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Motivating the Optimal Procurement and Deployment of Electric Storage as a Transmission Asset

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by

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Abstract

We analyze the design of policies to motivate an electric utility to employ its superior knowledge of industry conditions to: (i) choose between a traditional expansion of transmission capacity and storage as a transmission asset (SATA); and (ii) deploy SATA to either substitute for transmission service or supply electricity in wholesale markets. The optimal policy differs considerably from policies under active consideration, in part by paying the utility relatively little for implementing SATA. The utility often commands substantial rent from its privileged knowledge of the cost of installing and integrating SATA. However, the utility typically secures little additional rent from its superior knowledge of the likelihood of local network congestion.

Keywords: storage as a transmission asset, electricity network congestion

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1 Introduction

Local transmission congestion can occur on an electricity network when electricity demand at a specific location exceeds the amount of electricity that can be delivered to the location over existing transmission facilities. Historically, transmission capacity expansion (TCE) has been the primary means to relieve network congestion. Today, alternative remedies are available. In particular, electricity can be stored near the point of potential congestion and released to serve unusually high demand for electricity when it arises. Such use of stored electricity can avoid local congestion without having to expand the capacity of the existing transmission network.[1]

Electricity storage as a transmission asset (SATA) has become economical in recent years because of sharply declining battery costs. On average, the cost of lithium-ion batteries has declined by 23% annually between 2010 and 2015 (Ardani et al., 2017). These declining costs have led several U.S. states to set ambitious targets for SATA adoption. For example, California, New York, and New Jersey seek to implement 1,300 MW, 1,500 MW, and 2,000 MW of SATA, respectively, by 2030.[2]

SATA offers an additional benefit relative to TCE. If unusually high local demand for electricity ultimately does not arise, the stored electricity can be sold in wholesale electricity or ancillary services markets. The sale of electricity can generate revenue for the SATA owner, and may provide additional social benefits by, for example, reducing the wholesale price of electricity. SATA is thus a "hybrid" resource that can both substitute for transmission services and supply market services. The hybrid nature of SATA raises regulatory issues regarding appropriate utility compensation for SATA and the rules and conditions under which SATA can participate in energy markets (Bhatnagar et al., 2013).

[1] Electricity storage can also provide distribution-level benefits. It can do so by helping to avoid local outages, for example. Battery storage can also help to balance the flow of electricity from intermittent renewable energy sources. Brattle (2015), Chang et al. (2015), and Hledik et al. (2018) review the many potential uses for and benefits of stored electricity. For expositional ease, the ensuing discussion focuses on the benefits derived from avoiding local transmission congestion. However, the analysis applies more broadly.

[2] California Public Utility Commission (2013); New York Public Service Commission (2018); New Jersey Legislature (2018).

In February 2018, the Federal Energy Regulatory Commission (FERC) issued Order 841, which requires Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) to establish rules that facilitate the participation of storage resources in energy markets (FERC, 2018). Appropriate design of these rules entails many important challenges, including: (i) determining when SATA must provide transmission services and when it can participate in real-time markets; (ii) motivating utilities to employ SATA to participate in these markets when appropriate, without promoting double recovery of asset costs; and (iii) limiting any undesirable effects of market participation by assets whose costs are reimbursed in part according to cost-of-service principles (California ISO, 2018a, 2018b; FERC, 2017).

We are not aware of any formal analysis of the optimal design of policies to motivate the appropriate choice between TCE and SATA and the subsequent SATA deployment. This research provides such an analysis. We analyze this optimal design in settings where the regulated utility has privileged knowledge of the likelihood of local transmission congestion and the cost of acquiring, installing, and integrating SATA. We consider policies that entail elements of the plans under active consideration in California (CAISO, 2018a,b), which share many features with plans under study in other jurisdictions (Brooks, 2018). We allow the regulator to specify a fixed payment to the utility (P_S) if it implements SATA and a corresponding payment (P_T) if it implements TCE. The regulator can also set the fraction ($f \in [\,0, 1\,]$) of the revenue SATA generates in supplying market services that accrues to the utility.[3] In addition, the regulator can specify a critical day-ahead congestion probability ($\widehat{s} \in [\,0, 1\,]$) above which SATA must stand by to supply any transmission services that might be needed the following day.[4]

[3] CAISO (2018b, p. 17) envisions three variants of this policy. Under the *full cost-of-service* variant, P_S is effectively set equal to the difference between the fixed cost of SATA (K_S) and the revenue (R) the utility generates by supplying market services. Under the *partial cost-of-service* variant, P_S is set at a fixed level below K_S, and f is set above 0. Under the *full cost-of-service plus revenue sharing* variant, P_S is set equal to K_S and f is set above 0.

[4] CAISO (2018b, p. 29) envisions forecasting the local demand and supply of electricity one day in advance. Then, "[if] the load forecast for the local area ... exceeds the level identified as a reliability concern, considering the import capability and capacity resource availability in the local load pocket areas, the

We find that the optimal regulatory policy entails a relatively small fixed payment for implementing SATA (P_S). The small payment limits the rent the utility commands from its superior knowledge of SATA costs. However, the small payment sometimes induces the utility to implement TCE even though SATA would generate a higher level of expected welfare.[5] The optimal policy also typically distorts SATA assignment. For instance, the critical congestion probability ($\widehat{s}$) often is set above its efficient level, so SATA is permitted to participate in real-time markets even though expected welfare would be higher if SATA were assigned to provide transmission services. The increased deployment of SATA to supply market services, coupled with revenue sharing ($f > 0$), can render SATA implementation particularly profitable for the utility when (and only when) it knows that local congestion is relatively unlikely. Thus, the optimal distortion in SATA deployment helps to motivate the utility to employ its superior knowledge of congestion probabilities to implement the socially optimal choice between SATA and TCE.

