Regulatory Tailoring, Reliability, and Price Volatility with Stochastic Breakdowns

Howard Gruenspecht

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Resources for the Future
1616 P Street, NW
Washington, D.C. 20036
Telephone: 202–328–5000
Fax: 202–939–3460
Internet: http://www.rff.org

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Abstract

Although real-world energy supply systems are subject to stochastic failures, the impacts of proposed regulations affecting these systems have typically been evaluated using non-stochastic models. This paper develops an energy market model that explicitly allows for stochastic failures and demonstrates they play an important, or even dominant, role in determining the market impacts of environmental regulations that tailor product specifications to address local or regional conditions, such as fuel-formulation requirements specific to certain regional markets within the United States. While traditional non-stochastic analyses view the tailoring of regulatory requirements by location as an efficiency-enhancing alternative to a "one size fits all" regulatory approach, they fail to consider the adverse impact on reliability in all market segments resulting from the loss of product fungibility due to tailoring. We show that regulatory impact estimates developed without explicit consideration of reliability considerations may be highly inaccurate.

Key Words: reliability, boutique fuels, gasoline price spikes, stochastic failures, environmental regulation, tailored regulation.

JEL Classification Numbers: Q2, Q4

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Howard Gruenspecht*

1. Introduction

Recent events suggest that regional market imbalances leading to localized price spikes in energy markets are becoming increasingly common in a variety of contexts and seasons. In January 2000, the onset of a sudden cold spell—along with deliverability problems—combined to produce a dramatic price spike in the Northeast heating oil market. As supply responded to the availability of arbitrage opportunities, the spike rapidly abated, and a normal relationship between prices in different markets was restored.

As winter turned to spring, attention turned to gasoline prices. While the sharp rise in crude oil prices during the first half of the year increased the price of gasoline and other refined products in all markets, drivers in Chicago and Milwaukee faced much more dramatic increases than those faced by drivers in other areas. Consumers in California also have experienced several localized price spikes affecting gasoline in recent years. These spikes have become a significant political issue, with recriminations between industry, consumer, and government representatives flying before the cameras and the Congress.

This paper considers one cause of localized price volatility: the inherently stochastic nature of energy supply systems subject to unanticipated breakdowns. The possibility of supply failures induces an economically relevant scale economy within a market that can support multiple plants of minimum efficient scale in an engineering sense. The recognition of breakdowns creates a (positive) reliability externality associated with a high degree of substitutability among products sold in different areas. However, the tailoring of regulations by location, which has traditionally been viewed as an efficiency-enhancing alternative to a "one

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size fits all" regulatory approach, degrades the positive fungibility externality by creating a barrier to substitution across regional market boundaries.

Our framework builds on several strands in the existing literature. The solution and simulation of the rational expectations equilibrium draws extensively on analyses of agricultural markets with stochastic harvests and competitive arbitrage (Deaton and Laroque 1992; Chambers and Bailey 1996; Deaton and Laroque 1996). Our results also extend the literature on stochastic economies of scale and the economies of massed reserves, as explored by numerous authors (Levhari and Sheshinski 1970; Arrow, Levhari et al. 1972; Sheshinski and Dreze 1976; Rothschild and Werden 1979; Mulligan 1983). Finally, the reliability-based scale economies addressed in this paper echo earlier discussions of the role of conventional scale economies in regulatory policy design (Geller 1997).

The paper's main finding is that regulatory tailoring can have significant costs that have not been recognized in conventional engineering-economic analyses of regulatory impacts. We show that tailoring is likely to induce higher levels of capacity and inventory, both of which are costly. In addition, average price levels and price volatility in an equilibrium with tailoring can be significantly above levels suggested by a conventional analysis even after these responses are taken into account. Non-stochastic analyses are therefore shown to understate the consumer and social costs of a tailored regulatory regime. Furthermore, these are not "second-order effects"—under plausible parameterizations, the reliability cost of tailored regulations can significantly exceed their engineering cost.

While proper consideration of reliability raises the estimated cost of tailored regulations, the implications for regulatory design are ambiguous. In some cases, reliability and price volatility impacts will cause the tailored application of more stringent formulation requirements to have negative net benefits where traditional non-stochastic analysis suggests otherwise. Another possible outcome is that adoption of a tailored regulatory regime provides positive net benefits even after the extra costs resulting from adverse reliability and price volatility impacts are considered. Finally, where the market segment needing more stringent standards is relatively large, reliability and price volatility considerations could favor uniform adoption of the more stringent formulation requirement in order to preserve product fungibility, even when such application would not appear justified in "low-benefit" areas of the national market using a non-stochastic analysis. Given these possibilities, the parameters of the specific markets in question must be considered to determine the most advantageous approach to tailoring.

Finally, regulatory tailoring generally reduces the number of actual or potential competitors, increasing both the opportunity for market power abuse and its potential profitability. Although price spikes can (and do) arise without any abuse of market power, increased concentration in regional energy markets is an additional concern associated with regulatory tailoring, albeit one that is generally beyond the scope of this paper.

The paper is organized as follows. Section 2 presents background information on gasoline regulation and evidence regarding the effect of regulatory tailoring on gasoline price volatility. Section 3 develops a model of energy markets with stochastic failures. Section 4 presents initial simulations of the model's price process. Section 5 introduces region-specific tailoring of fuel formulations and demonstrates that its impact on prices in a stochastic environment may differ significantly from that estimated within a non-stochastic setting. Section 6 relates our findings to previous results on conventional scale economies and regulation, outlines policy implications, and identifies directions for future analysis.

2. Gasoline Reformulation: Requirements and Impacts

Prior to the Clean Air Act of 1970, decisions regarding gasoline formulation reflected only refining cost and vehicle performance considerations. However, the formulation of gasoline affects the level of pre- or post-combustion emissions covered by national air quality standards, the performance of emissions control equipment, the level of toxic emissions, and the economic value of particular additives and blendstocks. For all of these reasons, gasoline formulation has received significant attention under the nation's environmental laws since the 1970s.

Between 1970 and 1990, public policy in the area of gasoline formulation focused on the elimination of lead in gasoline. The shift to unleaded fuels, which was implemented on a national basis, allowed for the use of catalytic converters to reduce tailpipe emissions of hydrocarbons, carbon monoxide, and nitrogen oxides. It also dramatically reduced ambient concentrations of lead in the environment.

The Clean Air Act Amendments of 1990 established additional fuel-formulation requirements to further reduce smog and carbon monoxide pollution and to promote the use of ethanol and other fuel oxygenates. In contrast to the lead phase out, which was implemented on a nationwide basis, these requirements were targeted at specific areas of the country that had the greatest difficulty meeting ambient air quality standards. Starting in 1992, the use of oxygenated gasoline was required during the winter months in areas with high ambient carbon monoxide levels. In 1995, the use of reformulated gasoline was required in nine metropolitan areas that were classified as severe or extreme nonattainment areas for tropospheric ozone (smog). Other areas could opt in to the reformulated gasoline program to replace or supplement other emission reductions as a part of their plans to meet air quality standards or maintain their attainment status. In effect, the reformulated gasoline program split the national gasoline market into distinct segments for conventional gasoline (CG) and reformulated gasoline (RFG).

