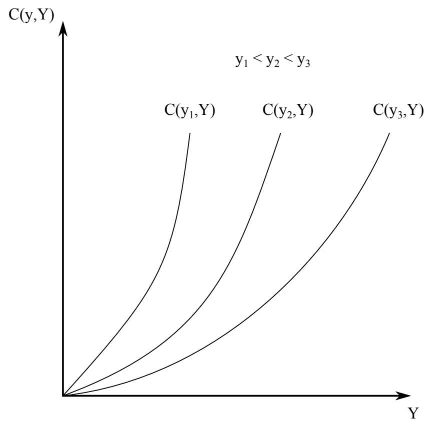
[5] The subscripts denote the first and second derivatives with respect to the corresponding variables.

Figure 1: Learning-by-Doing (Source: Own illustration)



The price of the output good is normalized to 1 in each period and there is a representative firm which maximizes its profit that is given by[6]

$$\pi = f(x, y) - (p + t)x - c(y) + \beta[F(X, Y) - (P + T)X - C(y, Y)] \tag{1}$$

where β is the standard discount factor and t and T denote the tax on fossil fuels in the corresponding period[7]. The prices p and P are the prices the firm pays to the resource sector.

The resource sector consists of a single resource owner who faces constant extraction costs g in each period. Under this assumption and the assumption of increasing marginal costs for renewable energy, the resource owner will completely exhaust the stock of resources $\bar{X}$ as long as the price is higher than the extraction costs implying that $x+X = \bar{X}$.[8] Full exhaustion occurs because we are still in a setting of an infinite time horizon where the second period represents the remaining future. Given the infinite time horizon, the resource owner will choose the optimal price path that allows him to extract all the resources even if the costs of the renewable technology are decreasing.

Then, the resource owner's profit is given by

$$\pi = px - gx + \beta[(\bar{X} - x)P - (\bar{X} - x)g].$$

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[6] Implicitly, we assume that the demand for the output good is completely inelastic and the firm can sell any amount to the consumers at this price.

[7] In fact, we consider the case where a tax that was introduced in the first period will be removed in the second one. However, our results will not change for a tax that applies in both periods as long as the discount factor β is smaller than one.

[8] See for example Gerlagh (2011) and Grafton et al. (2012).

The resource owner maximizes profits by choosing the extraction amount in the first period. Rearranging the first-order condition (FOC) gives

$$P = g + \frac{p - g}{\beta}. \tag{2}$$

This is Hotelling's rule for a two-period framework, which determines the optimal price path. Essentially, the rule states that the net profit in the future period $P - g$ must equal the inflated scarcity rent in order to guarantee absence of arbitrage. In a completely dynamic setting, the price path of the resource follows $p(t) = g + e^{rt}\lambda(0)$ where $\lambda(0) = p(0) - g$ represents the scarcity rent.

The output sector takes into account the pricing behavior of the resource sector. Thus, we can rewrite the profit function of the output sector when plugging (2) into (1) and taking into account that the fossil fuel is exhausted completely as

$$\pi = f(x, y) - c(y) - (t + g)x + \beta[F(\bar{X} - x, Y) - C(y, Y) + (T + g)x] - \beta \bar{X} z \tag{3}$$

with $z = \frac{p-g}{\beta} + g + T$. The firm maximizes profits by choosing the quantities x, y and Y which on their part depend on the two tax rates t and T. The FOCs of the firm are given by:

$$\frac{\partial \pi}{\partial x} = 0 \quad \Leftrightarrow \quad f_x - (t + g) = \beta[F_X - (T + g)] \tag{4}$$