Despite the regulator's best efforts to limit the utility's rent (in order to secure lower electricity prices for consumers), the utility often secures substantial rent from its privileged knowledge of the cost of installing and integrating SATA. However, the utility typically secures little additional rent from its superior knowledge of the likelihood of local network congestion. The limited additional rent reflects in part the fact that day-ahead congestion probabilities are ultimately observed publicly, which limits the utility's ability to misrepresent its superior *ex ante* knowledge of the prevailing congestion probability. This finding suggests that regulators often may be better served by improving their knowledge of SATA costs than by improving their understanding of local congestion probabilities.

We also find that the optimal policy can differ significantly from the policies presently under active consideration. Furthermore, implementation of the optimal policy can secure substantial gains for consumers relative to the policies under consideration. Consequently,

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SATA resource(s) in the local area will be designated as a transmission asset the following day."

[5] P_T is set equal to the (known) cost of TCE under the optimal policy.

further study of potential policy options may be constructive.

We develop these findings and others as follows. Section 2 explains the key elements of our formal model. Section 3 analyzes the optimal procurement policy in three benchmark settings. Section 4 presents our primary findings.[6] Section 5 concludes and identifies directions for future research.

2 Model Elements

We consider a setting where unusually high demand for electricity may occur at a given location on an electricity network. If the unusually high demand arises, it exceeds the amount of electricity that can be imported from other locations over the existing transmission facilities. The resulting network congestion imposes an expected loss of $L^e > 0$ on electricity consumers. This loss may stem from personal inconvenience or foregone or compromised commercial transactions, for example.

As explained in the Introduction, local market congestion can be avoided by TCE or SATA. TCE serves only to eliminate transmission congestion in our model. SATA can be employed either to mitigate congestion or to perform other welfare-enhancing activities, such as selling stored electricity in wholesale markets. However, because the SATA battery cannot be recharged instantaneously, it cannot provide transmission services (i.e., be prepared to meet an unusually high local demand for electricity) in the same period (e.g., in the same day) that it provides market services (i.e., supplies electricity in a wholesale market). Consequently, a decision must be made at the start of each period whether SATA will be deployed to provide transmission services or market services.

This decision is influenced by the realization of a public signal $s \in [\,0, 1\,]$, which reflects the probability that the unusually high local demand for electricity will arise in the coming period. In practice, this signal might reflect day-ahead projections of electricity demand that are delivered to an independent system operator. When projected demand is low relative to existing transmission capacity, the probability of congestion (s) will be small, so SATA may

[6] The Appendix provides the proofs of all formal findings.

optimally be assigned to supply market services. In contrast, when projected demand is close to or in excess of transmission capacity, s will be relatively high, so SATA may optimally be assigned to supply transmission services.[7]

The optimal choice between TCE and SATA depends in part on the relative costs of the two assets. $K_T > 0$ will denote the cost of TCE. This cost is known to both the regulator and the utility. In contrast, given the relative novelty of using storage to mitigate local congestion, the utility is assumed to be better informed than the regulator about the fixed cost of SATA. This cost includes the cost of acquiring the physical asset (including the battery), the cost of maintaining the asset, and the various costs associated with fully integrating the asset into network operations and ensuring its smooth, reliable functioning.[8] We assume the utility knows this fixed cost of SATA, $K_S \in \left[\underline{K}_S, \overline{K}_S \right]$. The regulator's beliefs about K_S are captured by the distribution function $G(K_S)$ and corresponding density function $g(K_S)$. In standard fashion, we assume $\frac{d}{dK_S}\left(\frac{G(K_S)}{g(K_S)}\right) \geq 0$ for all $K_S \in \left[\underline{K}_S, \overline{K}_S \right]$. This assumption is satisfied for many common distributions, including the uniform and normal distributions.[9]

Unlike TCE, SATA also entails a variable cost of operation. $v > 0$ will denote the variable cost of using SATA to supply market services or to supply the electricity required to meet unusually high local demand. v includes the cost of recharging the battery after its discharge and the depreciation cost associated with the discharge and recharge of the battery. We assume the regulator and the utility both know the magnitude of v.[10]

The optimal choice between TCE and SATA also depends on the likelihood that unusually high local demand for electricity will arise. If the high demand is likely, TCE can be the most economical means to eliminate the associated congestion. However, if the high demand

[7] When SATA is assigned to supply transmission services, it discharges its battery and thereby substitutes for transmission services if and only if the unusually high demand for electricity arises. When SATA is assigned to supply transmission services, it cannot simultaneously supply market services.

[8] Sandia (2010) reviews the many facets of this activity.

[9] See Bagnoli and Bergstrom (2005), for example. This assumption avoids unusual properties of $g(\cdot)$ that can complicate the characterization of optimal policies in the presence of asymmetric information.

[10] The presumed symmetric, perfect knowledge of v reflects the fact that battery technologies and depreciation schedules generally are relatively well known (e.g., Arteaga et al., 2017).

is unlikely, SATA may be the more attractive option because it can generate surplus by supplying market services when it is not being deployed to provide transmission services.[11] $R_1 > 0$ ($R_0 > 0$) will denote the revenue the utility derives from employing SATA to supply market services if the unusually high demand arises (does not arise). $M_1 \geq 0$ ($M_0 \geq 0$) will denote the incremental consumer welfare that arises when SATA is employed to supply market services and the unusually high demand arises (does not arise). This incremental welfare includes the consumer surplus that arises when an increased supply of electricity leads to a lower wholesale price of electricity.

