The roles of public and private storage in managing oil import disruptions

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and

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A government storing oil to reduce vulnerability to interruption in foreign supply should recognize the existence of private storage. In fact, public intervention is justified only if some distortion exists in the private market. A price ceiling that the government is unable to eliminate as a possible future policy is such a distortion. We show that public storage can indeed substantially alleviate a price ceiling's adverse effects. Appropriate public storage behavior depends importantly on tariff policy and other policy constraints as well as on private sector responses to current and anticipated public behavior.

1. Introduction

■ Interruptions in the supply of imported petroleum pose a grave threat to the United States. Because technology is fixed in the short run, the cost of achieving energy security through conservation or expansion in the supply of substitutes is extremely large. Within the next decade, therefore, storage of petroleum is the major means at hand for mitigating disruptions in the international oil supply network. In fact, economists advocated (in vain) public storage of petroleum, like the Strategic Petroleum Reserve initiated in 1977, well before the 1973 oil embargo.[1] But how should the government decide on the rate of buildup of its reserve, and the size of the maximum stock? Several authors (Nordhaus, 1974; Tolley and Wilman, 1977; Nichols and Zeckhauser, 1977; Maskin and Newbery, 1978; Newbery, 1981; Rowen and Weyant, 1980b; Teisberg, 1981; Aiyagari, Eckstein, and Eichenbaum, 1980) have used stylized models to study various aspects of optimal government intervention in the oil market. Here we use a similarly stylized model to address a fundamental issue which has been neglected in previous work: If government storage is justified, how does private storage affect optimal public behavior?

2. A model of optimal storage

■ We assume that the domestic supply of oil is completely price inelastic.[2] The excess consumption demand function for imported oil and any oil in store is

$$P_t = P(C_t), \tag{1}$$

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[1] See, for example, Cabinet Task Force on Oil Import Control (1970).

[2] Experience since 1973 confirms that the short-run domestic supply elasticity is in fact very low. National Petroleum Council (1981, p. 136) estimates that by 1985 total 6–12 months emergency production capability will be only about 140,000 barrels per day.

where P_t is price and C_t is consumption of previously stored plus imported oil in period t.[3]

Oil available at time t in excess of domestic production, I_t, includes current imports Q_t plus the discretionary storage carried over from the previous period, S_{t-1}, which is defined to be net of irreducible stocks in pipelines and tank bottoms:

$$I_t \equiv Q_t + S_{t-1}, \qquad S_{t-1} \geq 0. \tag{2}$$

For simplicity, changes in product inventories are ruled out. Thus C_t is the difference between I_t and current storage S_t:

$$C_t = I_t - S_t . \tag{3}$$

Total net carrying charge is

$$T(S_t) = K(S_t) + rP_tS_t , \qquad r > 0, \tag{4}$$

where $K(S_t)$ is the net cost of storage services and r is the interest rate.

The arbitrage conditions for private profit-maximizing storage are the complementary relationships,

$$\begin{aligned} \hat{P}(I_t - S_t^c) + K'(S_t^c) &= (1 + r)^{-1}E(\hat{P}_{t+1}), \qquad S_t^c > 0, \\ \hat{P}(I_t - S_t^c) + K'(S_t^c) &\geq (1 + r)^{-1}E(\hat{P}_{t+1}), \qquad S_t^c = 0, \end{aligned} \tag{5}$$

where $K'(S_t^c)$ is the marginal cost of storage services, $\hat{P}$ is the price received by private storers and importers, and $E(\hat{P}_{t+1})$ is the expectation of $\hat{P}_{t+1}$ conditional on information available in period t. In the arbitrage condition for positive storage, $E(\hat{p}_{t+1})$ is a function of S_t^c. Given a stationary stochastic import supply (such as (8) below) and the transversality conditions,

$$\lim_{T\to\infty} (1 + r)^{-T}S_t^c = 0 = \lim_{T\to\infty} (1 + r)^{-T}E\hat{\hat{P}}_t , \tag{6}$$

this equation can be solved numerically to obtain optimal storage as a function of amount available:

$$S_t^c = S^c(I_t), \qquad S_t^c \geq 0. \tag{7}$$

If public and private storage have the same cost function $T(S_t)$, then in the absence of all distributional concerns and market distortions such as taxes, price controls, or suboptimal tariffs, either the government or competitive profit-maximizing private agents can achieve the optimal level of storage. It would seem reasonable that private parties and the government could build and manage storage facilities at the same physical cost. But the observed behavior of private storers suggests that physical costs differ from the net cost of storage. Apart from oil in transit, most privately stored oil is placed in steel tanks, although the physical cost of storage in tanks exceeds the cost of storage in salt domes such as those the Strategic Petroleum Reserve uses in Louisiana and Texas. The reason is that more conveniently located storage allows processors and users immediate access to the product, and the value of this accessibility offsets the physical costs incurred.

