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Abstact

In this paper we derive optimal stockpiling policies for an economy that faces an embargo threat with respect to essential resources. The properties of the optimal program depend crucially on the access of this country to a perfect capital market and on the factor allocation in embargo periods. This paper is similar to Bergström/Loury/Persson (1985) but in contrast to them focuses on the relationship of stockpiling to domestically produced resources and on the use of these resources as an input in production.

1. Introduction

Commodity stockpiling has been for a long time a subject of policy discussion. In the aftermath of the two oil crises, efforts has been taken to stockpile oil and other resources to protect the economy against future supply disruptions. Given a positive probability of future increases in the price of oil or resources, private actors have an incentive to stockpile in order to get arbitrage returns. For a large

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importing country with market power, there is an additional incentive for public storage since the marginal social benefits are higher than the market price for oil. Those macroeconomic externalities that are not reflected in the market price may result from wage and price rigidities.

To our mind the policy of stockpiling succeded in the times after Iráq intervention. The western world held reserves of oil for about 100 days. Although the cut in supply was the same as during the iranian revolution, price increases was half.

This paper is similar to Bergström/Loury/Persson (1985) and Loury (1983), but in contrast to them focuses primarily on the relationship of stockpiling to domestically produced resources and on the use of resources as an input in production. Problems of trade disruptions have also been discussed in Dasgupta/Heal (1974), Hoel (1978), Arad/Hillman (1979), Dasgupta/Stiglitz (1981) and Hillman/Long (1983). What makes our analysis different from theirs is that they assume that once an embargo (new technology) has been imposed it will last forever. In contrast, we assume that periods of free trade and embargoes alternate. The attempt of this paper is to develop optimal stockpiling policies, considering the influence of perfect and non-perfect capital markets and derive comparative-statc results.

2. The Model

We consider an economy that can import a flow of resources R at a world market price p^R when there is free trade. Free trade is ocassionally interrupted by embargos, in which $R^{imp} = 0$. From the point of view of this economy it is not known, when an embargo will be imposed, nor, when it will end. The country uses a part, R^f of the imported resources as an input in the production of Y, a consumption good. The rest of the imported resources, $R^s = R^{imp} - R^f$, are stockpiled. Here we neglect the existence of storage costs. In the case of an embargo, the country will run down its stock with the rate R^e . The stock at hand at time t is denoted as S_t .

The model of this paper uses a continous time framework. The time index is omitted when there is no ambiguity. As described above, there are two regimes: free trade and embargo periods, thus

Regime:	Free Trade	Embargo	
	$R^{imp} = R^f + R^s$	$R^{imp} = 0$	(1)
	$dS_t = R^s\,dt$	$dS_t = -R^e\,dt$	(2)

The country pays for its imports by exporting its final good Y at the price p^y . For the moment it is assumed that no capital market exists. The implication of a perfect capital market will be discussed later in this paper. In times of free trade all sectors of the economy are assumed to be in competition with foreign firms, so that the terms of trade $p := p^R / p^y$ cannot be influenced. In times of trade disruptions, p^y remains exogenous, but p^R will now be determined domestically. The production of the final good Y is carried out by a profit-maximizing firm under conditions of perfect competition. The technology of production F is assumed to be neoclassical, i.e. F is linear homogenous and has the usual properties of neoclassical production functions.

$$Y = F(K^y, L, R^y), \qquad (3)$$

where K^y is the capital used in the production of the final good. The supply of labor L is fixed. The resources R^y used in the production process consist of imported resources R^f and domestically produced resources R^d . In the case of an embargo domestically produced resources are supplemented by resources from the reserve R^e . For simplicity it is assumed that no labor is used in the production of the domestic resource.