We assume the revenue and the incremental consumer welfare that SATA generates are more pronounced in the presence of the unusually high demand for electricity (hereinafter "congestion") than in its absence. (Formally, $R_1 > R_0$ and $M_1 > M_0$.) This assumption reflects the fact that high demand for electricity tends to be associated with both congestion and high prices for wholesale electricity and ancillary services. We further assume that SATA supply of market services generates positive surplus, i.e., $M_0 + R_0 > v$. In addition, if congestion arises, expected welfare is higher if SATA has been deployed to provide transmission services than if it has been deployed to provide market services, i.e., $L^e > M_1 + R_1$.[12]

The local demand for electricity cannot be predicted perfectly. However, because utilities often are more knowledgeable than regulators about specific customer needs and network capabilities, the utility is assumed to be initially better informed than the regulator about the probability of congestion (s). The prevailing cumulative distribution function of s can be one of $n \geq 2$ distributions, $H_1(s), ..., H_n(s)$. These distribution functions are ranked by first-order stochastic dominance, so the probability of congestion is systematically greater when $H_j(s)$ prevails than when $H_i(s)$ prevails for all $j > i$ ($i, j \in \{1, ..., n\}$).[13] The utility knows

[11] Sandia (2010) observes that the unusually high demand can arise very infrequently. Consequently, SATA may be able to deliver market services a large fraction of the time.

[12] Formally, if $L^e > M_1 + R_1$, then $-v$ (welfare when SATA avoids congestion) exceeds $M_1 + R_1 - v - L^e$ (expected welfare when SATA supplies market services and congestion occurs). Observe that $M_1 + R_1 - v - L^e < M_0 + R_0 - v$ when $M_0 + R_0 - v > 0$ and $L^e > M_1 + R_1$. Thus, when SATA supplies market services, expected welfare is lower when congestion occurs than when it does not occur.

[13] Formally, $H_1(s) > ... > H_n(s)$ for all $s \in (0, 1)$.

the prevailing distribution of s from the outset of its interaction with the regulator. The regulator knows only that distribution $H_i(s)$ prevails with probability ϕ_i. Unless otherwise noted, we assume $\phi_i \in (0,1)$ for each $i \in \{1, ..., n\}$.[14]

We assume congestion is sufficiently likely and the expected loss from congestion (L^e) is sufficiently pronounced that the regulator always induces the utility to implement either TCE or SATA. The regulator pays the utility P_T if it implements TCE. If it implements SATA, the utility receives payment P_S from the regulator and the fraction $f \in [\,0,1\,]$ of the revenue generated by employing SATA to deliver market services. The remaining fraction $(1-f)$ of this revenue accrues to consumers (in the form of lower retail charges for electricity, for example). The regulator also reimburses the utility for v, its variable cost of operating SATA.[15] The utility will operate as long as it anticipates nonnegative profit from doing so.

In addition to setting P_S, P_T, and f, the regulator specifies how SATA will be deployed, depending on the realized public signal. She does so by specifying a critical congestion probability, $\widehat{s} \in [\,0,1\,]$, and requiring SATA to supply transmission services when the realized signal exceeds $\widehat{s}$, while authorizing the utility to employ SATA to supply market services when $s \leq \widehat{s}$.

The utility will implement the asset that allows it to secure the highest (nonnegative) level of expected profit. The utility's profit when it implements TCE is:

$$\Pi_T \;=\; P_T - K_T\,. \tag{1}$$

The utility's expected profit when it implements SATA and when fixed cost K_S and cumulative distribution function $H_i(s)$ prevail is:

$$E_i\,\{\,\Pi_S(K_S)\,\} \;=\; P_S + f \int_0^{\widehat{s}} (\,s\,R_1 \,+ [\,1-s\,]\,R_0\,)\,dH_i(s) - K_S\,. \tag{2}$$

Expressions (1) and (2) imply that the utility will implement SATA rather than TCE when

[14] Findings 1 and 2 in Section 3.4 consider a benchmark setting where the regulator and utility both know that distribution $H_i(s)$ prevails, so $\phi_i = 1$ and $\phi_j = 0$ for all $j \neq i$ ($i, j \in \{1, ..., n\}$).

[15] This compensation structure reflects the structure in the proposed California ISO policy (CAISO, 2018a,b). Alternative compensation structures are discussed below.

distribution $H_i(s)$ prevails if:[16]

$$E_i\{\,\Pi_S(K_S)\,\} \;\geq\; \Pi_T \quad \Leftrightarrow \quad K_S \;\leq\; \widehat{K}_{Si}$$

$$\text{where } \; \widehat{K}_{Si} \;\equiv\; K_T - P_T + P_S + f \int_0^{\widehat{s}} (\, s\, R_1 \,+ [\,1-s\,]\, R_0 \,)\, dH_i(s)\,. \tag{3}$$