Subsequent action by states and localities led to further market segmentation. Notably, California adopted its own, more stringent requirements for reformulated gasoline sold throughout the state (CaRFG), which took effect in June 1996. Also, in response to consumer complaints about adverse health reactions to methyl tertiary butyl ether (MTBE), an additive used in most RFG as a source of oxygen and octane, several Midwestern states used a combination of tax incentives and regulations to create a market for RFG made with ethanol produced from locally grown agricultural crops. In order to stay within prescribed volatility limits, RFG made with ethanol must be manufactured using a special low-volatility gasoline blendstock.[1] Further environmental concern surrounding the use of MTBE arose with evidence that it diffused into groundwater more rapidly than other fuel components when it spilled or leaked from underground storage tanks. In March 1999, California announced a ban on gasoline formulated with MTBE effective in 2003.[2] Following California's lead, 13 additional states have passed legislation to ban or limit the use of MTBE within the next several years.[3]

Reviews of several California price spikes since 1996 and the Chicago-Milwaukee price spike in June 2000 have suggested that fuel-formulation requirements were an important contributor to price volatility (Energy Information Administration 1999; Energy Information Administration 2000; Energy Information Administration 2000). Table 1 reports the mean and

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[1] Reformulated gasoline (RFG) requires a minimum 2.1 percent oxygen by weight, which can be met using 5.8 percent ethanol by volume or an 11.7 percent MTBE by volume. However, summer RFG must also have a Reid Vapor Pressure (RVP) less than 7 to limit evaporative emissions. Since RVP for ethanol is much higher than that for MTBE (18 vs. 8) RFG made using ethanol requires a lower RVP blendstock than RFG made with MTBE meet the RVP requirement.

[2] In March 2002, California Governor Davis issued an Executive Order delaying the effective date of the MTBE ban by at least 1 year. Reasons cited by the governor include concerns about the adequacy of gasoline supply and the potential for gasoline price spikes which in his view were exacerbated by the refusal of the Bush Administration to waive the oxygenate requirement in the federal Clean Air Act.

[3] As of September 2002, Congress is conferencing energy legislation that would could make further significant changes in the RFG program. The Senate version of this legislation would phase out MTBE on a nationwide basis, eliminate oxygen content requirement for RFG, and create a new Renewable Fuel Standard (RFS) that would more than double the use of ethanol in motor fuel by 2012.

standard deviation of the gross spot margin, defined as the spot market price less the per-gallon cost of crude oil, for Los Angeles, New York Harbor, and Gulf Coast markets before and after the June 1996 initiation of the California RFG (CaRFG) program.[4] [5]

Table 1.
Gross Spot Margins for Reformulated Gasoline at Los Angeles, New York, and the Gulf Coast Before and After Implementation of the California RFG Program
(cents per gallon)

	Before CaRFG		After CaRFG	
	Mean	Std. Dev.	Mean	Std. Dev.
Los Angeles	19.40	8.37	21.69	11.38
New York	13.48	5.54	12.73	5.93
Gulf Coast	11.43	5.83	11.24	5.94

A standard F-test can be used to determine whether the standard deviation of the gross spot margin, the measure of volatility, changed significantly following the start of the CaRFG program. The hypothesis of a volatility increase in California is strongly supported, with the probability of no change in volatility less than 0.00005. However, for the New York and Gulf Coast markets, the main trading centers for RFG used outside of California, the hypothesis of a volatility increase is rejected. This is the expected result, since the significantly larger market for federal RFG was served by many more U.S. refineries and was also able to use fuels produced at many foreign refineries. Moreover, because CaRFG meets all federal RFG requirements, the opportunity for arbitrage holds federal RFG prices below the price of CaRFG plus (very

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[4] The California market has both higher average margins and more price volatility than the other two markets. Numerous state and federal studies over the years have examined the geographic isolation and other structural features of the California market that explain this outcome.

[5] Note that the mean of the gross spot margin in California is higher following the start of the CaRFG program, reflecting the increased cost of meeting more stringent formulation requirements that would be projected in either a traditional or stochastic analysis.

substantial) transportation costs. This arbitrage opportunity does not apply in the other direction, since federal RFG cannot be used in California.

3. The Basic Model

We consider the market for gasoline, which in the absence of tailored environmental regulation is a homogeneous product.[6] The market has three types of agents: consumers, refiners, and inventory holders[7]. Consumer demand depends only on the current price. Refiners make investment decisions, which determine the level of capacity, as well as period-by-period decisions regarding the operation of available capacity consistent with short-run profit maximization. Inventory holders carry stocks of gasoline from one period to the next for arbitrage purposes.

3.1 A model without inventories

We start with a case in where there are no inventories. In an application to electricity markets, this case reflects the real-world absence of a storage technology. In the present context of gasoline markets, it provides an easy starting point for considering stochastic production failures. Let z_t represent the amount of operable capacity at time t. Let y_t ($\leq z_t$) represent actual production.

Without stochastic failures, z_t equals K, the total physical capacity. With stochastic failures, the distribution of z_t depends on both K and the parameters of the failure distribution. z_t has compact support, with lower bound $\underline{z}$ (=0) and upper bound $\bar{z}$ (=K). Our stochastic failure process, where applicable, is serially uncorrelated, so that z_t is independently and identically distributed (i.i.d).[8]

We build upon the approach and notation of Deaton and Laroque (1992), who consider a market for agricultural commodities with stochastic harvests in which there are no short-run

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[6] This characterization is oversimplified, since even in the absence of environmental regulation, gasoline recipes are routinely adjusted to provide fuels that optimize driveability under climatic conditions that vary by location and season. However, unlike the product segmentation resulting from environmental requirements examined in this paper, such recipe adjustments do not preclude substitution among products produced at different refineries.

[7] A single economic entity can have both refining and stockholding interests.

[8] The implications of this assumption, which improves tractability, are discussed below.

operating decisions by producers. Let $D(p_t)$ be the deterministic demand function and $P(z_t)$ the inverse demand function. $D(p)$ is continuous and strictly decreasing, and $D(p) \rightarrow \infty$ as $p \rightarrow 0$. Furthermore, to assure the existence of a rational expectations equilibrium, we also assume that the inverse demand function satisfies $\infty > P(\underline{z}) > 0$. The (arbitrarily high) upper limit on price may reflect underlying consumer preferences, or represent a policy-determined cap beyond which rationing, rather than the market, is used to allocate product when supplies are extremely tight. Refineries have constant marginal costs of production up to the level of capacity. With short run profit maximization by capacity owners, the variable cost of production per unit, c, is the effective floor price, since production for sale at prices below this level would provide a negative profit contribution.