In the terminology of the trade, "Minimum Operating Inventory" includes, in addition to an irreducible minimum amount of inventory in pipelines, tank bottoms, processing equipment, etc. which is said to be "completely unavailable," an "amount of inventory necessary for the 'normal' operation of the distribution system."[4] Presumably as inventories increase in this range, their marginal accessibility value or "convenience yield" falls. For agricultural commodities such as wheat, empirical evidence strongly

[3] Trends in consumption or supply, price inflation, and the distinction between short- and long-run demand are ignored. Nordhaus (1974) and Tolley and Wilman (1977) discuss the implications of the latter distinction for government tariff policy.

[4] National Petroleum Council's Committee on Emergency Preparedness (1981, p. 125).

indicates that the accessibility value of stocks can be so high as to exceed the physical costs of storage. That is, private storers of agricultural commodities are observed to hold some stocks even when the price for delayed delivery is below the price for immediate delivery.

In the model used here, we have chosen a specification for the net marginal cost of discretionary private storage services, $K'_c(S^c)$, which is qualitatively consistent with industry descriptions of the convenience yield at different levels of inventories (National Petroleum Council, 1981, pp. 124–126; Exxon Corp., 1981), except that it ignores short-run constraints on storage capacity which could be important in actual cases. Its general form is similar to that for wheat.[5] Public storage costs, which include no convenience yield, are constant and equal private costs at high levels of private storage. Assuming efficient government management of the decentralized private inventory is infeasible, only competitive private storage achieves the maximum welfare in an otherwise undistorted economy.

We chose parameters for this model that represent a plausible version of the U.S. market for imported oil. The excess demand function for consumption of imported oil has a constant elasticity of −.20, consistent with the available evidence.[6] When storage is included in demand, the measured elasticity may appear somewhat higher (Wright and Williams, 1982).

The appropriate specification of the supply of foreign oil to the United States is certainly a very complicated problem. Given that there is no evident consensus on this issue, we chose the following simple specification in modeling the endogenous response of the supply of foreign oil. Foreign oil is controlled by a cartel, "OPEC," which offers to the world a supply completely unresponsive to price incentives. This supply is allocated by a large number of competitive petroleum corporations, with a one-period lag, to consuming countries so as to maximize expected profits. Since the United States has over one quarter of the international oil market, it faces an upward-sloping excess supply curve for oil imports,

$$Q_t = gE(\hat{P}_t) + v_t , \tag{8}$$

where $E(\hat{P}_t)$ is the price expected in period $t - 1$ by the petroleum corporations, who are assumed to have rational expectations. Their expectations about price and about the actions of the government are consistent with the predictions of the model.[7]

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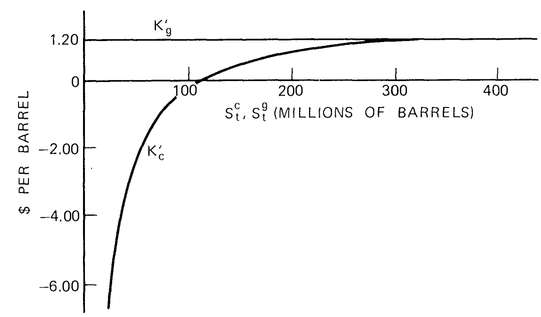
[5] For studies on the net costs of storing wheat, see Working (1953) and Gray and Peck (1981). The private net marginal storage cost function K'_c used here reflects the private demand for accessibility (Williams, 1980).



[6] For example, on the basis of evidence from the model of Kline and Weyant (1979), Rowen and Weyant (1980a, p. 20) assume a one-year price elasticity of crude oil demand of −.08, consistent with our import demand elasticity, given inelastic short-run domestic supply response. Nordhaus (1980, pp. 342–346) surveys the recent evidence on demand elasticity and its relation to response time.

[7] A richer specification of the supply sector would recognize that OPEC countries may well respond to attempts by importers to exercise market power through tariffs and also to storage activity in importing countries. For examples of this approach, and its complications in a finite-resource context, see Maskin and Newbery (1978) and Newbery (1981).