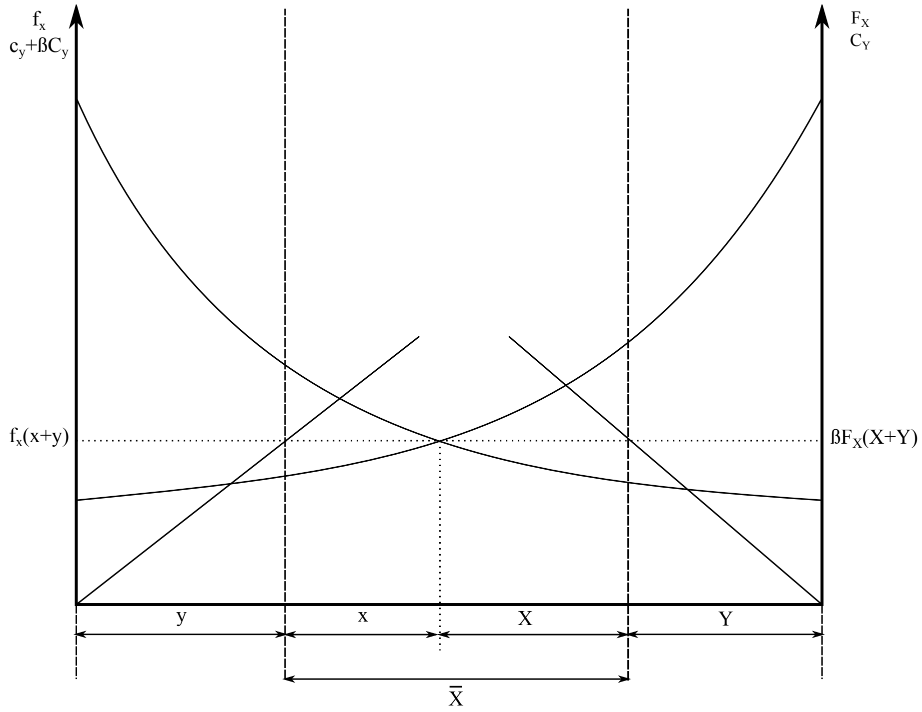
$$\frac{\partial \pi}{\partial y} = 0 \quad \Leftrightarrow \quad f_y = c_y(y) + \beta C_y(y, Y) \tag{5}$$

$$\frac{\partial \pi}{\partial Y} = 0 \quad \Leftrightarrow \quad F_Y = C_Y(y, Y) \tag{6}$$

Figure 2 incorporates the three equilibrium conditions given by the equations above.

The falling curves from upper left to lower right and from upper right to lower left represent the marginal products of both types of energy for the first and second period, respectively. The ascending lines starting from the origin illustrate the marginal cost curves of renewable energy for both periods, i.e. the right hand sides of equations (5) and (6). In the center of Figure 2, the total amount of fossil fuels $\bar{X}$ is represented by the two vertical lines. The output firm chooses the amount of fossil fuels as to equalize the marginal products of energy in both periods which is shown by the intersection of the marginal product curves. Furthermore, the output firm employs renewable energy as long as the marginal costs are smaller than the marginal product. Graphically, the amount of y is determined by the intersection of the marginal cost curve with the dashed

Figure 2: Equilibrium Conditions (Source: Own illustration)



line and the left vertical line. The same applies for the amount of Y.

In the next section, we will analyze how climate policies affect the use of fossil fuel in the first period. In particular, we analyze whether the green paradox arises when we increase the tax rates t or T, subsidize the renewable energy y or establish a budget-neutral tax and subsidy scheme where the carbon tax revenues are used to finance the subsidies.

3 Evaluating Climate Policies

3.1 Effect of Taxation

Before analyzing the effect of a present tax increase on the present extraction of fossil fuels x, we turn to the case of the standard green paradox. According to the paradox, the extraction in the first period should increase with higher taxation in the future period because fossil fuels in the future become relatively more expensive. Formally, we would expect $\frac{\partial x}{\partial T} > 0$. In order to quantify this partial derivative, we differentiate the FOCs (4), (5) and (6) with respect to T, taking into account that the endogenous variables x,

y and Y depend on the tax rate. Thus, we get

$$\underbrace{\begin{pmatrix} f_{xx} + \beta F_{XX} & f_{xy} & -\beta F_{XY} \\ f_{yx} & f_{yy} - c_{yy}(y) - \beta C_{yy}(y,Y) & -\beta\psi \\ -F_{YX} & -\psi & F_{YY} - C_{YY}(y,Y) \end{pmatrix}}_{M} \begin{pmatrix} \frac{\partial x}{\partial T} \\ \frac{\partial y}{\partial T} \\ \frac{\partial Y}{\partial T} \end{pmatrix} = \begin{pmatrix} -\beta \\ 0 \\ 0 \end{pmatrix} \tag{7}$$

The LBD effect is represented by the parameter $\psi = C_{yY}(y,Y) < 0$ where higher absolute values of ψ indicate stronger learning effects.