With no inventories, equilibrium price is given by the following relationship:

$$D(p_t) = y_t \tag{1}$$

$$\text{where } y_t = z_t \text{ for } p_t > c$$

$$y_t \le z_t \text{ for } p_t = c$$

3.2 A model with storage

We now introduce inventories. Suppose there is a constant returns storage technology that yields (1-d) units of commodity at time t+1 for each unit stored at t. Inventory holders, who are risk-neutral, can borrow and lend from a perfect capital market where the rate of interest is r. Given $r > 0$ and $d \geq 0$, there are real costs to holding inventories.

Let I_t be the level of inventories at t, and $E_t p_{t+1}$ represent the expected value of p_{t+1} given information available at t. Clearly, inventories will not be held if there is an expected loss from holding them. Furthermore, a necessary condition for holding a positive profit-maximizing level of inventories is that the current market price equal the present discounted value of next period's expected price adjusted for real holding costs and stock deterioration (if any). Thus:

$$I_t = 0 \quad \text{if } p_t > \beta(1-d)\,E_t(p_{t+1}) \tag{2a}$$

$$I_t \geq 0 \quad \text{if } p_t = \beta(1-d)\,E_t(p_{t+1}) \tag{2b}$$

In equilibrium, supply, including inventories carried from the previous period, must equal demand, including demand for inventories to carry forward into the next period. Thus:

$$y_t + (1\text{-}d)I_{t-1} - I_t = D(p_t) \qquad (3)$$

where $y_t = z_t$ for $p_t > c$

$y_t \leq z_t$ for $p_t = c$

Combining (2) and (3) we have:

$$p_t = \max[\beta(1\text{-}d)\, E_t(p_{t+1}),\ P(z_t + (1\text{-}d)I_{t-1} - I_t)] \qquad (4)$$

In equation (4), expectations regarding future prices are based on the current value of a state variable that characterizes supply. The state variable at time t, x_t, is the maximum available supply, defined as available production capacity plus any inventories carried over from the previous period. Clearly, inventories must be non-negative at all times. In addition, because profit- maximizing operating decisions insure that prices never fall below the variable cost of production, c, the level of inventories is bounded from above by I_{MAX}, the inventory level that satisfies (2b) when $p_t = c$. Applying these inventory limits, x_t lies in the interval $[\underline{z}, \overline{z} + I_{MAX}]$.

3.3 Short-run equilibrium

Given the above, a stationary rational expectations equilibrium (SREE) is a price function f: $X \rightarrow \Re$ which satisfies for all x_t,

$$p_t = f(x_t) = \max[\beta(1\text{-}d)\, E_t f\{z_{t+1} + (1\text{-}d)I_t\},\ P(x_t)] \qquad (5)$$

where $I_t = x_t - P^{-1}(p_t) - (z_t - y_t) = x_t - P^{-1}\{f(x_t)\} - (z_t - y_t)$

and $(z_t - y_t) = 0$ if $p_t > c$.

Equation (5) restates equation (4), with the expectation of next period's prices in the first argument now expressed as the expectation taken over the equilibrium price function applied to next period's uncertain state value. The second argument in (5), which by (2a) can exceed the first argument only if inventories are zero, is the price given the current state variable assuming that no inventory is carried forward. Equation (5) is also subject to the definition of inventories and short run profit maximization by producers, which dictates that all available capacity be used ($y_t = z_t$) if price exceeds marginal cost.

Theorems 1 and 2 of Deaton and Laroque (1992), appropriately modified to account for the possibility of slack production capability resulting from short-run profit maximization by refinery operators, establish the following properties:

P1. There is a unique SREE, f(x), in the class of non-negative, continuous, non-increasing functions.

P2. Let $p^* = \beta(1-d)\,Ef(z)$. Then $f(x) > P(x)$ for $P(x) < p^*$. Also, $f(x) = P(x)$ for $P(x) \geq p^*$.

P3. f(x) is strictly decreasing in x for $P(\underline{z}) > f(x) > c$.

P4. The equilibrium level of inventories is strictly increasing whenever $p^* > P(x) > c$.

P5. Stockouts occur in finite time.

By P2, there is a critical price level, p^*, equal to the expectation of the equilibrium price from current production, adjusted for real holding costs and stock deterioration (if any). At prices at or above p^*, stocks are reduced to zero, since the expected price in the next period starting from a position of zero stocks would not satisfy the arbitrage condition for holding inventory today . For prices below p^*, inventories are held, and prices are above those that would prevail if all available supply was immediately consumed.

3.4 Long-run equilibrium

In the long run, the amount of refining capacity is endogenous. The condition that investors earn the normal rate of return determines the equilibrium level of capacity. In our framework, investment decisions are not sensitive to the current realization of the failure process, since the stochastic failure realizations that drive the process determining prices are independent across time.[9] However, they do depend on its parameters, which determine the probability distribution for the number of operable units in each market period. Generally, investors have an incentive to build more capacity than they would if capacity were not subject to stochastic breakdowns. With highly inelastic demand, competitive prices may be driven down to the level of variable cost during periods of high capacity availability. However, owners of operable facilities will be able to earn significant rents at times when competitors' facilities are unavailable to operate.[10] In a competitive equilibrium, capacity will be added to the point where the next addition would not earn normal profits. Let:

CAP = capital cost of plant ($ per unit capacity)
r = required rate of return on investment
π_K (J) = probability of J operable plants given K total plants
O_K (J) = J/K (probability that a particular plant is available when J out of K plants are operable.
$P(J)$ = price of output when J units are operable

Then, the equilibrium condition for investment is :

$$rCAP \;>\; \sum_{J=0}^{K+1} \pi_{K+1}(J) O_{K+1}(J)(P_{K+1}(J) - c) \tag{6}$$

$$rCAP \;<\; \sum_{J=0}^{K} \pi_K(J) O_K(J)(P(J) - c)$$

In applications where both additional capacity and arbitrage operate to reduce price volatility, increases in total capacity directly affects the profitability of arbitrage by shifting the distribution of z_t, while the prospect of arbitrage affects the profitability of investment in (6).

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[9] While our assumption of complete serial independence is not strictly realistic, allowing for the modest degree of time dependence in failure realizations that is typical of energy systems would not change the key point that the present failure realizations and their price implications contain little information regarding the returns to potential investment projects. See Section 3.5 below.

[10] Recent experience in electric power markets, where demand variability as well as stochastic failures contributes to short-term imbalances, shows that rents earned during the relative handful of hours when markets are tight are the primary motivation for adding capacity.

However, arbitrageurs cannot commit to behavior that would preclude the entry of new capacity, but is not ex-post optimal if that capacity actually existed. Our solution for optimal competitive capacity is therefore calculated under the assumption that investment decisions occur first.

Because there is no simple analytical form for the rational expectations equilibrium price function, the next section explores its properties and the effects of both untailored and tailored fuel-formulation requirements using numerical and simulation methods. Before turning to that task, however, we briefly reconsider our earlier assumption that the stochastic shocks affecting supply are independent and identically distributed (IID).