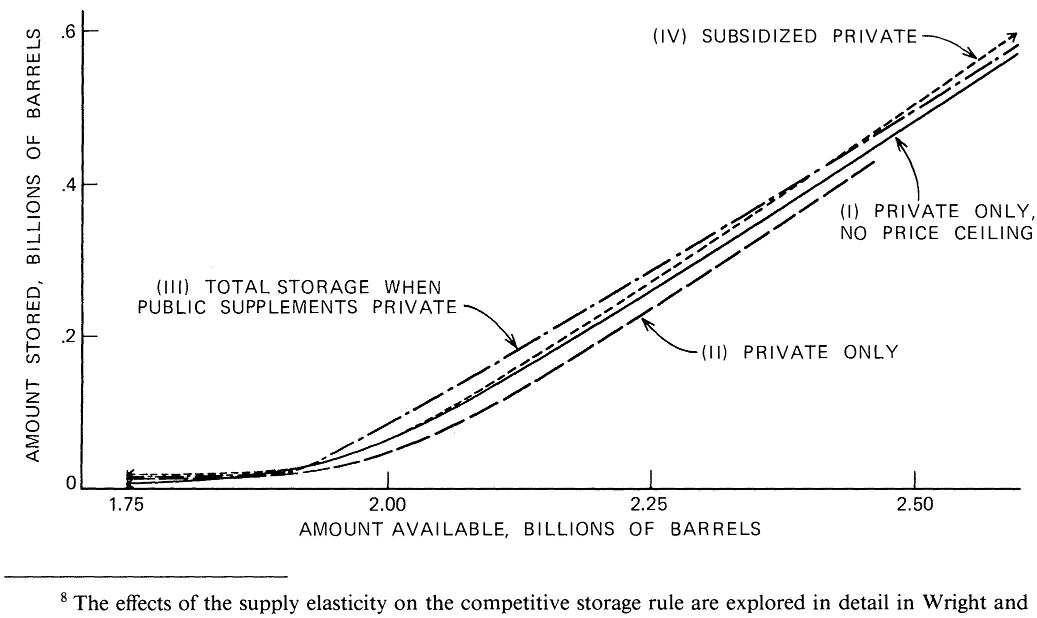
A previous analysis of the strategic petroleum reserve assumed an infinite foreign supply elasticity to the United States in a "slack" market, and price behavior in a "tight" market that indicates an elasticity between .3 and .4 (U.S. Department of Energy, Office of Oil Policy, 1979, pp. 26–27). Here we make no distinction between tight and slack markets, but assume an intermediate elasticity in an "uninterrupted" market of 1.0.[8]

The disturbances v_t represent interruptions in the supply of oil to the United States due to random events that are independent of decisions by exporters or importers, such as destruction of oil field equipment and pipelines or interference with shipping. When supply is not interrupted, $v_t = 0$. Because supply decisions are made with a one-period lag, supply within a period is perfectly inelastic; the foreign spot market is ruled out as a source of emergency imports.[9] Another assumption, which simplifies the storage rules derived below, is that there is no serial correlation in the disturbance v_t. In the real world, the probability of a cutoff in the next period $(t + 1)$ would tend to depend on the value of v_t (a pipeline broken in one period is more likely to remain broken in the next).[10] The disturbance v_t is assigned four values—0, −15%, −30%, −45%—of the fixed amount which would be imported in the nonstochastic case (which is 2.0 billion barrels of imports a year at $30.00 a barrel) with probabilities .7, .15, .10, and .05, respectively.[11]

In the model just described, the competitive private storage rule with no price ceiling is shown as the middle curve in Figure 1. The amount stored in period t depends on the

FIGURE 1

STORAGE RULES WITH PRICE CEILING OF $45.00
(TARIFF IS FIXED AT OPTIMUM LEVEL FOR NONSTOCHASTIC CASE)



[8] The effects of the supply elasticity on the competitive storage rule are explored in detail in Wright and Williams (1982). Here a higher elasticity would mean a lower optimal tariff and faster accumulation after a shortfall; otherwise, the qualitative results shown here would still hold.

[9] Recent work by Verleger (1982) suggests that the spot market in fact plays an important role in determining subsequent OPEC pricing policy.

[10] Teisberg (1981) presents a model in which the probability of a given shortage depends on v_t, the stockpile size, and time.

[11] The magnitudes of these cutoffs are roughly equivalent to scenarios 1, 1A, and 3 in Table 1, p. 21 of the Report of the National Petroleum Council's Committee on Emergency Preparedness (1981). The first two scenarios represent an OAPEC-plus-Iran export curtailment of 5% and 10%, respectively, against the United States only (a 1 or 2 million barrels per day U.S. import shortfall). The third represents an OAPEC-plus-Iran curtailment of 40%, in which case the International Energy Agency's mechanism for sharing crude is assumed to be activated. The report does not discuss the probability of occurrence of any of its scenarios.

amount of oil available, I_t, which is the sum of current imports and storage from the previous year. For example, when 2.5 billion barrels are available, 484 million are stored and 2.016 billion barrels are consumed.[12] If current supply were interrupted, however, reducing available oil, inventory would be reduced, cushioning the fall in consumption.

This type of storage behavior in undistorted markets has been derived and examined by Teisberg (1981) and by several others in studies of grain markets (Gustafson, 1958; Johnson and Sumner, 1976; Gardner, 1979; Newbery and Stiglitz, 1981; Wright and Williams, 1982). Teisberg (1981, pp. 544–546) considered private storage as an alternative to public storage in an appendix. However, apart from studies of arbitrary "price band" or "price peg" government storage rules (Gardner, 1979; Salant, forthcoming), previous works have not considered the case where some private storage would remain when a government reserve is initiated. Because of the high convenience yield of private storage, this case is surely the most reasonable scenario for a strategic petroleum reserve.