The effect of taxation in the second period on x is finally given by

$$\frac{\partial x}{\partial T} = (-\beta)\frac{1}{det(M)} \underbrace{[f_{yy} - c_{yy}(y) - \beta C_{yy}(y,Y)][F_{YY} - C_{YY}(y,Y)] - \beta\psi^2}_{N} \tag{8}$$

In the following, we focus on a specific cost function that incorporates LBD in a multiplicative way, i.e. $C(y,Y) = c_0 + aY^b y^{-c}$. According to Thompson (2010), this type of cost function is commonly used in the LBD literature.[9] We show in the Appendix that $det(M)$ is negative whenever $b \geq c+1$ - though $det(M)$ may be also negative when $b < c+1$. Given the functional form and the assumptions about the cost parameters, also the sign of the numerator is positive and the standard result of the green paradox occurs.

Next, we turn to the effect that an increase of T has on the quantity of the renewable energy y and Y. Analytically, the effect is ambiguous and depends, in particular, on the size of the learning effect ψ. For small values of ψ, a tax increase yields higher use of Y and lower use of y. However, as the size of the learning effect gets larger, we observe less input of Y and more input of y in response to taxation in the second period.

For the interpretation of this result, we distinguish two different effects: the taxation effect and the experience effect which is caused by LBD. The taxation effect results from the fact, that the tax causes a differential between the marginal product of fossil fuels in the first and second period according to equation (4). In Figure 2, the curve for the marginal product in the second period would shift downwards. The initial reaction of the output sector will be to employ less fossil fuel in the future, but more today. As a consequence, this affects also the use of renewable energy since it is a perfect substitutes for fossil fuels. In particular, a decrease of X causes the marginal product of energy to increase and finally leads to a higher use of Y. The same logic applies to the demand of

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[9] See for example Spence (1981) and Dutton and Thomas (1984), where the latter makes use of a progress function which has basically the same features as the cost function we employ.

y which is falling because of a higher use of x. Graphically, both y-axes would shift to the left until the marginal costs equal again the corresponding marginal product. Thus, we conclude that the taxation effect causes a higher use of x and Y and a lower use of X and y.

We next turn to the experience effect. The experience effect affects the input demand of the firm via two channels. First, a higher use of regenerative energy today will decrease the marginal costs of renewable energy in the second period which finally leads to an increase in Y according to equation (6). Second, the firm takes into account the amount of renewable energy in the second period when optimizing its use of y. The more renewable energy the firm plans to apply in the future, the more it will benefit from the learning effect and the higher will be the amount of renewable energy that is employed today. Thus, a higher y causes an increase in Y and vice versa. Graphically, the respective marginal cost curve becomes flatter (steeper) as the use of renewable energy in the other period increases (decreases).

The taxation effect leads to the standard results of the green paradox and to a higher demand for Y and a lower one for y. Given the changes in demand for regenerative energy, the experience effect works diametrically, causing the use of y to increase and the use of Y to decrease.[10] Thus, the experience effect attenuates the taxation effect partially and can even lead to a reversion of the demand for renewable energy in both periods if the size of the learning effect, i.e. the parameter ψ, is sufficiently large. However, a reversion of the fossil fuel demand is not possible since the experience effect cannot outweigh the initial effect of taxation on fossil fuel input which, in the first place, was the causation for the experience effect. Notwithstanding, as the size of the learning effect goes to infinity, the overall effect of taxation on x approaches zero as we would have expected.

Now, we analyze the case of a tax increase in the first period. Proceeding analogously as above, we obtain again equation (7) with the only difference that the vector on the right-hand side contains a positive 1 instead of a negative β. Thus, we obtain the same results - though with reversed signs, meaning a decrease of present fossil fuel use and a higher or lower demand for regenerative energy depending on the size of the learning effect ψ. The reason for this is analogous to the reasoning above. In short, the increased demand for y caused by the taxation effect can be offset completely by the experience effect if ψ is sufficiently large. Finally, Proposition 1 summarizes the results:

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[10] In Figure 2, the left marginal cost curve becomes flatter while the right one becomes steeper.