The regulator seeks to maximize expected consumer welfare, which is the difference between: (i) the sum of the incremental consumer welfare generated when SATA provides market services and the fraction $(1-f)$ of the revenue from such activity that is awarded to consumers; and (ii) the sum of variable SATA costs, payments to the utility, and the losses that consumers incur when unmitigated congestion arises (because SATA provides market services). Formally, the regulator's problem, [RP], is to choose P_T, P_S, $f \in [\,0,1\,]$, and $\widehat{s}$ to:

$$\text{Maximize } \sum_{i=1}^{n} \phi_i\, J_i \tag{4}$$

subject to, for each $i = 1, ..., n$:

$$\Pi_T \;\geq\; 0 \quad \text{and} \quad E_i\{\,\Pi_S(K_S)\,\} \;\geq\; 0 \;\; \text{for all } \; K_S \in [\,\underline{K}_S,\, \widehat{K}_{Si}\,]\,, \;\; \text{where} \tag{5}$$

$$\begin{aligned} J_i \;\equiv\; G(\,\widehat{K}_{Si}\,) \Bigg\{ & \int_0^{\widehat{s}} (\, s\,[\,M_1 + (1-f)\,R_1 - L^e\,] + [\,1-s\,]\,[\,M_0 + (1-f)\,R_0\,] - v\,)\, dH_i(s) \\ & - P_S - \int_{\widehat{s}}^{1} s\, v\, dH_i(s) \Bigg\} - \Big[\,1 - G(\,\widehat{K}_{Si}\,)\Big]\, P_T\,. \end{aligned} \tag{6}$$

Expression (6) reflects the fact that when distribution $H_i(s)$ prevails, the utility implements SATA when $K_S \leq \widehat{K}_{Si}$, whereas it implements TCE when $K_S > \widehat{K}_{Si}$.[17] Furthermore, SATA is deployed to supply transmission services when $s > \widehat{s}$ and to supply market services when $s \leq \widehat{s}$. The constraints in expression (5) ensure the utility secures nonnegative expected profit whether it implements TCE or SATA. V_0 will denote the maximized value of $\sum_{i=1}^{n} \phi_i\, J_i$ at the solution to [RP].

[16] We follow the standard convention by ensuring that when the utility is indifferent among multiple actions, it undertakes the action preferred by the regulator.

[17] We assume $\widehat{K}_{Si} \in (\,\underline{K}_S, \overline{K}_S\,)$ for each $i \in \{1, ..., n\}$ at the solution to [RP]. This will be the case if, for instance, $\underline{K}_S$ is sufficiently small and $\overline{K}_S$ is sufficiently large relative to K_T.

The interaction between the regulator and the utility proceeds as follows. First, the utility learns privately the fixed cost of SATA (K_S) and the prevailing distribution of the congestion probability ($H_i(s)$). Second, the regulator specifies payments to the utility (P_T and P_S), the extent of revenue sharing (f), and the critical congestion probability ($\widehat{s}$) that determines whether SATA is assigned to deliver transmission or market services. Third, the utility decides whether to implement TCE or SATA. Fourth, the actual congestion probability (s) is realized and observed publicly. Fifth, if SATA has been implemented, it is assigned to provide transmission services if $s > \widehat{s}$ whereas it is assigned to supply market services if $s \leq \widehat{s}$. Finally, if SATA is implemented and $s \leq \widehat{s}$, the revenue SATA generates in supplying market services is realized, and the fraction $1 - f$ is delivered to consumers.

3 Benchmarks

Before characterizing the optimal regulatory policy in the setting of primary interest, we briefly explain the optimal policy in four benchmark settings.

3.1 Full Information Setting

First consider the *full information setting*, in which the regulator shares the utility's knowledge of K_S and $H_i(s)$ from the outset of their relationship. In this setting, the regulator dictates the efficient (welfare-maximizing) asset choice and SATA assignment while eliminating the utility's rent.

The regulator ensures the efficient SATA assignment by requiring it to supply market services if and only if the corresponding expected welfare exceeds the expected welfare from supplying transmission services, i.e.,

$$s\,[\,M_1 + R_1 - L^e\,] + [\,1 - s\,]\,[\,M_0 + R_0\,] - v \;\geq\; s\,[\,-v\,]$$

$$\Leftrightarrow \quad s \;\leq\; s^* \;\equiv\; \frac{M_0 + R_0 - v}{M_0 + R_0 - v + L^e - M_1 - R_1} \;\in\; (0, 1)\,. \tag{7}$$

It is readily verified that:

$$\frac{ds^*}{dL^e} < 0\,, \quad \frac{ds^*}{dv} < 0\,, \quad \frac{ds^*}{dR_0} > 0\,, \quad \frac{ds^*}{dM_0} > 0\,, \quad \frac{ds^*}{dR_1} > 0\,, \text{ and } \frac{ds^*}{dM_1} > 0\,. \tag{8}$$

Thus, in the full information setting, SATA is deployed to deliver transmission services over a broader range of s realizations as congestion imposes greater social losses (L^e) and as the variable cost of SATA operation (v) increases.[18] In contrast, SATA is deployed to deliver market services over a broader range of s realizations when the market services generate higher levels of revenue (R_0, R_1) and/or incremental consumer welfare (M_0, M_1).