3. The role of public storage

■ Given optimal tariffs and in the absence of market imperfections, risk-neutral competitive private agents would provide optimal storage—there would be no role for public storage at all. To justify public storage, we explicitly include a market distortion in the model. Given recent history, the oil industry has abundant reason to believe that there is some oil price at which government will intervene to control the realizations of oil drawn down from private storage in times of shortage, when profit-maximizing private storers and importers may well be branded as "speculators" or "price gougers." In fact, it may well be impossible for any administration credibly to guarantee against such action by itself or its successors. Accordingly, in this article we concentrate on a price ceiling as the source of the market distortion. Other distortions, such as the presence of oligopoly, a difference between the social risk premium on oil imports and the premium implicit in the market price, possible macroeconomic implications of oil price changes (Nordhaus, 1980), or a divergence in the cost of capital due to taxation, could also be taken into account by modifying the arbitrage conditions. The general conclusions derived here are relevant for public intervention justified by such other distortions.

In this article we consider two price ceilings, at \$45 and \$36 per barrel, 50 and 20%, respectively, above the equilibrium price of \$30 when v_t is zero in all periods. Above the ceiling, consumption is rationed by marketable coupons distributed to consumers, who are assumed to be incapable of significant storage. Either price ceiling shifts the undistorted storage rule to the right at prices below the ceiling, as can be seen for the storage rule II with a price ceiling of \$45.00 also illustrated in Figure 1. But the ceiling shifts the rule up when current price is at the ceiling, because the ceiling narrows the spread between the current market price and the (lower) price expected in the next period.

In most circumstances, the depressing effect on oil availability of a price ceiling lowers welfare. But this is not true if the set of policy options available to the government is sufficiently circumscribed. A price ceiling can crudely substitute for an optimal tariff, if the latter cannot be implemented. If there is no price ceiling, implicit or explicit, in our model, there will be too much private storage when there is no tariff, and the public response should not be to add to storage. The tariff may not in fact be a control variable. The Carter Administration, for example, attempted to impose an oil import fee, but had its action ruled unconstitutional. If a price ceiling is also ruled out, a tax on storage may be advocated as a next-best policy, because it indirectly lowers the derived demand for

[12] 484 million barrels of usable stocks would represent 88 days of mean consumption of imported oil in this case. We do not follow the common practice of expressing stocks in days of consumption, as mean consumption is endogenous in our model, as shown in Table 1.

oil toward its optimal level. But it seems implausible that the government can only exploit U.S. market power in oil indirectly through a tax on storage.

If the government could impose any tariff it wanted and convince importers and storers that it would never impose a price ceiling, it could achieve the highest level of domestic welfare in our model, all without public storage. But when the oil supply is uninterrupted, the government cannot convince private storers and importers that it and its successors will never impose a price ceiling, even if there is no explicit ceiling in force now. Indeed, the nature of the constraints on policy options available to the government is crucial. In what follows, we take a price ceiling as inevitable, but examine three alternative regimes for tariffs; the case of no tariff, the case of a tariff set at the level which would be optimal in the absence of supply interruptions, and a state-independent tariff which is optimally adjusted to account for the price ceiling and the operation of public storage.

4. Public storage rules

■ If government cannot or will not preclude the imposition of a price ceiling in some future period of scarcity, an argument can be made for government storage. But unless the government can prohibit private storage, it must be taken into account in calculating the public storage rule. Consequently, two sets of intertemporal storage rules must hold in equilibrium. The conditions for competitive private storage S^c take government storage S^g as given:

$$\begin{aligned} \hat{P}(I_t - S_t^g - S_t^c) + K_c'(S_t^c) &= E(\hat{P}_{t+1})(1 + r)^{-1}, \qquad S_t^c > 0, \\ \hat{P}(I_t - S_t^g - S_t^c) + K_c'(S_t^c) &\geq E(\hat{P}_{t+1})(1 + r)^{-1}, \qquad S_t^c = 0, \end{aligned} \tag{9}$$

where $\hat{P}$, as before, is the price received by private storers and importers.

We assume that the government's objective with an infinite horizon is to maximize the present value of current and future social welfare (discounted domestic surplus), given current availability I_t, and taking the price ceiling as given. The rule should be believable to the private sector in the sense that the government will have no incentive to change its rule in the future if the private sector acts at all times as if current public storage behavior will be maintained indefinitely. Then this private sector behavior conforms with rational expectations. That is, the rule should be a time-consistent, feedback rule (Kydland, 1975, 1977). Since we have already assumed that the government as a dominant player cannot make a credible promise never to impose a price ceiling, it is natural that we rule out time-inconsistent open or closed loop public storage policies, and confine our attention to "feedback" solutions. If one rule, consistently applied, provides a higher value of the objective function than another candidate, at any initial level of availability, the first dominates the second, in the sense that a social-welfare-maximizing government under no prior constraints would always prefer the former.