3.5 Representing stochastic breakdowns

Generally, the use of an IID process to represent breakdowns is most plausible when the time required to restore inoperable capacity to service is short compared to the time interval over which the market is evaluated. Thus, it is likely to be more acceptable for analysis of monthly gasoline prices than for an examination of hourly electricity prices, since in the latter setting current forced outages would carry important information about expected capacity availability in the next hour. Where serial correlation matters, it can be explicitly incorporated using the methods of Chambers and Bailey (1996), who extend the basic Deaton and Laroque model to the case of serially correlated agricultural harvests. They demonstrate that a unique rational expectations equilibrium exists in which price is a function of both x_t and z_t. z_t matters independently of x_t because it carries information regarding z_{t+1}.

Suppose, for example, that a low harvest realization (or, in the present context, low plant availability) increased expectations of a low realization in the next period. This would increase p^* and the level of inventory holding associated at each x_t level compared to the equilibrium for i.i.d. realizations of harvest or available capacity. High values of z_t have the opposite effect. Thus, with serial correlation, the equilibrium is characterized by a family of state-to-price mappings, one for each possible value of z_t.

In theory, serial correlation in breakdowns could also affect the long-run equilibrium level of capacity, making it more attractive to invest when plant availability is low. Dixit and Pindyck (1994) provide a useful synthesis of models of investment and equilibrium capacity determination in markets with stochastic prices that are serially dependent. In their framework, current prices provide information regarding the future price level that will prevail during the useful lifetime of an investment project that is currently being contemplated. However, a price process driven by stochastic failures in the energy supply chain carries little if any information relevant to investment decisions, since the gestation period of investments is far longer than the time required to return inoperable capacity to service.

To illustrate this point, consider a two-box (Ehrenfest) model breakdown and repair in which operable refineries fail at rate μ per unit time and inoperable refineries reenter service at rate λ per unit time, typically with $\lambda >> \mu$. The transition rates for variables representing the numbers of operable and inoperable refineries at a time when j refineries are operating are given by:

$$T(\text{operable to inoperable}) = j\mu \qquad j = 0,1, \ldots..K \tag{7}$$

$$T(\text{inoperable to operable}) = (K-j)\lambda \qquad j = 0,1,\ldots\ldots K$$

Consider an example where the there are 10 refineries, a failure rate (μ) of 10% per month and a restoration rate (λ) of 80% per month. Table 2 compares the equilibrium distribution of the number of operable refineries (J), to the distributions six months from the present time (t=0) for the two extreme initial states: no refineries currently operable (J(0)=0) and all refineries currently operable (J(0)=10). Form Table 2, it is apparent that the probability that any given number of refineries will be operable 6 months in the future is virtually independent of the initial condition of the system. This shows that the present operational status of refineries provides no useful information about the probability distribution of prices six months in the future, let alone over the much longer period required to bring a new project on-line.[11] Therefore, we would not expect to find a tangible effect on investment decisions in a setting where the gestation period of investment dwarfs the typical breakdown cycle.[12]

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[11] This argument clearly applies in the context of electricity generation. An unusually high realization for the daily "forced outage" rate can significantly boost spot-market electricity prices. However, this should have almost no impact on decisions regarding investments in additional capacity that have a gestation period of 18 months or longer.

[12] Other option value considerations, such as movements in the price process that are unrelated to the current operational status of existing capacity can affect investment decisions. For example, high prices resulting from factors unrelated to stochastic failures, such as higher-than-anticipated demand growth, may signal investors to add capacity.

Table 2.

Probability Distributions for the Number of Operable Units Six Months into the Future Under Alternative Initial Conditions

(K =10, λ= .8, μ =.1)

J(0) (number of operable plants at t=0)	Probability of J(6) =n, n = 0,1,....10										
	0	1	2	3	4	5	6	7	8	9	10
0	2.9e-10	2.3e-8	8.3e-7	.00002	.00025	.00237	.01579	.07219	.21654	.38493	.30792
10	2.9e-10	2.3e-8	8.2e-7	.00002	.00025	.00237	.01579	.07217	.21652	.38493	.30795
Equilibrium distribution	2.9e-10	2.3e-8	8.3e-7	.00002	.00025	.00237	.01579	.07218	.21653	.38493	.30795

4. Numerical Solutions and Simulation Results

We begin by specifying functional forms for the basic model outlined in the previous section. For demand, we use a constant elasticity function, truncated at an arbitrary ceiling value, p_{MAX}, to insure $\infty > P(\underline{z}) > 0$.[13] Using P2 from the previous section, we also identify p^*, the critical price level at or above which no inventories are held, to characterize the two middle segments of the inverse demand function. The final segment of the inverse demand function reflects short-run profit maximization by producers, who will not use all of their available capacity unless price is at or above marginal cost. Taken together:

$$
\begin{array}{lll}
P(x_t) = & p_{MAX} & \text{for } A(x_t)^{-\varepsilon} \geq p_{MAX} \\
 & A\,(x_t)^{-\varepsilon} & \text{for } p_{MAX} > A(x_t)^{-\varepsilon} \geq p^* \\
 & A\,(x_t - I_t(x_t))^{-\varepsilon} & \text{for } p^* > A\,(x_t - I_t(x_t))^{-\varepsilon} \geq c \\
 & c & \text{for } A\,(x_t - I_t(x_t))^{-\varepsilon} < c
\end{array}
\qquad (8)
$$

---

[13] The price ceiling can be interpreted as representing either a backstop technology – when gasoline costs $200 per gallon, consumers switch to another fuel or walk – or suppliers' expectation that the government will rely on rationing rather than markets to allocate supplies during extreme shortages.

For the failure process, we consider the short run in which the total number of refineries is fixed at $\overline{K}$. In any period, each refinery is inoperable with probability μ. The number of available (operable) refineries at any point in time is a binomial random variable, so the probability that z refineries are operable is:

$$\pi(z) = \binom{\overline{K}}{z}(1-\mu)^{j}\mu^{\overline{K}-j} \qquad \text{for } j = 0, 1, \ldots..\ \overline{K} \tag{9}$$

with mean $(1-\mu)\overline{K}$ and variance $(1-\mu)\mu\overline{K}$.

In addition, we adopt the following parameter values:

$$p_{MAX} = 200, \text{ demand elasticity} = -0.2,\ c = 1.2,\ A = 243,\ \mu = .1 \tag{10}$$

Using (2) through (5) and (8) through (10), it is straightforward to compute f(x), the unique short run SREE, for a candidate value of K. We then simulate the model for 1000 periods of random realizations of z_t to determine rents earned per unit of capital. K^e, the long-run equilibrium capital stock, is the highest K that satisfies (6).

4.1 Simulation Results for an Unregulated Sector With Stochastic Breakdowns

With f(x) in hand, it is easy to simulate the market. Table 3 reports, for alternative levels of total capacity, K, the mean and variance of prices, the mean and variance of rents, and the maximum level of inventories drawn from simulations for 1,000 realizations of available capacity, z_t.