The regulator ensures the efficient asset choice in the full information setting by specifying payments that induce the utility to implement SATA if and only if the associated expected welfare exceeds the expected welfare from implementing TCE. This is the case when distribution $H_i(s)$ prevails if

$$W^e_{Si}(s^*) - K_S \;\geq\; -K_T \quad \Leftrightarrow \quad K_S \;\leq\; K^*_{Si} \;\equiv\; K_T + W^e_{Si}(s^*)\,, \quad \text{where} \tag{9}$$

$$W^e_{Si}(\widehat{s}) \;\equiv\; \int_0^{\widehat{s}} (\, s\,[\,M_1 + R_1 - L^e\,] + [\,1 - s\,]\,[\,M_0 + R_0\,] - \,v\,)\,dH_i(s) - \int_{\widehat{s}}^1 s\,v\,dH_i(s) \tag{10}$$

is the aggregate expected welfare (not counting the fixed cost, K_S) SATA generates when $H_i(s)$ prevails, given $\widehat{s}$. This expected welfare is the difference between: (i) expected revenue and incremental consumer welfare when SATA provides market services; and (ii) expected variable SATA costs and expected losses from congestion when SATA provides market services. The regulator can ensure the desired utility behavior while eliminating the utility's rent by setting:

$$P_T \;=\; K_T, \;\; P_S \;=\; K_S, \text{ and } \; f \;=\; 0\,. \tag{11}$$

The payments in expression (11), coupled with reimbursement of variable SATA costs, ensure the utility always secures exactly zero profit. Because the utility's profit does not vary with its asset choice, the utility will implement the asset that maximizes expected welfare, given K_S and $H_i(s)$.

The regulator's expected payoff in the full information setting is:

[18] Observe that the variable cost is always incurred when SATA supplies market services whereas this cost is only incurred when congestion arises if SATA is deployed to provide transmission services.

$$V_1 \;\equiv\; \sum_{i=1}^{n} \phi_i \left[\int_{\underline{K}_S}^{K_{Si}^*} \left[\, W_i^e(s^*) - K_S \,\right] dG(K_S) - \left[\, 1 - G(K_{Si}^*) \,\right] K_T \right]. \tag{12}$$

3.2 Setting Where Utility has Private Knowledge of $H_i(s)$ Only

Now suppose the regulator knows the fixed cost of SATA (K_S) but does not share the utility's private knowledge of $H_i(s)$. This form of limited information is not constraining for the regulator because as long as she knows K_S (and K_T), she can institute the payments in expression (11).[19] Doing so ensures the utility receives the same (zero) profit whether it implements TCE or SATA, so the utility will implement the welfare-maximizing asset choice, given the prevailing $H_i(s)$ distribution. Consequently, the regulator's expected payoff in this setting is V_1.

3.3 Setting with Symmetric Uncertainty about $H_i(s)$ Only.

Next suppose the regulator observes K_S and K_T before setting P_S, P_T, f, and $\widehat{s}$, but neither she nor the utility knows the prevailing $H_i(s)$ distribution. Both parties believe $H_i(s)$ prevails with probability $\phi_i \in (0,1)$. The regulator can again eliminate the utility's rent by setting $P_T = K_T$, $P_S = K_S$, and $f = 0$ in this setting. The regulator will also ensure the efficient SATA assignment by setting $\widehat{s} = s^*$. In addition, SATA will be implemented if and only if it generates a higher level of expected welfare than TCE, i.e.,

$$\sum_{i=1}^{n} \phi_i \, W_i^e(s^*) - K_S \;\geq\; -\, K_T \quad \Leftrightarrow \quad K_S \;\leq\; \widehat{K}_S^{e*} \;\equiv\; K_T + \sum_{i=1}^{n} \phi_i \, W_i^e(s^*)\,. \tag{13}$$

The regulator's expected payoff in this setting is:[20]

$$V_2 \;\equiv\; \sum_{i=1}^{n} \phi_i \left[\int_{\underline{K}_S}^{\widehat{K}_S^{e*}} \left[\, W_i^e(s^*) - K_S \,\right] dG(K_S) - \left[\, 1 - G(\widehat{K}_S^{e*}) \right] K_T \right]. \tag{14}$$

[19] The regulator can also set $\widehat{s} = s^*$ to ensure the efficient deployment of SATA.

[20] $V_2 \leq V_1$ in part because $\widehat{K}_S^{e*}$ is a constant that does not vary with the prevailing $H_i(s)$ distribution. In contrast, the regulator can choose a different $\widehat{K}_{Si}^*$ for each $i \in \{1, ..., n\}$ to match the prevailing $H_i(s)$ distribution in the full information setting.

3.4 Setting Where Utility has Private Knowledge of K_S Only

Finally suppose the regulator knows the prevailing $H_i(s)$ distribution but does not share the utility's knowledge of K_S. In this setting, the regulator sets P_S, P_T, f, and $\widehat{s}$ to maximize J_i as specified in expression (6). Finding 1 characterizes the optimal regulatory policy in this setting.

Finding 1. *Suppose $\phi_i = 1$. Then at a solution to [RP]: (i) $\widehat{s} = s^*$; (ii) $P_T = K_T$; (iii) $f = 0$; and (iv) $P_S = \widehat{K}_{Si}$, where*

$$\widehat{K}_{Si} \;=\; W^e_{Si}(s^*) + K_T \;-\; \frac{G(\widehat{K}_{Si})}{g(\widehat{K}_{Si})}\,. \tag{15}$$

Expressions (9) and (15) imply that the largest SATA fixed cost ($\widehat{K}_{Si}$) for which the utility implements SATA when $H_i(s)$ prevails is smaller when the regulator does not know K_S than when she knows K_S. Thus, asymmetric information about K_S leads the regulator to promise the utility relatively modest compensation for implementing SATA.[21] The modest compensation helps to limit the utility's rent when K_S is low. However, the relatively low compensation sometimes induces the utility to implement TCE even when expected welfare would be higher if SATA were implemented (i.e., when $K_S \in (\,\widehat{K}_{Si}, K^*_{Si})$). Therefore, the regulator intentionally induces the prospect of an inefficient asset choice in order to limit the utility's rent.[22]