One possible rule arises from a decentralized government storage policy which directs the storage authority to use the market price plus the shadow price of a ration coupon as its price incentive. In this case the public arbitrage conditions are:

$$\begin{aligned} P(I_t - S_t^g - S_t^c) + K_g'(S_t^g) &= E(P_{t+1})(1 + r)^{-1}, \qquad S_t^g > 0, \\ P(I_t - S_t^g - S_t^c) + K_g'(S_t^g) &\geq E(P_{t+1})(1 + r)^{-1}, \qquad S_t^g = 0, \end{aligned} \tag{10}$$

where K_g' represents the marginal cost of public storage and P is the shadow price of consumption. P exceeds $\hat{P}$ when a price ceiling is in force.

The arbitrage conditions in (10) imply Nash behavior on the government's part. A question naturally arises as to whether the government, recognizing its dominant market position, would not exercise von Stackelberg leadership instead, again under the constraint of time consistency. Under this behavioral mode, it would maximize, subject to private behavior implied by (10), the objective function J, consistently applied, where

$$J(S_t) = \int_0^{I_t - S_t} P(C_t)dC_t - K_g(S_t^g) - K_c(S_t^c) + (1 + r)^{-1} W(S_t^c + S_t^g), \tag{11}$$

where S_t is total storage, $S_t^c + S_t^g$, and $W(S_t)$ is the present value of expected future net welfare in this market, net of costs, given S_t, and

$$W(S_t) = E[J(S_{t+1})] - G(gE(\hat{P}_{t+1}(S_t))), \tag{12}$$

where G is the cost of imports ordered in period t for delivery (subject to interruption) in period $t + 1$. Both $E(\hat{P}_{t+1}(S_t))$ and $W(S_t)$ are derived by a process of successive numerical approximation, as described in detail in Appendices 1 and 2 of Wright and Williams (forthcoming). Note that (11) and (12) together reflect the restriction on future public behavior to that consistent with current actions. The public arbitrage conditions derived under von Stackelberg public behavior are

$$\begin{aligned} &P\left(1 + \frac{\partial S_t^c}{\partial S_t^g}\right) - \frac{\partial W}{\partial S}\left(1 + \frac{\partial S_t^c}{\partial S_t^g}\right)(1 + r)^{-1} + K_g'(S_t^g) + K_c'(S_t^c)\frac{\partial S_t^c}{\partial S_t^g} = 0, \qquad S_t^g > 0, \\ &P\left(1 + \frac{\partial S_t^c}{\partial S_t^g}\right) - \frac{\partial W}{\partial S}\left(1 + \frac{\partial S_t^c}{\partial S_t^g}\right)(1 + r)^{-1} + K_g'(S_t^g) + K_c'(S_t^c)\frac{\partial S_t^c}{\partial S_t^g} \geq 0, \qquad S_t^g = 0. \end{aligned} \tag{13}$$

The private reaction $\partial S_t^c/\partial S_t^g$ when private storage is positive is

$$\frac{\partial S_t^c}{\partial S_t^g} = \frac{\hat{P}'(C_t) + (1 + r)^{-1}E\hat{P}'(S_t^g + S_t^c)}{-\hat{P}'(C_t) - K_c''(S_t^c) - (1 + r)^{-1}E\hat{P}'(S_t^g + S_t^c)}, \qquad S_t^c \geq 0 \tag{14}$$

where (14) is obtained from implicit differentiation of (9).

The choice between Nash and von Stackelberg public storage behavior depends on their relative performance when consistently applied now and in the future. The measure of performance, given an initial level of availability, is $J(S_t)$ from (11) above.

The comparison of Nash and von Stackelberg behavior for fully optimized tariff (10% reduction from the optimal tariff with no supply interruptions for Nash, 36% reduction for von Stackelberg) is illustrated in Figure 2. The difference between Nash and von Stackelberg behavior in the welfare criterion (11), graphed as ΔJ, is substantial; Nash is superior by about \$900 million. In other words, regardless of the availability in the current period, the government can achieve higher welfare through Nash behavior rather than von Stackelberg. Thus, given these two choices, private storers and importers know the government will follow the Nash rule. The government makes no promise to behave in this way; but the government will always find itself preferring Nash, at least in the case we are considering, as long as the choice of von Stackelberg behavior would engender expectations that such behavior would be permanent.

As anticipated, the von Stackelberg case, by reducing public storage relative to Nash behavior, encourages more private storage in the current year t, over most of the relevant range of I_t. Why, then, does Nash behavior dominate von Stackelberg, which seemingly takes better account of the effect of public storage on private storage?

What is missing from the dynamic programming calculus of optimal public storage is any recognition that the amount which will be available in the current period depends upon anticipations of public storage behavior in that period. In other words, I_t changes with S_t^g, although that partial derivative does not appear in the arbitrage condition. In fact, it cannot. Once the current period arrives, I_t is fixed; the past is inflexible. Because every government, including the present government, will take its availability as fixed, and is by assumption not bound to past commitments, it can never allow for its full effect on private behavior. Relative to the Nash alternative, von Stackelberg behavior leads to lower total storage, given I_t, in any subsequent period t, and thus to reduced demand.