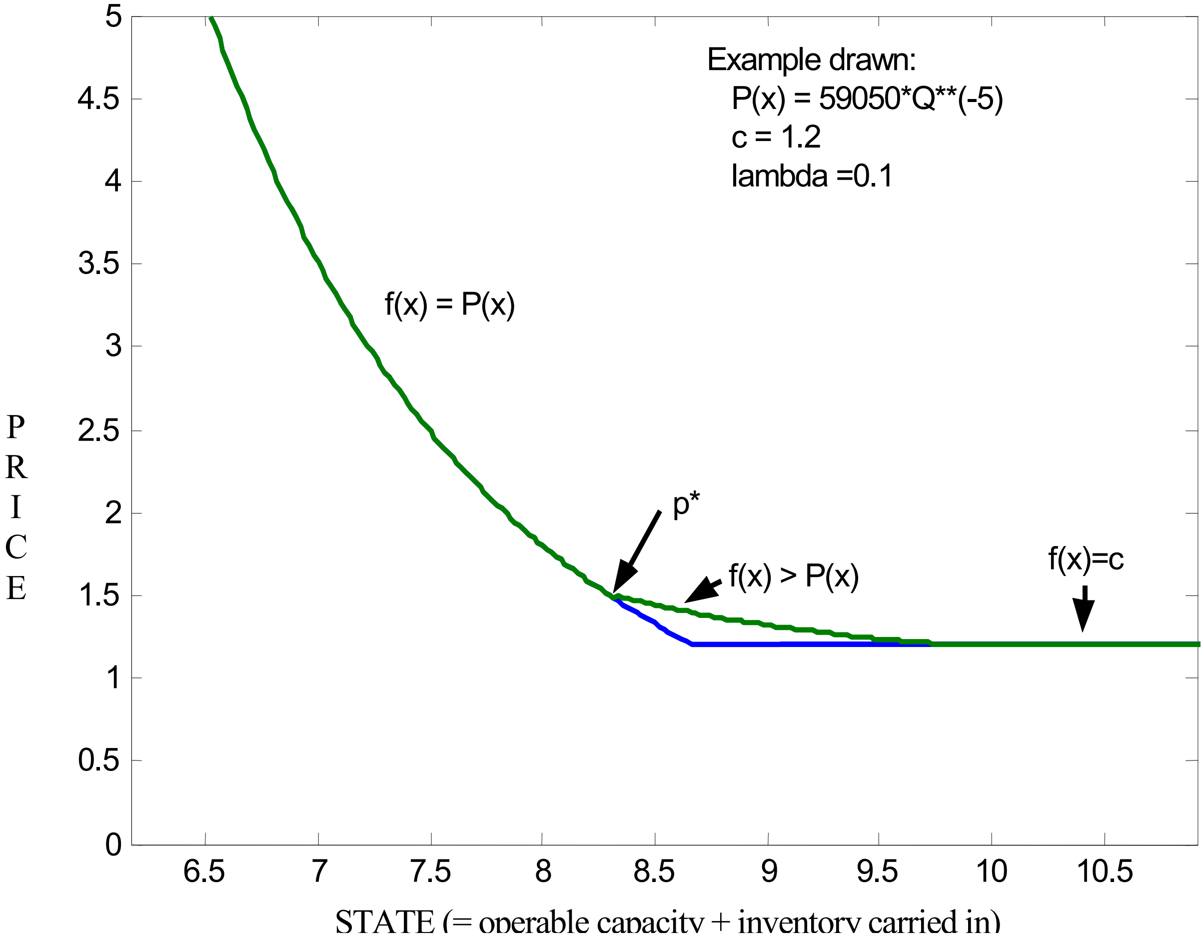
Table 3.
Prices, Rents, and Maximum Inventories as a Function of Capacity:
Simulation Results for 1000 Periods

K	PRICES		RENTS		I_{MAX}
	mean	var	mean	var	
9	1.735	0.341	0.451	0.154	4.162
10	1.301	0.105	0.074	0.046	1.182
11	1.252	0.051	0.036	0.022	0.202

Note that as total capacity increases, maximum inventory levels are reduced – inventories and excess capacity are substitutes in reducing price volatility. Also, additional capacity serves to reduce both the mean price level and the variance of prices, as well as the mean and variance of rents to capacity owners.

For high candidate values of K, the distribution of z_t is shifted far enough to the left that inventory holding is not attractive. For the parameter values in (10), $K^e = 10$ and inventories range between 0 and 1.182 units. Figure 1 graphs the rational expectations equilibrium price function f(x) for K=10 together with P(x), the demand function.

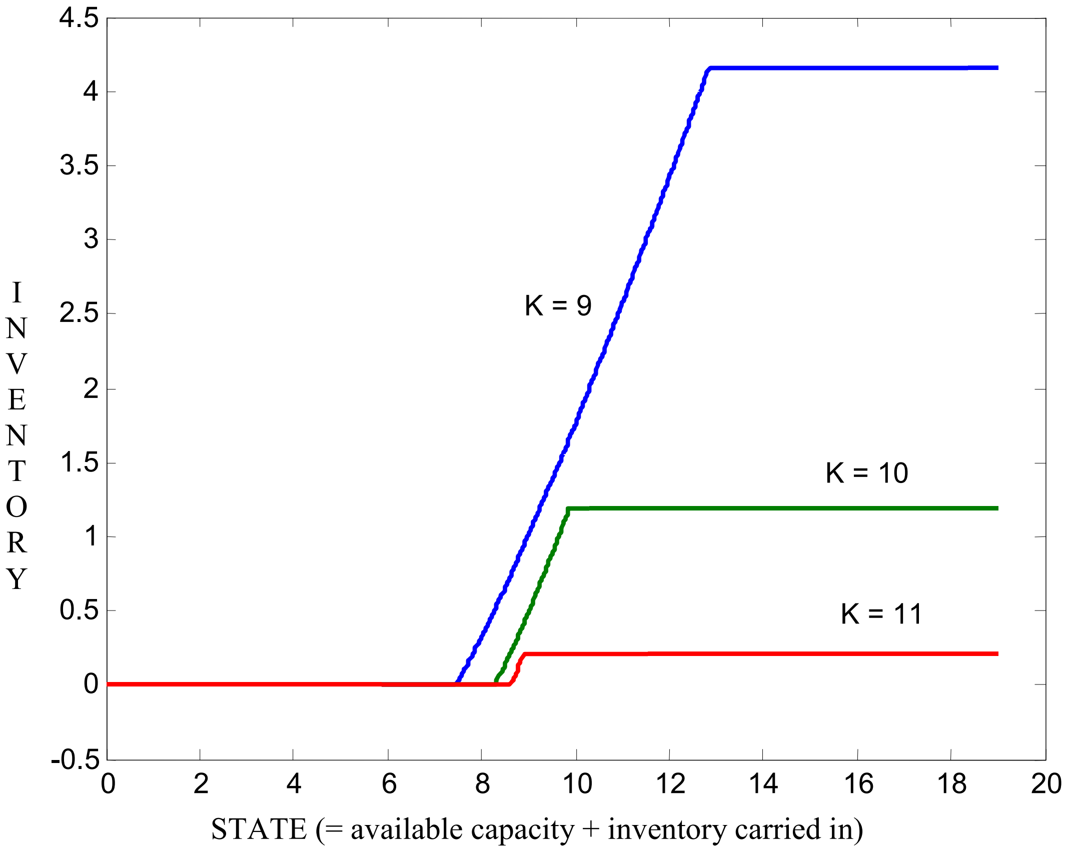
Figure 1
Demand Function (P(x)) and Rational Expectations Equilibrium (f(x))
for K = 10