Regime: Free Trade | Embargo

$$K = K^{y} + K^{d} \qquad\qquad K = K^{y} + K^{d}$$

$$\text{or } K^{y}, K^{d} = \text{fixed} \tag{4}$$

$$K , L = \text{exogenous and fixed} \tag{5}$$

$$R^{y} = R^{f} + R^{d} \qquad\qquad R^{y} = R^{e} + R^{d} \tag{6}$$

$$R^{d} = G (K^{d}) , \tag{7}$$

$$\text{where } G' > 0 , \quad G'' < 0 , \quad G (0) = 0$$

$$\text{and } \lim_{K^{d} \to 0} G' = \infty .$$

The country`s budget constraint is:

$$p (R^{s} + R^{f}) = Y - C \tag{8}$$

where C denotes domestic consumption. Note that R^{f} is assumed to be positive, to ensure that the country remains a resource-importing country for all time. The country in question is assumed to have a social welfare function U which depends only on consumption and has the usual properties.

$$U = U (C) , \quad \text{with } U' > 0 , \quad U'' < 0 ,$$

$$U (0) = 0 , \tag{9}$$

$$\text{and } \lim_{C \to 0} U' = \infty .$$

This assumption of infinite marginal utility ensures positive consumption in each period and avoid the necessity of a "minimum-subsistance" constraint. The utility function implies that society is risk avers. It is assumed that the private sector does not anticipate embargoes, so that no assumptions need to be made about their risk preferences. This is a very strong assumption, but without it the factor allocation in times of free trade would be influenced and so the effect of stockpiling might be superimposed.

In the long run we assume that periods of free trade alternate with times of embargoes in infinite sequence. Periods of free trade and embargoes are governed by a two-state Markov process $\{ x_t \}$. The state $x_t = 0$ represents an embargo, and the state $x_t = 1$ free trade. Let a_0 denote the probability that the regime changes from embargo to free trade independent of time. Then the duration z_0 of an embargo is exponentially distributed with the parameter a_0 . So the density function f_0 for the duration of an embargo is:

$$f_0 (z_0) = a_0 \exp (-a_0 z_0), \qquad (10)$$

where $E (z_0) = 1 / a_0$, and $var (z_0) = 1 / a_0^2$. The same holds for the probability distribution in times of free trade. Let a_1 be the probability that the regime changes from free trade to embargo, then the duration z_1 of free trade is likewise exponentially distributed, with the density function f_1 .

$$f_1 (z_1) = a_1 \exp (-a_1 z_1). \qquad (11)$$

Let $V (x ; S , K^E_x)$ be the optimal expected present value of welfare under free trade $(x = 1)$ and under an embargo $(x = 0)$, with the allocation of factors[2] K^E_1 / K^E_0 . Therefore, with an embargo in effect, and with v as the social preference rate, optimal stockpiling policy implies:

---

[2] K^E_i does not denote a variable, but generally denotes the allocation of factors.

$$V(0; S, K^E_0) = \max_{R^e} \int_0^\infty a_0 \exp(-a_0 z_0)$$

$$\left\{ \int_0^{z_0} \exp(-vt) \; U(C) \, dt \right.$$

$$\left. + \exp(-v z_0) \, V(1; S(z_0), K^E_1) \right\} dz_0$$

$$\begin{aligned} \text{s.t.} \quad dS_t &= -R^e \, dt \\ C &= f(K^E_0, R^e) \\ f(K^E_0, R^e) &= F(K - K^d, L, R^e + G(K^d)) \end{aligned}$$

(A`)

In times of free trade optimal stockpiling implies:

$$V(1; S, K^E_1) = \max_{R^s} \int_0^\infty a_1 \exp(-a_1 z_1)$$

$$\left\{ \int_0^{z_1} \exp(-vt) \; U(C) \, dt \right.$$

$$\left. + \exp(-vz_1) \; V(0; S(z_1), K^E_0) \right\} dz_1$$

$$\begin{aligned} \text{s.t.} \quad dS_t &= R^s \, dt \\ C &= f(K^E_1) - p(R^s + R^f) \\ K^E_1 &= K^E_1 \; (\text{ private behaviour }) \end{aligned}$$

with

$$\frac{\partial C}{\partial Rs} = -p$$

(B`)

K^E arise from the first order conditions of profit maximizing behaviour. Note that in times of free trade the allocation of factors is not influenced by the stock-policy. Let r denote the nominal interest rate of capital, and w the nominal wage rate, it follows:[3] *(i)* $r = p^y F_1$, *(ii)* $w = p^y F_2$, *(iii)* $p^R = p^y F_3$. And for the resource producing firm: *(iv)* $r = p^R G^{`}$. It follows that:

$$\text{(v)} \qquad \frac{F_1}{G^{`}} = F_3$$

In times of free trade the ratio of marginal capital productivities from capital in different uses equals the marginal productivity of resources used in the production of the consumption good.