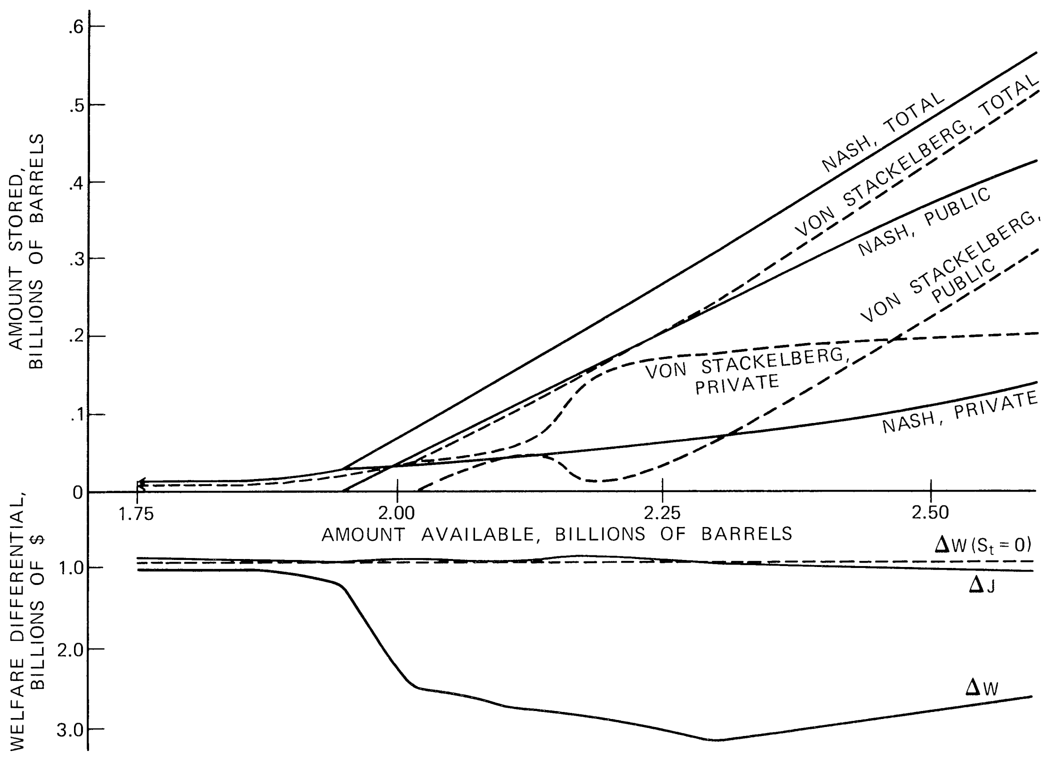
This change in anticipations weakens the current reaction of private storage to the reduction in current public storage, and also reduces imports ordered in the current period, relative to Nash behavior, thus reducing future availability. (The tariff reduction cushions, but does not eliminate, these effects.)

The resulting difference in expression (12), welfare in future periods under Nash and von Stackelberg behavior, is graphed as a function of I_t in Figure 2. Marginal increases in ΔW are due to higher storage under the Nash rule at any given availability, and are counterbalanced by increases in current period welfare (the first three terms of (11)) under von Stackelberg behavior. The superiority of the Nash rule is entirely attributable to the difference in $W(0)$, future welfare with nothing carried over from the present, which is \$914 million. The difference in expression (11), the net present value of welfare, is close to \$914 million at all I_t for which $S^g > 0$, so if the future welfare difference were ignored (as in the conventional dynamic programming approach) von Stackelberg behavior could be socially preferable. But the future implications completely dominate current period differences, rendering the conventional "optimal control" solution nonoptimal, a possibility noted by Kydland and Prescott (1977). Figure 2 shows that at any current I, social-welfare-maximizing government not bound by past commitments should prefer Nash behavior over von Stackelberg.

Note, however, that this conclusion depends on the parameters of the model. If, for example, the elasticity of supply of imports is 0.0, von Stackelberg behavior dominates Nash. And Nash public behavior does not necessarily yield the best possible storage policy, even when the elasticity of supply is high. All we can claim is that besides dominating the von Stackelberg alternative for the cases considered below (the domination being much greater where the tariff is fixed), it is relatively straightforward, time-consistent, and

FIGURE 2

PUBLIC AND PRIVATE STORAGE UNDER TWO PUBLIC BEHAVIORAL RULES
(PRICE CEILING IS \$45.00, AND TARIFF IS FULLY OPTIMIZED IN EACH CASE)