The induced inefficiency can be substantial. To illustrate, suppose each of the possible K_S realizations is equally likely, so $g(K_S) = \frac{1}{\overline{K}_S - \underline{K}_S}$. Further suppose TCE and SATA deliver the same expected welfare when $H_i(s)$ prevails, so $W^e_{Si}(s^*) - K^e_{Si} = -K_T$ where $K^e_{Si} = \frac{1}{2}\left[\,\underline{K}_S + \overline{K}_S\right]$. Then, as Finding 2 reports, the regulator optimally fails to induce the welfare-maximizing asset choice for one quarter of the possible K_S realizations.[23]

[21] Payments need not take the exact form specified in property (iii) of Finding 1. It is only necessary that the utility's expected profit is zero when it implements SATA and $K_S = \widehat{K}_{Si}$.

[22] Borgers (2015, p. 22) observes that in related but distinct settings, the regulator effectively acts as if the cost of SATA is the virtual cost $K_S + \frac{G(K_S)}{g(K_S)}$ rather than the actual cost K_S. The virtual cost accounts for the rent afforded the utility when $K_S < \widehat{K}_{Si}$.

[23] $K^e_{Si} - \left(\frac{3}{4}\,\underline{K}_S + \frac{1}{4}\,\overline{K}_S\right) = \frac{1}{2}\,\underline{K}_S + \frac{1}{2}\,\overline{K}_S - \left(\frac{3}{4}\,\underline{K}_S + \frac{1}{4}\,\overline{K}_S\right) \;=\; \frac{1}{4}\left[\,\overline{K}_S - \underline{K}_S\,\right].$

Finding 2. *Suppose* $\phi_i = 1$, $g(K_S) = \frac{1}{\overline{K}_S - \underline{K}_S}$, *and* $W^e_{Si}(s^*) - K^e_{Si} = -K_T$. *Then at a solution to [RP],* $\widehat{K}_{Si} = \frac{3}{4}\underline{K}_S + \frac{1}{4}\overline{K}_S$. *Consequently, for all* $K_S \in [\frac{3}{4}\underline{K}_S + \frac{1}{4}\overline{K}_S, K^e_{Si})$, *TCE is implemented even though expected welfare would be higher if SATA were implemented.*

The regulator's *ex ante* expected payoff in this setting is $V_3 \equiv \sum_{i=1}^{n} \phi_i J_i^*$, where J_i^* denotes the maximized value of J_i.

4 The Solution to [RP]

Finding 3 records some key features of the optimal regulatory policy in the setting of primary interest where the utility is privately informed about both K_S and $H_i(s)$.

Finding 3. *At the solution to [RP]: (i)* $P_T = K_T$*; (ii)* $\widehat{s} = s^*$ *if* $f = 0$*; and (iii)*

$$\sum_{i=1}^{n} \phi_i \, g(\widehat{K}_{Si}) \left[K_T - \left(\widehat{K}_{Si} + \frac{G(\widehat{K}_{Si})}{g(\widehat{K}_{Si})} - W^e_i(\widehat{s}) \right) \right] = 0 \, . \qquad (16)$$

By setting $P_T = K_T$, the regulator eliminates the utility's rent when it implements TCE. Doing so also limits the payment the regulator must deliver to the utility to induce it to implement SATA rather than TCE when K_S is relatively low.

If $f = 0$, the utility receives none of the revenue that SATA generates when it delivers market services. Consequently, the utility's expected payoff is the same whether it implements TCE or SATA, regardless of the prevailing $H_i(s)$ distribution. In this case, setting $\widehat{s} \neq s^*$ would be counterproductive for the regulator because doing so would reduce total expected surplus without inducing the utility to use its privileged knowledge of $H_i(s)$ to choose between SATA and TCE.

When the regulator cannot observe $H_i(s)$, she cannot choose payments to induce the optimal $\widehat{K}_{Si}$ identified in equation (15) for each $H_i(s)$ distribution. Equation (16) indicates that, instead, the regulator essentially sets P_T and P_S (and f and $\widehat{s}$) to ensure the optimal $\widehat{K}_{Si}$ are induced in expectation.[24] Thus, relative to the choices between SATA and TCE

[24] As explained further below, setting $f > 0$ plays an important role in inducing the utility to implement SATA when congestion is relatively unlikely and to implement TCE when congestion is relatively likely.

characterized in equation (15), the utility will implement SATA for additional K_S realizations under some $H_i(s)$ distributions and implement SATA for fewer K_S realizations under other $H_i(s)$ distributions. The particular $H_i(s)$ distributions and K_S realizations for which SATA implementation is expanded or contracted varies with the regulator's beliefs about s and K_S.[25]

Additional analytic characterization of the solution to [RP] is problematic because the qualitative properties of the optimal regulatory policy can vary as model parameters and the functional forms of $G(K_S)$ and $H_i(s)$ change. To illustrate the optimal regulatory policy under conditions that might reasonably arise in practice, consider the following *baseline setting*.[26] In this setting, SATA is presumed to be a 1 MW battery.[27] The fixed cost of SATA, which encompasses purchase, installation, and integration costs, range from $\underline{K}_S = 100,000$ to $\overline{K}_S = 350,000$, reflecting estimates in Hledik et al. (2018, Table 4) and Lazard (2018, Slide 12), for example. For simplicity, K_S is assumed to have a uniform distribution on $\left[\, \underline{K}_S, \overline{K}_S \,\right]$, so $g(K_S) = \frac{1}{\overline{K}_S - \underline{K}_S}$ and the expected fixed cost of SATA, $E\{K_S\}$, is $\frac{1}{2}\left[\, \underline{K}_S + \overline{K}_S \,\right] = 225,000$. K_T is taken to be $250,000$, which is approximately 110% of $E\{K_S\}$.[28]