Note that some possible equilibrium outcomes are quite unlikely. For example, the probability that 8 or more out of 10 plants will be operable in any period exceeds 90 percent[14]. In addition to operable capacity, the state variable also includes any inventories that have been carried forward. Therefore, the chances of realizing a state value of less than 8.3, consistent with outcomes along the P(x) = f(x) part of the demand curve in which all available stocks are drawn down, are small. Situations where f(x) >c and positive inventories are carried forward, as well as outcomes along the f(x) = c segment of the demand curve where maximum inventories are held and some available capacity is idle, occur far more frequently.

Figure 2

Equilibrium Inventory Behavior as a Function of Total Capacity (K)



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[14] The probability of 8 or more plants being available are somewhat higher than those presented in Table 2, given the assumption here that plant breakdowns are serially uncorrelated.

Figure 2 (above) provides another perspective on the market by graphing the equilibrium inventory level against the state variable for a range of possible K values. From Figure 2, it is clear that capacity and inventories are substitutes in providing reliability to the market. Where capacity is tight, arbitrageurs see opportunities for significant profit potential in holding inventories against the prospect of a shortfall in available capacity. The prospect of a capacity shortfall becomes more remote as the amount of capacity increases, so competitive arbitrageurs reduce their inventories. With enough capacity, the prospects of profiting from arbitrage would be so remote that potential gains would not offset the costs of holding inventories, there would be no arbitrage, and f(x) would be identical to P(x).

4.2 Simulating the Impact of Regulation

In a nonstochastic model, the impact of cost-increasing regulation in a competitive sector is straightforward—the full cost of regulation is passed forward to consumers. We now consider the effect of uniformly-applied fuel formulation requirements in the context of production systems subject to stochastic failures. Table 4 compares the $K=K^e$ case from Table 3 to results from simulations with alternative formulation requirements that raise c, the variable cost of production to c'.

Table 4.
Impact of Variable Cos Increase on Prices, Rents, and Inventories: Simulation Results for 1000 Periods

C	PRICES		RENTS		I_{MAX}
	mean	var	mean	var	
1.2	1.301	0.105	0.074	0.046	1.182
1.26 (+5%)	1.355	0.104	0.068	0.045	1.087
1.32 (+10%)	1.411	0.105	0.064	0.045	0.986
1.44 (+20%)	1.526	0.109	0.060	0.046	0.813
1.50 (+25%)	1.584	0.110	0.058	0.046	0.741

In contrast to the situation in a competitive market without stochastic breakdowns, the full incremental costs of regulation are not reflected in market prices. Producers lose the opportunity to profitably produce at prices between c and c'. Moreover, rents during periods when capital availability is a constraint on production are reduced. For example, when prices are above p*, unit rents are reduced from p*-c to p*-c'. Thus, while measures of social costs derived from a certainty analysis are approximately accurate, the introduction of stochastic supply failures has significant distributional implications that favor consumers at the expense of producers.

In the next section, we consider regulatory tailoring, which is shown to have dramatically different impacts on consumers and producers.

5. Tailored Regulation

Our analysis of tailored regulation starts with calculation of the equilibrium price functions for distinct markets separated by region-specific fuel-formulation requirements that preclude the flow of product across market boundaries. We then simulate these markets and examine the outcomes for equilibrium capacity, inventory levels, and the mean and variance of prices and rents. The results are then compared to outcomes for a unified (untailored) market with stochastic failures and for tailored markets in the absence of stochastic breakdowns. The section closes with a discussion of "one-way" tailoring, a situation that arises where fuel designed to meet a high regulatory specification can be sold in both markets, but low-specification fuel is excluded from the market where the higher standard is set.

5.1 A Model of Tailored Regulation

Let regions 1 and 2 represent, respectively, areas where the baseline and tailored fuel formulation requirements are applicable. Let n_i represent the fraction of the population in market i. Assume for expositional convenience that consumers in all regions have the same per-capita demand function, so that $D_i(p_t) = n_i D(p_t)$ where D_i represents the regional market demand function. Start from a situation where $K=K^e$ in the national market. When tailoring is introduced, refineries must be configured to produce output that meets the applicable specification in each region. New formulation requirements may increase variable cost, require capital deepening, or both. Let K_i be the number of (identically sized) refineries configured to provide output meeting the region i specification. K_i, which will depend on the relative size of markets, can be (is) endogenously determined, but we start by assuming that K_i equals n_iK^e rounded to the nearest integer value.

5.2 Impacts of tailoring a "costless" regulation

To highlight the impact of regulatory tailoring, we start with a polar case of tailoring a regulation that separates regional markets but is "costless" in the traditional sense -- it does not increase variable costs or require capital deepening in either region. Existing refineries can be configured to produce fuel meeting either specification at the same cost, but the configuration cannot be rapidly reversed, so that each refinery must be dedicated to a specific regional market. In a non-stochastic setting, it is obvious that tailored regulation under these conditions has no impact on competitive prices, refiner profitability, or total equilibrium refinery capacity.

Table 5.
Impact of "No Cost" Tailored Regulation on Prices, Rents, and Inventories: Simulated Results for 1000 Periods

CASE	TAILORED MARKET					BASE MARKET				
n_1, Δc_1, K_1, K_2	PRICES		RENTS		I_{MAX}	PRICES		RENTS		I_{MAX}
	mean	var	mean	var		mean	var	mean	var	
.1, 0, 1, 9	1.925	43.70	0.220	0.417	2.092	1.306	0.118	0.077	0.035	1.250
.2, 0, 2, 8	1.453	0.984	0.144	0.096	2.105	1.311	0.115	0.080	0.050	1.298
.3, 0, 3, 7	1.420	3.549	0.127	0.422	1.957	1.319	0.181	0.084	0.067	1.406
.4, 0, 4, 6	1.344	0.119	0.099	0.040	1.809	1.333	0.267	0.092	0.081	1.533
.5, 0, 5, 5	1.348	0.196	0.102	0.065	1.681	1.348	0.196	0.102	0.065	1.681

With stochastic failures, the situation changes. The mean and variance of prices and profitability, as well as inventory levels and capacity levels are all affected by the introduction of no-cost tailored requirements that separate one national market into two regional ones. Interestingly, these effects are felt in both the market where the tailored rules are applied and in the base market where no change in regulation occurs.