3. Optimal Stockpiling in the Absence of a Perfect Capital Market

We are now able to determine optimal stockpiling policy. The results depend crucially on the factor allocation in periods of embargoes and on the market structure, since this influences the marginal utility that is gained by running down the stock. That again drives optimal stock policy in embargo periods and even in times of free trade. To analyse which marginal utility can be gained from a marginal depletion of reserves, total differentiation of *(3)* - *(8)* gives us:

$$\text{(vi)} \qquad \frac{dC}{dR^e} = F_3 + (F_3 G^{`} - F_1) \frac{dK^d}{dR^e}$$

[3] The subscript denotes the partial derivative of the function F with respect to the i-th argument. In the analysis that follows, a dot above a variable denotes its partial derivative with respect to time.

So in times of embargoes, three cases can be distinguished, that can serve as points of reference: (a) The factor adjustment goes with infinite speed and the domestic resource industry gains *no* monopoly power in times of supply disruptions. Here is $F_3 G' - F_1 = 0$ for each point of time, and the marginal utility that can be gained from an additional unit of the stock comes only from its effect in the production of the final good Y. (b) The factor adjustment speed is infinite but the domestic resource industry gains monopolistic power in the embargo, meaning that $F_3 G' - F_1 \geq 0$. Up to the point of an efficient allocation of capital, running down the stock yields additional marginal utility, because it improves the monopoly situation. (c) If the adjustment is lagged, then again $F_3 G' - F_1 \geq 0$, but also $dK^d / dR^e = 0$. Now running down the stock will not induce a more efficient factor allocation. To improve the situation in this case, other instruments (taxes or tariffs) have to be used.

Integrating by parts, (A') can be written as:

$$V(0; S, K^E_0) = \max_{R^e} \int_0^\infty \{ U(C) + a_0 V(1; S_t, K^E_1) \} \exp\{-(v + a_0)t\} dt$$

$$\text{s.t.} \quad dS_t = -R^e dt$$

$$C = C(K^E_0, R^e)$$

$$(A) \qquad R^e, S_t, C, V(\ ), a_0, a_1, v \geq 0$$

The Hamiltonian gives us the first order conditions:[4]

$$\beta_t^0 = U^{`} \{ C (K^E_0 , R^e) \} \; F_3 (K^E_0 , R^e) \qquad (12)$$

$$\dot{\beta}_t^0 = (v + a_0) \beta_t^0 - a_0 V_s (1; S_t , K^E_1) \qquad (13)$$

What follows is:

$$\frac{\dot{\beta}_t^0}{\beta_t^0} + a_0 \frac{V_s (1; S_t , K^E_1) - \beta_t^0}{\beta_t^0} = v \qquad (14)$$

where β_t^i is the costate-variable for $V (i ; \;)$. *(12)* is the usual result.[5] The shadow price β_t^0 of the resource should equal the marginal utility of an additional resource depletion. *(14)* reminds to the well known *Hotelling-Rule*.[6] The expected rate of price increase of resources in the stock should equal the social discount rate v. The expected rate of price increase if an embargo is still going on at date t, consists of the rate of shadow price increase $\dot{\beta}_t^0 / \beta_t^0$ and the expected marginal gain from stockpiling if an embargo will end in the next instant, where a_0 is the probability for that to happen. $V_s (1; S_t , K^E_1)$ gives the marginal valuation of the stock at the time z_0. Now we turn to the optimal policy in times of free trade, i.e. building up the stock. Again integrating by parts, it follows:

$$V (1; S, K^E_1) = \max_{R^s} \int_0^\infty \{ U (C) + a_1 V (0; S_t , K^E_0) \} \exp \{ - (v + a_1) t \} \, dt$$

$$\text{s.t.} \quad dS_t = R^s \, dt$$

[4] V_s denotes the partial derivative of V ( ) with respect to S. It is assumed that the Hamiltonian is concave in the control and in the state variable (i.e. $D^2 H > 0$). That ensures that second order conditions are satisfied, and that the saddle path of the optimal solution in the state-costate-space is negatively sloped.