Proposition 1

For any cost function for regenerative energy in the second period which is of the form $C(y, Y) = c_0 + aY^b y^{-c}$ *with* $b \geq c+1$*, taxation affects the demand for the energy sources according to the following table:*

Table 1: Effect of Taxation

Variable	*Effect of t*		*Effect of T*	
	ψ *small*	ψ *large*	ψ *small*	ψ *large*
x	-	-	+	+
y	+	-	-	+
Y	-	+	+	-

3.2 Effect of Subsidy

In this section, we analyze the effect of a subsidy for the regenerative energy. We limit our attention to a subsidy in the first period since this tends to raise the use of regenerative energy in this period and thus will - in turn - induce beneficial LBD effects on the regenerative energy sector. Technically, the profit function of the output sector from equation (3) changes to:

$$\pi = f(x, y) - c(y) + sy - gx + \beta[F(\bar{X} - x, Y) - C(y, Y) + gx] - \beta\bar{X}[\frac{p-g}{\beta} + g] \quad (9)$$

Proceeding analogously as above, we get again equation (7) though the vector on the right-hand side changes to $(0, -1, 0)'$.

We observe that a subsidy increases the amount of renewable energy y regardless of the size of the learning effect. The amounts of x and Y decrease for small ϕ and become larger for higher values of ϕ. The explanation is quite similar to the reasoning above, though there is a subsidy rather than a taxation effect. The subsidy reduces the costs of renewable energy in the first period and leads to a higher demand for y which is the initial effect. As a consequence, a higher use of y lowers the marginal product of x, causing a shift of fossil fuel demand from the first to the second period which finally leads to less use of Y. This mechanism is the subsidy effect which is at work regardless of any learning effect. Graphically, a subsidy shifts the marginal cost line in Figure 2 downwards.[11]

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[11] As the marginal cost line in Figure 2 shifts downwards, the left y axes has to shift to the left so that

The experience effect works again diametrically to the subsidy effect, leading to an increase of Y and a decrease of y. If the learning effect is sufficiently large, the increased demand for Y caused by the experience effect will outweigh the negative subsidy effect. In this situation, the marginal product of energy from fossil fuel in the second period increases, leading to a higher use of X and consequently to a lower use of x. Thus, the overall effect of a subsidy on x and Y change for sufficiently high values of ψ.

This result differs from the result of the effect from taxation. While a tax on fossil fuels in the first period always yields lower demand for x, a subsidy on renewable energy may increase the amount of fossil fuels employed in the first period. The Climate change economics and the literature on the green paradox suggest that we should reduce the GHG emissions rather in the nearer than in the more distant future.[12] If we focus on the combustion of fossil fuels in the nearer future, our analysis implies that in the presence of a high LBD effect, a carbon tax is more appropriate than a subsidy to achieve this objective. Next, we will analyze if this conclusion still holds when the subsidy is financed by the revenues generated by a carbon tax.

3.3 Tax-Financed Subsidy

In this section, we analyze the effect of a budget-neutral tax and subsidy scheme. Thus, we require the total expenditures for the subsidy to be equal to the total tax revenue in the first period, i.e. $sy = tx$. If the output firm anticipates this relationship entirely, neither the tax nor the subsidy will have any effect on the input allocation because the firm knows that it will retrieve all of its tax payments in form of a higher subsidy. For this reason, we assume that the firm is aware of a relationship between taxes and subsidy without knowing the true relationship. Formally, we suspect the firm to have expectations about the subsidy in form of $s = s(t)$ with $s_t(t) > 0$, meaning that a higher tax rate implies also higher subsidies for the renewable energy.[13] The firm's profit function changes to

$$\pi = f(x,y) - c(y) + s(t)y - (g+t)x + \beta[F(\bar{X}-x,Y) - C(y,Y) + gx] - \beta\bar{X}[\frac{p-g}{\beta} + g] \quad (10)$$

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the marginal costs equal again the marginal product of energy use.

[12] See e.g. IPCC(2007) and Sinn (2012). Furthermore, technologies such as Carbon Capture and Storage (CCS) may become competitive in the future, converting energy from the combustion of fossil fuels into a clean energy source.

[13] In fact, we would obtain the same results, if we assumed the firm to be completely unaware of the tax and subsidy scheme, maximizing first its profit $\pi = f(x,y) - c(y) + sy - (g+t)x + \beta[F(\bar{X} - x,Y) - C(y,Y) + gx] - \beta\bar{X}[\frac{p-g}{\beta} + g]$ with respect to x, y and Y and substituting the budget-neutrality condition afterward.