Simulations reported in Table 5 suggest that the short-run effects of tailoring even a "costless" regulation are a first-order consideration. In the extreme case where 10% of a formerly unified market served by 10 plants is subject to a tailored formulation requirement, average prices rise by approximately 50% relative to the pre-tailored value (1.925 in the first line of Table 5 vs. 1.301 in the second line of Table 3). Price variance also increases substantially, as do expected rents and their variance. While transfers to refiners serving the tailored segment are significant, most of the higher prices faced by consumers reflect the real costs of operating in a shallower, less reliable marketplace, including the costs of a significant increase in the market's reliance on inventories in place of capacity redundancy to address stochastic failures.

The impact of tailoring is not limited to the market where new formulation rules are applied, since the size of the market for the base product also is reduced. For the case where the tailored market is small, as in the first line of Table 5, these effects are modest. However, as the size of the tailored market increases, the effects on average prices and price variability in the base market grow, just as they shrink in the tailored market. The fifth line of Table 5 considers the case where no-cost tailored regulation splits the original market in half. For our parameters, this case increases the average price in each market by 3.6% and increases the price variance by more than 86% relative to levels experienced in the original "unified" market.

Clearly, tailoring can lead to higher prices and greater price variability for consumers in the base market when a dominant segment tailors regulation to serve its specific needs. This suggests the possibility that consumers in the base market can benefit from a strategy of "following the leader" to achieve the reliability benefits of product standardization even where the tailored formulation provides no direct benefit. The case for standardization, which is strongest in the polar case of no-cost regulation considered above, becomes a tougher tradeoff as the cost of the tailored formulation, as defined under a traditional non-stochastic analysis, increases.

5.3 Impacts of tailoring "costly" regulation

Table 6 considers the effects of applying fuel formulation requirements that increase production costs in a tailored manner. In contrast to the uniformly applied requirements considered in Table 4, the effect on average prices to consumers in the regional market where the new requirements are imposed exceeds the increase in production costs. For example, with a 5% increase in variable costs, the application of fuel formulation requirements in a region comprising 30% of the national market increases the average price in that market by 13.1%

(1.472 vs. 1.301), compared to an average national price increase of 4.2% (1.355 vs. 1.301) when the same requirement is applied uniformly. Furthermore, while uniform regulation that has little impact on price variance, tailored regulation can dramatically increase it—in our example, price variance increases by a factor of 30 when tailored regulation is introduced. Clearly, reliability effects can be a dominant factor in driving both the mean and variance of the price process in fully competitive markets. For this reason, engineering cost estimates that ignore stochastic breakdowns and reliability considerations may provide highly inaccurate estimates of regulatory impacts.

Table 6.
Impact of "Costly" Tailored Regulation on Prices, Rents, and Inventories.
Two Way Fungibility Barrier Case
Simulated Results for 1000 Periods

CASE	TAILORED MARKET					BASE MARKET				
$n_1, \Delta c_1, K_1, K_2$	PRICES		RENTS		I_{MAX}	PRICES		RENTS		I_{MAX}
	mean	var	mean	var		mean	var	mean	var	
.3, + 0%, 3, 7	1.420	3.550	0.127	0.422	1.957	1.319	0.181	0.840	0.068	1.406
.3, + 5%, 3, 7	1.472	3.389	0.121	0.402	1.882	1.319	0.181	0.840	0.068	1.406
.3, +10%, 3, 7	1.526	3.229	0.116	0.384	1.806	1.319	0.181	0.840	0.068	1.406
.3, +20%, 3, 7	1.632	2.787	0.105	0.332	1.690	1.319	0.181	0.840	0.068	1.406
.3, +25%, 3, 7	1.685	2.549	0.101	0.305	1.650	1.319	0.181	0.840	0.068	1.406

As with the zero-cost regulation considered in Table 5, prices in the base market also affected by the adoption of new formulation requirements in another region through a reduction in the scale of production for the standard formulation that degrades reliability. However, the impact on average base market prices in our example is relatively modest (1.319 vs. 1.301, or 1.2%). In weighing a decision to voluntarily adopt the more stringent formulation, which in our example would increase average price impacts in the base market from 1.2% to 4.2%, authorities in the base region would need to consider both the value of the environmental benefits that might result from adoption of the new formulation requirements and the size of the side payments they may be able to extract from the tailored region for taking an action that would substantially reduce average prices and enhance reliability in that market.

To this point, the analysis has considered the case where tailoring presents a two-way barrier to fungibility. In some settings, however, tailoring is more likely to involve a one-way barrier. Suppose, for example, that a "high" tailored standard is adopted for one region. Assume that a product meeting the "high" standard also is suitable for use in the area with "base" standards, and that the distribution system in the latter area can readily accommodate a mixture of products meeting the "high" and "base" standards. Under these circumstances, the high-specification product can be brought into the region with base standards to ameliorate price spikes that might otherwise occur due to stochastic breakdowns in capacity to produce the base-specification product, but the reverse flow of base-specification fuel into the high-standard market is precluded.

In this scenario of one-way fungibility, authorities in the base region would have less reason to standardize on the higher specification to reduce price volatility, since they already have access to fuel produced for other markets. High-specification areas, however, are worse off on average with one-way fungibility; they face higher prices when shortages of "base" product in the other market lead to diversion of high-specification product, but gain no comparable access to external supplies that might lower prices when their own supplies are short.

6. Discussion of Policy Implications

6.1 Tailoring/Targeting and Regulatory Efficiency

In a certainty setting, where reliability is not an issue, targeting or tailoring is typically seen as a means to increase the overall efficiency of regulation where there is significant interregional variation in the benefit function. Tailoring avoids overcontrol (marginal costs exceed marginal benefits) in some areas and undercontrol (marginal benefits exceed marginal costs) in others; both are inherent in a "one-size-fits-all" regulatory system. Absent significant conventional scale economies in production and/or distribution systems, the degree of customization is limited only by administrative costs and concerns related to the prospect of circumvention by consumers in stringently-controlled markets.

Our framework introduces reliability as a competing factor in the consideration of tailored regulation. Even if a market segment is large enough to be served by one or more plants of minimum efficient scale, the costs of maintaining reliability are likely to increase significantly as the market becomes balkanized. The costs of maintaining reliability mitigate against approaches that customize product specifications to local conditions. However, the analysis does not necessarily imply that relaxation of stringent formulation requirements is desirable. Since standardization of formulation at either the stringent level or the base level can restore fungibility and reliability, the implications of the analysis for the average stringency of optimal regulation are ambiguous.