[5] Here it was assumed that in embargo periods an efficient allocation takes place.

[6] Cf. Hotelling (1931).

$$(B) \qquad C = C(K^E_1, R^s)$$

First order conditions in times of free trade are:

$$\beta_t^1 = -U' \frac{dC}{dR^s} = U' p \qquad (15)$$

$$\dot{\beta}_t^1 = (v + a_1)\beta_t^1 - a_1 V_s(0; S_t, K^E_0) \qquad (16)$$

What follows is:

$$\frac{\dot{\beta}_t^1}{\beta_t^1} + a_1 \frac{V_s(0; S_t, K^E_0) - \beta_t^1}{\beta_t^1} = v \qquad (17)$$

(15) implies that at each point of time under free trade one should balance marginal costs $U' p$ and marginal benefits β_t^1 of stockpiling. *(17)* can be interpreted the same way as *(14)*. The social discount rate v should equal the expected rate of price increase of the resources, that consists again of the two components mentioned before. *(12)* and *(15)* show that the optimal change of the stock in the respective regime is an implicit function $IF^i(\ )$ of the shadow price β_t^i, with $i = 0, 1$.

$$\dot{S}_t^i = (-)IF^i(\beta_t^i), \text{ with } IF'^i \geq (\leq)\ 0, \text{ for } i = 1(0) \qquad (18)$$

It is easy to see that if (in embargo periods) the shadow price β_t^0 rises, it becomes more costly to deplete the stock, so the depletion rate R^e falls. In free trade, with rising β_t^1 it becomes less costly to fill the stock, and so R^s rises. Together with *(13)* and *(16)* this yields two systems of differential equations that specify optimal policy in each regime. In embargo periods:

$$\dot{\beta}_t^0 = (v + a_0)\beta_t^0 - a_0 V_s(1; S_t, K^E_1) \qquad (13)$$

$$\dot{S}_t^{0} = - IF^{0} (ß_t^{0}), \text{ with } IF^{0`} \leq 0 \qquad (18a)$$

And in free trade:

$$\dot{ß}_t^{1} = (v + a_1) ß_t^{1} - a_1 V_s (0; S_t , K^E_0) \qquad (16)$$

$$\dot{S}_t^{1} = IF^{1} (ß_t^{1}), \text{ with } IF^{1`} \geq 0 \qquad (18b)$$

These equations determine the properties of the optimal path. The path $\dot{S}_t^0 = 0$ can only be associated with an infinitely large $ß_t^0$. The path $\dot{S}_t^1 = 0$ can only be associated with $ß_t^1 = 0$. Under reasonable assumptions it can be shown that the path $\dot{ß}_t^i = 0$ is negatively sloped and convex to the origin. If the systems *(13)* resp. *(16)* and *(18a)* resp. *(18b)* are linearized around the steady state, it follows:

$$\begin{bmatrix} \dot{S}_t^{i} \\ \dot{ß}_t^{i} \end{bmatrix} = \begin{bmatrix} 0 & (-)\ IF^{`i} \\ -a_i V_{ss} & v + a_i \end{bmatrix} \begin{bmatrix} S_t^{i} - S_t^{i*} \\ ß_t^{i} - ß_t^{i*} \end{bmatrix} \qquad (19)$$

We see that $det\ J\ (\ ) = (-)\ IF^{`i}\ a_i\ V_{ss} < 0$ *and trace* $J\ (\ ) = v + a_i > 0$, so the optimal path is a saddle path. From these equations we obtain the phase diagram in the state-costate space in times of embargoes:

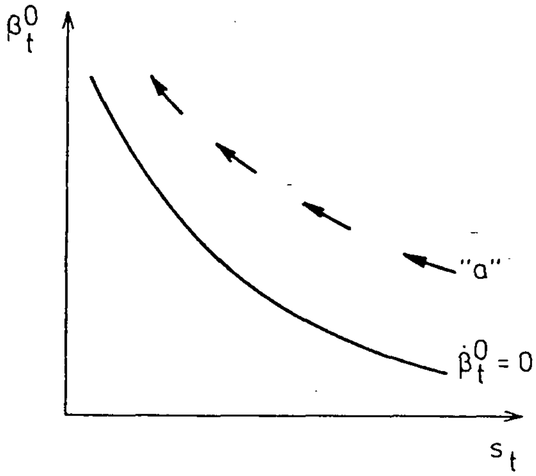

Figure 1:

And in free trade (again state-costate):

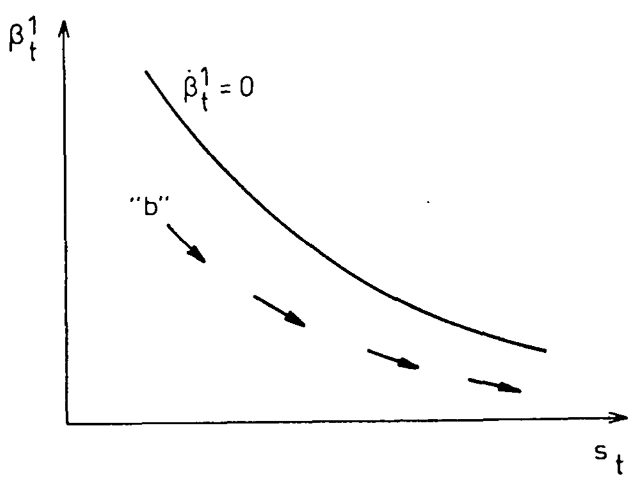

Figure 2:

For completeness, it must be noted that in order to get the full solution it is necessary to combine the two problems in the different regimes. V_s ($0; S_t$, K^E_0) denotes the marginal valuation of an additional unit in the stock, if the times of free trade end. This expression should obviously be equal to the initial shadow price β_0^0 of the resource in this regime. The same is true for $V_s\ (1;\ S_t\ ,\ K^E_1\ )$. This expression should equal the initial shadow price β_0^1 in times of free trade.

$$V_s\ (0;\ S_t\ ,\ K^E_0\ ) \quad = \quad \beta_0^0 \qquad (20)$$

$$V_s\ (1;\ S_t\ ,\ K^E_1\ ) \quad = \quad \beta_0^1 \qquad (21)$$

In this model the long-run embargo steady-state is associated with a zero stock and will only be reached in infinite time and with zero probability. The path $\dot{\beta}_t^1 = 0$ does not intersect the S_t - axis, because this would imply that $V_s\ (0\ ,\ .\ ) = 0$. When an embargo is in place, the country will be on the path "a". The stock is depleted with a falling rate. When the the embargo ends and free trade comes, the country jumps on the path "b". The steady state in free trade will only be reached with zero probability.

This implies the following for the stock-development: On the optimal path "b" under free trade, the shadow price β_t^1 of *not*-building up the stock goes down, but with a falling rate, i.e. in the first days of the free trade regime the filling rate will be relatively high. The economy substitutes consumption by security. As free trade continues, the amount that is stockpiled is reduced. At some random date, an embargo is imposed. So the economy jumps to the path "a", and the stock is now depleted. As the embargo goes on, the increase of the shadow price induces the economy to a economically use of the resource. After a certain time the embargo will end, and the process starts again. The development of the stock might be the following:

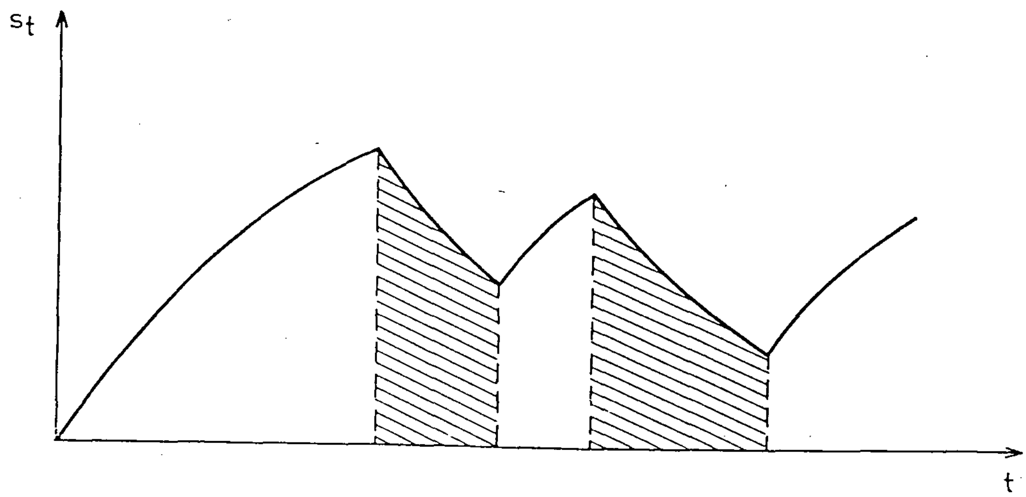

Figure 3:

Turning to the comparative-dynamic properties of the model, it is easy to see that the paths $\dot{S}_t^i = 0$ are invariant with regard to parameter variations. Therefore, we have to look how the paths of the costate variables change if the parameters of the system had changed.

a) If the expected duration of free trade is lengthened ($da_1 < 0$), the economy expects to have more time to build up the stock. The optimal filling rate R^s will go down and the renunciation of consumption in each period doesn`t have to be as large as before. The shadow price β_t^1 of *not*-filling up the stock, will go down, but the stock at hand at the expected end of free trade will be higher. The reason for that is, given a constant expected duration of the embargo, it cannot be optimal that the economy in times of supply disruptions won`t benefit from a relaxed restriction. So at the expected begin of an embargo more resources will be available and the marginal costs β_t^0 of depleting the stock will also go down. We can state: *The more unlikely it is that* *an embargo is to be imposed (da_1 < 0), the larger will be the optimal expected stock.*

b) If the expected duration of an embargo is lengthened (da_0 < 0), the country has to be more careful with the resources. A constraint is aggravated. Less resources per unit of time are depleted from the stock. Consumption will go down. Nevertheless, it must be optimal to take over a part of the stronger restriction in times of free trade. So the optimal filling rate in the free trade regime will go up. *Therefore, the more unlikely it is that an embargo expires (da_0 < 0), the larger will be the optimal expected stock.*

c) If the relative price of the resource rises ($dp > 0$), stockpiling is not as profitable as before. The economy is induced to expand domestic production of the resource and the resource imports in times of free trade will go down.

4. Optimal Stockpiling with Perfect Capital Markets

Up to now we have assumed that the economy in question has no access to a capital market, on which they can borrow, for example to finance the stock of resources. This is rather restrictive and can serve as a frame of reference. In reality, the economy might be able to encumber with debt. If we assume perfect capital markets, one constraint is suspended, namely that building up the stock is associated with postponing of consumption. But now a new constraint becomes relevant, namely that after some time debt must be repaid. Again this implies an intertemporal shift in consumption.

In the presence of perfect capital markets, the "Fisher-Separation-Theorem" allows us to devide the problem into two parts. The stock-policy can now be separated from the decision how to finance it. It is a standard result[7] that it

[7] Cf. Siebert (1988).

is optimal for the country to fill the stock immediately to its optimal level S^* after the embargo has expired. In comparison with the case of no capital market, the development of the stock might be the following way:

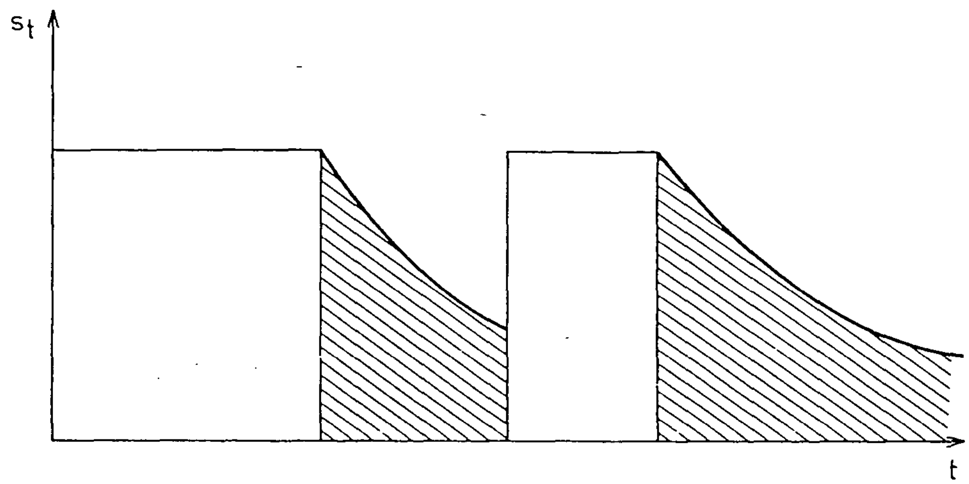

Figure 4:

The comparative-dynamics are straightforward, if we go back to *(16)* and note that in this case $\beta_t^1 = 0$. It follows:

a) If the expected duration of free trade goes up ($da_1 < 0$) the optimal stock will be smaller, because an embargo is less likely. So at the begin of an embargo, there are less resources at hand, and thus the shadow price β_t^0 rises. As soon as the embargo ends, the stock is again at the optimal level, β_t^1 remains constant. So *the more likely it is that an embargo is to be imposed* ($da_1 < 0$), *the smaller will be an optimal stock*. This is the crucial difference to the case without perfect capital markets. The reason is, that now it is possible to invest a surplus on the capital market (that surplus may arise, if free trade goes on longer than expected). Without perfect capital markets an intertemporal shift in consumption was only possible by stockpiling.

b) If the expected duration of an embargo is lengthened ($da_0 < 0$), the non-capital-market result holds. *The more unlikely it is that an embargo expires* ($da_0 < 0$), *the larger will be the optimal stock.*

c) *For an exogenous rising price* ($dp > 0$), *the optimal stock goes down.*

d) The world interest rate influences the size of the optimal stock, because this is the price for debt. It is obvious that, *the higher the interest rate on the world capital market, the smaller the optimal stock.*

5. Concluding Comments

If an economy faces an embargo threat with respect to essential resources, the success of policy instruments depend crucially on the speed of adjustment of the factors and the degree of market power that arises in the domestic resource industry in times of supply disruptions. As a frame of reference *three* cases can be distinguished: a) The factor adjustment speed is infinite and the domestic resource industry gains no market power. This "neoclassical vision" occures when there are many small resource producing firms in the home country. b) The factor adjustment speed is infinite but the domestic resource industry gains some monopolistic power in embargo times. A inefficient factor allocation results. This is not desirable, because this profit incentive will not induce the domestic resource industry to produce more resources. Monopoly theory shows that in this case the movement of capital is too low, and thus the supply of domestically produced resources is too low. c) The factor adjustment is lagged or will not take place at all.

In the first two cases *stockpiling* is an efficient instrument for managing embargo threats. The knowledge of possible supply disruptions is fully exploited. In the second case, a stock will yield an additional effect. Namely stock depletion in embargo periods will reduce the market power of the domestic resource producing firm. Economic losses from a monopoly position will be reduced. Capital is induced to move in its more efficient use. If the *factor adjustment is hindered*, depleting the stock gives indeed a high marginal utility, but does not force a more efficient allocation. Here the policy should provide incentives for factor movements.

If we *give up the small country assumption*, our arguments gain strength. Stockpiling becomes a more efficient instrument, since the larger demand for resources in times of free trade, increases the price of the resource (like it would after a tariff has been levied) and so it promotes conservation of the resource in times of free trade. In the case of an embargo the stock is depleted and price increases are reduced. Stockpiling can serve as an "automatic stabilizer".

Tariffs and taxes normally go hand in hand with a inefficient allocation of factors. In the case of stockpiling these undesired consequences are avoided. Beyond it, it becomes possible to reduce the losses in efficiency due to monopoly power.

In this model we have derived properties of optimal stock management. The question arises, who should do this, the private sector or the government. The answer has obviously to do with externalities.[8] Without externalities the private sector should be able to hold a socially optimal stock. If external effects arise due to monopolistic power in embargo periods, or due to asymmetric information, governmental intervention is required. This can be done by a government owned resource stock, with which they compete with private firms in times of supply disruptions. Alternatively, this can be done by law, but then the impact on the incentive structure has to be carefully checked. If a private firm antici-

[8] Cf. Wright/Williams (1985).

pate that it cannot dispose freely of its stock in periods of embargoes, the incentive for building up a stock will lessen. A market solution should be prefered.

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