Proceeding as in the previous sections, we get equation (7) with the right-hand side changed to $(1, -s_t(t), 0)'$. If the subsidy depends on the tax revenues, the effect of taxation on all of the endogenous variables is dependent of the extent of LBD. In particular, for small values of ψ we observe a positive effect on y and a negative effect on x and Y. Notably, the negative effect on x is even larger than in the case where taxation is not flanked by the subsidy. As ψ becomes larger, the effects on the endogenous variables turn to its opposite and we obtain a lower use of y as well as a higher use of x and Y.

The economic interpretations of the results are analogous to those given above. The reason for the ambiguous result for all endogenous variables is that we have both the taxation and the subsidy effect at the same time. While it was impossible to outweigh the initial effect in the two previous scenarios even in the presence of a very large LBD effect, we now have two different initial effects where each of them can be dominated by the experience effect. Table 2 summarizes the results of our analysis:

Table 2: Effect of Climate Policies

Variable	Effect of t		Effect of s		Effect of t and s	
	ψ small	ψ large	ψ small	ψ large	ψ small	ψ large
x	-	-	-	+	-	+
y	+	-	+	+	+	-
Y	-	+	-	+	-	+

If we restrict our attention to the effect of climate policies on GHG emissions in the nearer future, our analysis yields unambiguous policy implications. First, we should introduce a carbon tax on present fossil fuel consumption and should avoid the implementation of higher taxes in the future. Second, if the LBD effect is small, revenues from carbon taxes should be used to subsidize renewable energy while the subsidy is counterproductive for high LBD, causing the green paradox to occur.

4 Conclusion

Using a two-period model, we investigate the effect of climate policies on the extraction of fossil fuels in the presence of a clean alternative energy source which exhibits LBD. While a carbon tax on present fossil fuels reduces the use of the conventional energy sources, the effect of a subsidy for regenerative energy is ambiguous, depending on the size of the LBD effect. For small LBD effects, a subsidy reduces the present use of fossil fuels since their substitute becomes comparatively cheap. However, for larger LBD a subsidy leads to the green paradox as the cost reduction in the clean energy sector reduces the future demand for conventional energy and brings forward the extraction. We conclude that the best way to reduce present emissions is the implementation of a carbon tax whose revenues should additionally finance a subsidy if the LBD effect is small.

Our results are essentially driven by the assumption of complete exhaustion of the fossil fuels. Thus, in a two-period framework, the output sector inevitably has to employ the resources that have not been extracted in the first period in the second one. Contrariwise, if the future demand for fossil fuels decreases due to cost reductions in the production of regenerative energy, the present use of conventional energy necessarily increases. However, in a deterministic and fully dynamic setting with infinite time horizon, the resource owners would adjust their price and extraction paths such that full exhaustion occurs.[14]

There are at least three extensions of the proposed framework which deserve consideration in future research. The first extension should analyze whether our results remain robust in a completely dynamic setting with increasing marginal extraction costs for fossil fuels. Under this assumption, physical exhaustion of the resource will not occur anymore.[15] Thus, it is not sure whether a strong LBD effect still leads to the green paradox. Furthermore, this setting allows for welfare analysis by using a damage function for GHG emissions since climate policy will probably bring forward fossil fuel extraction (negative welfare effect), but at the same time reduce the overall amount of emissions (positive welfare effect)[16]. Secondly, the model can be extended by including uncertainty about future costs of renewable energy. As can be observed e.g. by the tariffs and the adjustments of the German Renewable Energy Act, the predictions for future costs of renewable energy differ substantially from the costs that have been realized ex post, indicating substantial uncertainty. It is not sure, how these uncertainties will affect our results. Finally, it may be also worthwhile to incorporate cost reductions that arise (stochastically) by research and development as this seems to be the main channel for improvements in the production of renewable energy[17].

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[14] See Gerlagh (2011) and Grafton et al. (2012).

[15] For a formal analysis of this result, see Hoel and Kverndokk (1996), Gerlagh (2011) and van der Ploeg and Withagen (2012b).

[16] For this kind of analysis, see e.g. van der Ploeg and Withagen (2012a).