For simplicity, the baseline setting assumes there are three equally likely distributions of s (so $n = 3$ and $\phi_1 = \phi_2 = \phi_3 = \frac{1}{3}$). Each of these distributions is a Beta distribution with parameters α and β.[29] The baseline setting assumes $\beta = 2$ and $\alpha \in \{1, 3, 16\}$ to permit

[25] Equation (16) implies that the regulator optimally ensures the $\widehat{K}_{Si}$ identified in equation (15) is approximated relatively closely when $H_i(s)$ is likely to prevail (so ϕ_i is large), *ceteris paribus*.

[26] The baseline setting posits one particular set of model parameters. Substantial variation in these parameters will be considered.

[27] American Electric Power has proposed the implementation of a 1 MW SATA and a 0.5 MW SATA to relieve congestion at two substations in Texas (Maloney, 2017).

[28] In practice, TCE costs can either exceed or be less than corresponding SATA costs, depending on the nature and extent of the capacity expansion (Eyer, 2009). The assumption that $E\{K_S\} < K_T$ in the baseline setting is consistent with ongoing reductions in storage capacity costs (Hledik et al., 2018, pp. 12-13). SATA projects have been supported in several jurisdictions (e.g., Arizonza and New York) recently on the grounds that SATA is less costly than TCE (Chew et al., 2018).

[29] The Beta density is $h(s) = \frac{s^{\alpha-1}[1-s]^{\beta-1}}{B(\alpha,\beta)}$ for $s \in [0,1]$, where $B(\alpha,\beta) \equiv \int_0^1 x^{\alpha-1}\,[1-x]^{\beta-1}\,dx$. This density is employed because it can assume a wide variety of shapes as its parameters (α,β) change. The Beta density is symmetric about its mean $(\frac{\alpha}{\alpha+\beta})$ when $\alpha = \beta$, skewed to the left when $\beta > \alpha > 1$, and skewed to the right when $\alpha > \beta > 1$.

substantial variation in the potential distributions of s.[30] The corresponding cumulative distribution functions for s are illustrated in Figure 1.

[Figure 1 Here]

Problem [RP] assumes congestion is sufficiently deleterious that the regulator prefers to implement TCE than to risk congestion. To ensure this is the case in the baseline setting, L^e is set at $750,000$.[31]

The potential gains from employing SATA to deliver market services include the corresponding reductions in the cost of producing electricity and associated reductions in generation capacity costs.[32] Hledik et al.'s (2018) estimates of cost savings from these sources imply a 1 MW SATA would secure annual cost savings of approximately $\$102,065$.[33] These cost savings arise primarily during hours of peak demand for electricity, when congestion is most likely to arise. The estimates in E3's (2018) Avoided Cost Model imply that in California, the ratio of hourly avoided production and capacity costs in peak periods to the corresponding avoided costs in off peak periods is 2.813.[34] If $M_1 + R_1 = 2.813 [M_0 + R_0]$, then annual expected cost savings of $\$102,065$ arise when $M_0 + R_0 \approx \$74,084$ and $M_1 + R_1 \approx \$208,397$.[35] For simplicity, the baseline setting rounds these numbers and assumes the cost

[30] The substantial variation in these distributions generates significant variation in the expected congestion probability as $H_i(s)$ varies. Letting $E_i\{s\}$ denote the expected value of s when $H_i(s)$ prevails, $E_1\{s\} \approx 0.33$, $E_2\{s\} = 0.60$, and $E_3\{s\} \approx 0.89$.

[31] The regulator will always prefer to implement TCE than risk congestion if $K_T \leq E_1\{ s \} \times L^e$. Because $E_1\{ s \} = \frac{1}{3}$ in the baseline setting, this inequality is satisfied if $L^e \geq 750,000$. Alternative values of L^e are considered below.

[32] See Sandia (2010), Chang et al. (2015), and Hledik et al. (2018), for example.

[33] Hledik et al. (2018, p. 18) estimate the reduction in production costs to be $4.5 million for a 200 MW SATA, which implies cost savings of $\$22,500$ (= $4.5 million ÷ 200) per MW-year. Hledik et al. (2018, p. 23) estimate that a 200 MW SATA enables a 179 MW (or 89.5%) reduction in generation capacity. Newell et al. (2018, Table ES-2) estimate the cost of a new combustion turbine natural gas generating unit to be $\$88,900$ per MW-year. Together, these two estimates imply a 1 MW SATA would permit an annual reduction of approximately $\$79,565$ (= $\$88,900 \times 0.895$) in generation capacity costs. The implied combined annual cost savings from employing a 1 MW SATA is approximately $\$102,065$ (= $\$22,500 + \$79,565$).

[34] Specifically, in Climate Zone 6 (in the Los Angeles region), this avoided cost measure is: (i) $113.70 during the 4:00 – 9:00 pm (peak demand) period; and (ii) $40.42 during other hours. Boampang and Brown (2018) document the relatively pronounced demand for electricity in California during the 4:00 – 9:00 pm time period.

[35] $\frac{5}{24} [208,397] + \frac{19}{24} [74,084] \approx 102,065$.

savings increase consumer welfare and profit symmetrically, so $M_0 = R_0 - v = 37,500$ and $M_1 = R_1 - v = 105,000$.