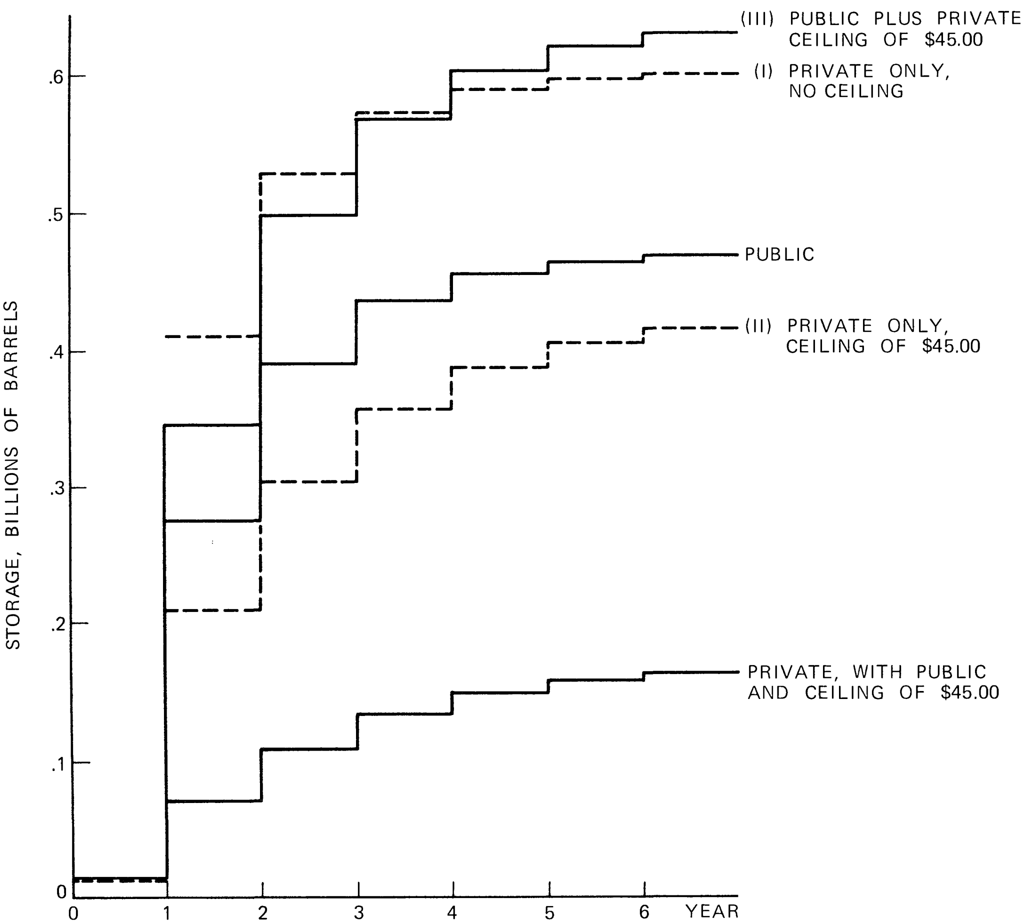
far superior to previous rules which ignore private storage reactions altogether, and to simple "price band" rules which are subject to speculative attack (Salant, forthcoming). On this basis, we concentrate on Nash public storage behavior below.

Under Nash behavior, Figure 2 shows that at availabilities below 1.86 billion barrels, a constant 13.4 million barrels is stored, all in private hands. Above 1.95 billion barrels, in contrast, most marginal storage is public. If the price ceiling were lower, private storage behavior would be quite different. Results for a $36 per barrel ceiling show that although total storage rises monotonically with availability, the private storage curve first falls and then rises with higher current availability. Observers could well infer that private storers who were increasing stocks as availability fell were collusively manipulating the market, yet such behavior is consistent with perfect competition, given the price ceiling and government storage.

Accumulation of stocks reflects all the interactions discussed above. Figure 3 shows accumulation in a string of uninterrupted years, starting with availability of 1.4 billion barrels, for Cases I–III with all having the same tariff, which would be optimal in the nonstochastic case.[13] In all cases the bulk of the accumulation occurs in the first three

FIGURE 3

STORAGE DURING A STRING OF GOOD YEARS
(TARIFF IS FIXED AT OPTIMUM LEVEL FOR NON–STOCHASTIC CASE)



[13] Public and private accumulation with fully optimized tariff (Case VI, the Nash Case in Figure 2) is very similar to that in Case III.

years. Case I actually has the highest storage in years 1 through 4. Despite lower storage than Case III at any given availability in the range seen from year 1 on (see Figure 1), storage is higher because availability is higher, because of higher imports in the first few years, reflecting the absence of a price ceiling. In Case II the combined twin effects of the price ceiling—lower storage rule, plus the lower import response—result in a much lower accumulation path, relative to the other cases, than a casual glance at Figure 1 would indicate. Mean storage figures in Table 1 below confirm that seemingly small differences in storage rules can be consistent with large differences in stock holding behavior.

The net contribution made by a public petroleum reserve to total stocks is greatly overstated by gross public storage. Table 1 shows that mean public storage of .37 increases mean total storage over Case II by only .21; 43% of gross public storage merely replaces reductions relative to Case II in private storage, which has lower marginal net storage costs due to its convenience yield. (This "replacement rate" is only 10% at a $36.00 price ceiling.) Simulations for the equivalent von Stackelberg case with the same tariff show a mean public storage of 150 million barrels, and mean private storage of 180 million barrels for this rule. Paradoxically, the negative response of I induces a higher replacement rate (67%) than in the Nash Case III, even though the von Stackelberg approach tries to take special account of offsetting private behavior!