[17] Research and development in the backstop technology and the extraction of nonrenewable resources has been explored by Dasgupta et al. (1977) and Davison (1978). In the context of environmental regulation, Henriet (2012) studies the optimal extraction path under research and development .

Appendix

First, we show that $det(M)$ is always negative. Given equation (7), the determinant of the matrix M can be written as:

$$\begin{aligned}
det(M) =&[f_{xx} + \beta F_{XX}][f_{yy} - c_{yy}(y) - \beta C_{yy}(y, Y)]F_{YY}\\
&[f_{xx} + \beta F_{XX}][f_{yy} - c_{yy}(y)][-C_{YY}(y, Y)]\\
&[f_{xx} + \beta F_{XX}][-\beta C_{yy}(y, Y)][-C_{YY}(y, Y)]\\
&+ 2f_{xy}F_{xy}\beta\psi\\
&- \beta F_{XY}F_{YX}[f_{yy} - c_{yy}(y) - \beta C_{yy}(y, Y)]\\
&- [f_{xx} + \beta F_{XX}]\beta\psi^2\\
&- f_{xy}f_{yx}[F_{YY} - C_{YY}(y, Y)]
\end{aligned}$$

where the first three lines represent the first product according to Cramer's rule and all terms except $-[f_{xx}+\beta F_{XX}]\beta\psi^2$ are negative. For a cost function of the form $C(y, Y) = c_0 + aY^b y^{-c}$, we have

$$\begin{aligned}
C_{yy}(y, Y) &= ac(c + 1)Y^b y^{-c-2}\\
C_{YY}(y, Y) &= ab(b - 1)Y^{b-2}y^{-c}\\
C_{yY}(y, Y) &= ab(-c)Y^{b-1}y^{-c-1} = \psi.
\end{aligned}$$

Given these second derivatives and looking at the third and fifth line of $det(M)$, we find that $det(M)$ is strictly negative as long as $\beta a^2 Y^{2(b-1)}y^{-2(c+1)}[b^2c^2 - b^2c^2 + cb(b-c-1)] \geq 0$, i.e. as long as $b \geq 1 + c$. Moreover, observe that $det(M) \to -\infty$ as $\psi \to -\infty$.

Second, we present the partial derivatives of x and y with respect to s and t:

$$\begin{aligned}
\frac{\partial y}{\partial t} &= \frac{1}{det(M)}[\beta F_{XY}\psi - f_{xy}[F_{YY} - C_{YY}(y, Y)]]\\
\frac{\partial x}{\partial s} &= (-1)\frac{1}{det(M)}[\beta\psi F_{YX} - f_{yx}[F_{YY} - C_{YY}(y, Y)]]\\
\frac{\partial y}{\partial s} &= (-1)\frac{1}{det(M)}[[f_{xx} + \beta F_{XX}][F_{YY} - C_{YY}(y, Y)] - \beta F_{XY}F_{YX}]
\end{aligned}$$

While the sign of the the last derivative is unambiguous positive, the sign of the first two derivatives depends on the size of ψ. In particular, for small (large) absolute values of ψ, we have $\frac{\partial y}{\partial t} > (<)0$ and $\frac{\partial x}{\partial s} < (>)0$. Finally, when the tax revenues finance the subsidy the partial derivatives of x and y with respect to t are given by

$$\begin{aligned}\frac{\partial x}{\partial t} =& \frac{1}{det(M)}\Bigg[\Big([f_{yy} - c_{yy}(y) - \beta C_{yy}(y,Y)][F_{YY} - C_{YY}(y,Y)] - \beta\psi^2\Big) \\ & - s_t(t)\Big(\beta\psi F_{YX} - f_{yx}[F_{YY} - C_{YY}(y,Y)]\Big)\Bigg] \\ \frac{\partial y}{\partial t} =& \frac{1}{det(M)}\Bigg[\Big(\beta F_{XY}\psi - f_{xy}[F_{YY} - C_{YY}(y,Y)]\Big) \\ & - s_t(t)\Big([f_{xx} + \beta F_{XX}][F_{YY} - C_{YY}(y,Y)] - \beta F_{XY}F_{YX}\Big)\Bigg].\end{aligned}$$

In this case, both derivatives depend on the size of ψ, i.e. $\frac{\partial x}{\partial t} < (>)0$ and $\frac{\partial x}{\partial s} > (<)0$ for small (large) absolute values of ψ.

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