6.2 Allegations of Price Gouging

Recent price volatility in regional markets for motor fuels, which have provided apparent windfall profits to those with the luck (or foresight) to have product available to sell, has sparked allegations of price gouging. State and federal officials have generally responded to the public outcry over price spikes by pursuing an agenda of investigation and short-term palliation, while aggressively proclaiming their complete lack of culpability in exacerbating volatility. Many factors unrelated to government policies have undoubtedly played a significant role in recent events, but there are two distinct avenues through which federal and state regulatory policies could have contributed to the volatility.

The first contribution is via the impact of tailoring on the reliability of supply, as analyzed in this paper. Our analysis demonstrates that tailoring can increase average product prices by a multiple of certainty-based engineering compliance costs estimates while also significantly increasing the variance of prices, even if producers and arbitrageurs are pure price takers. Markets clear at the margin, so policies that have even modest effects on reliability in markets where demand is inelastic can have a large impact on prices. For this reason, efforts by regulators to disclaim direct responsibility for any price increases that exceed certainty-based engineering estimates of regulatory compliance costs are not very convincing.[15]

Second, although price spikes may arise without any abuse of market power in a setting with stochastic failures, the absence of workable competition in regional energy markets is itself

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[15] See testimony of Robert Perciasepe, Assistant Administrator for Air and Radiation, U.S. Environmental Protection Agency before the Committee on the Judiciary, U.S. House of Representatives, June 28, 2000.

a potentially significant issue. Regulatory tailoring generally increases the market power of local producers by reducing the number of actual or potential competitors, increasing both the opportunity for market power abuse and its potential profitability. While consideration of market power is beyond the scope of this paper, the effect of tailored regulatory strategies on competition merits attention as regulatory programs are designed. Regulators whose own actions substantially raise market power are in a particularly poor position to cast stones when and if that power is exercised.

6.3 Relationship to Literature on Conventional and Stochastic Scale Economies

Our analysis, like the literature on commodity prices from which it is derived, emphasizes the effects of stochastic supply on market-clearing prices. In the context of markets with highly inelastic demands, we show that economically important reliability benefits can be compromised by reducing the scale of product markets through regulatory balkanization of product specifications. Even if an individual market segment is large enough to be supplied by one or more plants producing at minimum efficient scale in an engineering sense, economies of scale in providing a reliable supply can still be adversely affected by regulatory barriers to fungibility across a broader market area.

Another strand of literature considers stochastic scale economies from a production function perspective. This literature, beginning with Palm and Feller's consideration of the machine repairman problem, focuses the coordination of effective factor inputs on the supply side of the market. Several authors suggested that stochastic scale economies are not likely to be economically significant (Rothschild and Werden 1979) and/or that indivisibilities have been mistaken for scale economies (Levhari and Sheshinski 1970; Arrow, Levhari et al. 1972; Sheshinski and Dreze 1976) based on statistical evidence indicating that constant returns functional forms provide good fits to data generated from such processes. However, Mulligan (1983, 1985, 1986) argues that scale economies are likely to be important, noting that the datasets used in studies showing good fits for constant-returns functional forms include a disproportionate number of observations where the ratio of factors is far from the level where scale economies are likely to be significant.

In this paper, where available refinery capacity is the single essential factor of production, there is no coordination-of-factors issue and no economies of scale in the production-function sense – expected production possibilities are homogeneous of degree one in total refinery capacity at all capacity levels. However, while there are constant expected returns to scale on the production side, the coordination of supply and demand through competitive markets raises a different type of coordination issue that is sensitive to the scale of operations. Markets characterized by inelastic demand and non-trivial inventory costs show higher average prices and higher volatility when scale is reduced even though there is no loss in the expected physical productivity of capital.

The distinction between the production function and market perspectives on stochastic scale economies is particularly clear in the electricity context where, absent a storage technology, supply and demand must be balanced instantaneously. The advantages of interconnecting loads with multiple power plants have been widely recognized from the inception of electricity markets. In the last 50 years, interconnection has extended well beyond individual utility service territories, to a point where the entire power system in the United States and Canada is now organized into three large synchronous grids. Given the diversity of loads and generation sources, interconnection supports efficient provision of electricity by enabling resource sharing creating pathways for economy transactions that exploit opportunities to substitute low-cost generation from remote sources that would otherwise be idle for high-cost local generation.

The most important benefit of interconnection, enhanced reliability, results directly from the possibility of stochastic failures in generation and transmission systems. Consider a case in which there is no diversity in the timing or shape of loads or in generation technologies, so that there are no opportunities to "wheel" generation to serve non-coincident peak loads or make economy sales that maximize utilization of low-cost generators. The only benefit of interconnection under such circumstances is to reduce the number of redundant plants required to assure reliability. To illustrate the reduction in reliability costs from interconnection, suppose that the forced outage rate for a generation plant is 10%—a "round number" that is within the range of recent forced outage experience for U.S. power plants[16]. A generator without any interconnection would therefore need two standby plants to provide its local customers with 99.9% reliability. If capital cost accounts for ½ of total generation cost[17], backup capacity costs would double the levelized cost of generation. Now consider the benefits of interconnecting 100

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[16] Capacity-weighted equivalent forced outage rates (WEFOR) for the 1995 to 1999 period reported by the North American Electric Reliability Council (NERC) range from 4.1 percent for hydro plants to 12.1 percent for nuclear plants. For fossil-fired plants, WEFOR averaged 7.6 percent over this period.

[17] This is broadly characteristic of current technologies. Capital costs represent roughly 1/3, 2/3 and 4/5 of total levelized generation for gas-fired, coal-fired, and nuclear plants respectively.

such identical local markets. The same 99.9% reliability in meeting all load could be provided by a system of 124 plants, a dramatic reduction in the reserve margin required to assure reliability. With minimum efficient scale for central station generation plants ranging between 300 MW (gas turbines) and 1000 MW (coal-fired boilers), it is interesting to note that the three large regional interconnections spanning the United States and Canada[18] are between 50 to 500 times an upper-range estimate of plant-level minimum efficient scale. With reserve margins at the interconnection level of between 8% and 18%, grid reliability is well in excess of 99.9%.

Finally, it should also be noted that the link between regulatory policy and conventional scale economies also has received considerable attention in several policy contexts. For example, while manufacturers have often questioned the need for energy-efficiency standards at either the state or federal levels, they have strongly supported federal laws that pre-empt the setting of standards that could disrupt production at efficient scale. Indeed, the threat of balkanized markets resulting from divergent state-level energy efficiency standards appears to have been a dominant consideration in winning the active support of home appliance manufacturers for legislation that bundled federal energy-efficiency standards for appliances with a strong pre-emption clause in 1987 (Geller 1997; McInerney 1997). Full or partial preemption provisions also have figured prominently in automobile regulation, where all states are precluded from establishing fuel economy standards, and California alone has the right to set emissions standards stricter than those implemented under the federal Clean Air Act.

Much could be done to extend the analysis, but the results so far point to the important role of supply uncertainty in estimating the effects of tailored regulation on average prices and price volatility.

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[18] A small part of Mexico (Baja California) is also part of this interconnected system.

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