5. Market behavior under different storage regimes

■ Market behavior for six cases is summarized in Table 1. Note that when Nash public storage is used (Cases III, V, VI), mean total storage is almost identical to that in the undistorted Case I, regardless of the tariff. If an optimal storage subsidy could be costlessly and perfectly administered, as in Case IV, private storage would be much higher, and welfare at given I would be comparable to Case VI; $W(0)$, which dominates the comparison (see Figure 2) is only $57 million less. If the tariff is optimized jointly with the subsidy—7% tariff reduction, $1.50 subsidy per barrel—$W(0)$ is $657 million above Case VI. However, if informational difficulties rule out a decentralized public storage program with the same net storage costs as the private market (a program which would yield still higher welfare), they might well preclude storage subsidies also.

The perverse market effects of a price ceiling on oil are clearly shown in Table 1. Naturally the ceiling (Case II), because of its negative effects on imports and storage, actually raises the shadow price, relative to Case I, and almost triples its standard deviation. But the indirect adverse effects of a ceiling also outweigh its direct effect on market price; mean market price is increased by $1.01 and its standard deviation is almost doubled. Thus, it is an unfortunate political-economic fact that price ceilings can furnish the very market instability which justifies their perpetuation. This cautionary tale is reinforced by the last column. A ceiling set at a price that would occur in only .3% of all periods in an undistorted market generates a price which hits the ceiling 6.1% of the time, or about twenty times as often!

6. Conclusions

■ The most important protection against near-term insecurity of petroleum supply is the availability of domestic inventories of crude oil and products. Since the oil market is in fact subject to many distortions, there is a role for government intervention in the oil market to improve social welfare.

Using the example of a perceived price ceiling on oil, we have shown that though a very high ceiling may be welfare-improving if it is impossible to impose an optimal tariff, even apparently mild and infrequent price controls can excessively reduce the level of storage by private oil suppliers and increase the instability of oil consumption. A government stockpile can alleviate a major part of the harm done by a distortion in

TABLE 1 Market Behavior under Different Storage Regimes (Mean Values, with Standard Deviations in Parentheses)[a]

	Private Storage (Bbbls.)	Public Storage (Bbbls.)	Market Price ($/bbl.)	Shadow[b] Price ($/bbl.)	Consumption (Bbbls.)	Percentage of Periods with Shadow Price Over $45.00
A. *Tariff Optimized for Nonstochastic Undistorted Case before Price Ceiling*:						
Case I: No Ceiling	.48 (.16)	0.0	29.15 (2.21)	29.15 (2.21)	2.01 (.03)	.3
Ceiling of $45.00:						
Case II: Only Private Storage	.28 (.13)	0.0	30.16 (4.36)	30.94 (7.91)	2.00 (.07)	6.1
Case III: Public and Private	.12 (.04)	.37 (.12)	30.38 (2.67)	30.41 (2.92)	2.00 (.03)	.4
Case IV: Private with Optimal Storage Subsidy ($1.65/bbl)	.57 (.20)	0.0	30.51 (1.82)	30.55 (2.24)	1.99 (.02)	.5
B. *No Tariff and $45.00 Ceiling*:						
Case V: Public and Private	.35 (.17)	.13 (.10)	16.00 (1.21)	16.01 (1.22)	2.27 (.03)	.02
C. *Tariff Fully Optimized, $45.00 Ceiling*:						
Case VI: Public and Private[c]	.12 (.04)	.36 (.12)	29.07 (2.56)	29.10 (2.76)	2.01 (.03)	.3

[a] Calculated from simulations of 10,000 periods.
[b] Marginal consumption value.
[c] 10% tariff reduction.

market price. But except at low levels of availability, private storage is reduced by the presence of a public stockpile. Thus, an extra barrel added to a strategic petroleum reserve does not in general mean that an extra barrel is available during an import disruption. This replacement effect, which can be very important, varies with the severity of the price ceiling. However, it is possible to pay too much attention to this effect. Attempts by the government to act as a von Stackelberg leader who takes account of the private storage reaction function lead to a feedback rule which is in this model inferior to a simple Nash rule, by which the public accumulates stocks till the marginal cost of a unit publicly stored equals the consumption value expected in the next period.

Of course, our quantitative results are dependent on our parameter choices,[14] and our qualitative results are highly sensitive to constraints on the set of feasible policies. For example, we have shown that the mean government (but not total) stockpile is strongly dependent on the size of the import tariff, and a subsidy to decentralized private storers could be an attractive alternative, if its administration proved economically feasible. Further, our model could be modified to consider storage responses by end-users in the face of possible or actual price ceilings and rationing, which would be important in implementing a public storage scheme.

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[14] We have studied many cases not reported here, including higher demand elasticities, lower supply elasticities, smaller disturbances, symmetric disturbances, multiplicative disturbances, and different storage costs. These indicate that our qualitative results are quite robust, except as noted in the text. For the sensitivity of private competitive storage to many of the above parameter changes, see Wright and Williams (1982).

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