The baseline setting further assumes the variable cost of SATA (v) is the sum of the cost of the electricity required to recharge the battery and depreciation cost. The battery is assumed to be re-charged during off-peak hours each day (Brattle, 2015; Arciniegas and Hittinger, 2018). E3 (2018) estimates the wholesale marginal cost of electricity in California during off-peak hours to be \$37.13/MWh. The corresponding annual cost is approximately $\$13,552$ ($\approx 365 \times \$37.13$).

Annual depreciation cost is estimated as the product of annual battery decay and the expected fixed cost of SATA ($225,000$). The annual battery decay is approximated as the ratio of the annual number of charge and discharge cycles (365) and the estimated battery cycle life ($6,500$).[36] Thus, the annual depreciation cost is taken to be approximately $12,635$ ($\approx \frac{365}{6,500} \times 225,000$). The sum of this depreciation cost and the recharging cost is $26,187$. Reflecting this estimate, the baseline setting assumes $v = 25,000$.

Table 1 records key features of the optimal regulatory policy (i.e., the solution to [RP]) in the baseline setting.[37] The first row of data reports outcomes in the full information (FI) setting.[38] The second row of data pertains to outcomes at the solution to [RP]. $E\{\Pi\}$ denotes the utility's expected profit.[39] $\widehat{V}$ reflects the maximum expected gain from SATA.[40] Formally,

[36] Arteaga et al. (2017) report battery cycle lives between $3,000$ and $10,000$. We employ the mid-point of this range ($6,500$) and, for simplicity, abstract from the nonlinear battery depreciation rates that prevail in practice.

[37] We specify [RP] as a mixed complementarity program (MCP). We employ the software GAMS and the PATH solver to identify the solution to the MCP. Because the identified solution to nonlinear programs can be sensitive to the starting values, we employ a Monte Carlo approach that randomly selects 1,000 starting values and solves the MCP for each set of values. We observe systematic convergence to a unique solution to our MCP.

[38] The entries for P_S and f in the full information setting are not unique. One way to ensure the efficient implementation of SATA is to compensate the utility (only) for its realized costs regardless of its asset choice (i.e., set $P_T = K_T$, $P_S = K_S$, and $f = 0$).

[39] Formally, $E\{\Pi_S\} \equiv \sum_{i=1}^{n} \phi_i \, E_i \{ \Pi_S(K_S) \}$, where $E_i \{ \Pi_S(K_S) \}$ is defined in expression (2).

[40] The entries for P_S, $\widehat{K}_{S1}$, $\widehat{K}_{S2}$, $\widehat{K}_{S3}$, $E\{\Pi\}$, and $\widehat{V}$ in Table 1 are rounded to the nearest whole number. The entries for f and $\widehat{s}$ are rounded to the nearest ten-thousandth.

$\widehat{V}$ is the difference between the maximized value of the regulator's objective function and the corresponding value when SATA is not available (so TCE is always implemented).[41]

	P_T	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
FI	$250,000$	K_S	0	0.1271	$250,797$	$235,142$	$227,778$	0	$38,220$
RP	$250,000$	$165,542$	0.6232	0.1273	$175,454$	$165,863$	$165,542$	$9,551$	$19,103$

Table 1. Outcomes in the Baseline Setting

Four elements of the solution to [RP] in the baseline setting warrant emphasis, in part because these features persist much more generally. First, the regulator promises the utility a relatively small fixed payment for implementing SATA.[42] Even after accounting for revenue sharing, the relatively small expected return from implementing SATA induces the utility to implement TCE for many realizations of K_S for which expected welfare would be higher if SATA were implemented. To illustrate, Table 1 reports that when distribution $H_2(s)$ prevails, the utility will implement TCE at the solution to [RP] when $K_S \in (165,863,\ 235,142)$ even though expected welfare would be higher if SATA were implemented. As noted above, the relatively modest compensation for implementing SATA helps to limit the rent the utility secures when K_S turns out to be low.

Second, f is strictly positive, so revenue sharing is implemented. The revenue sharing ensures the utility's expected profit when it implements SATA is higher if the realized congestion probability (s) is low (i.e., $s \leq \widehat{s}$) than if it is high (i.e., $s > \widehat{s}$, so SATA is assigned to supply transmission services). When $\widehat{s}$ is relatively small, the likelihood that $s \leq \widehat{s}$ typically is substantially higher when congestion is unlikely (e.g., when $H_1(s)$ prevails) than when congestion is likely (e.g., when $H_3(s)$ prevails). Thus, revenue sharing ($f > 0$) serves to render SATA implementation relatively profitable for the utility when it knows congestion is

[41] Specifically, $\widehat{V} = V_1 - (-K_T) = V_1 + 250,000$ in the full information setting, whereas $\widehat{V} = V_0 + 250,000$ for the solution to [RP]. The regulator's expected payoff is expressed relative to her expected payoff in the absence of SATA to facilitate a focus on positive numbers.

[42] Observe, in particular, that $P_S = 165,542 < E\{K_S\} = 225,000$ at the solution to [RP].

unlikely. Consequently, revenue sharing can help to induce the utility to employ its superior knowledge of $H_i(s)$ to implement SATA when congestion is relatively unlikely (and K_S is relatively small) and to implement TCE when congestion is relatively likely.[43]

Third, the utility commands considerable rent from its private knowledge of K_S and $H_i(s)$. This rent is almost 50% of the regulator's expected gain from having SATA available at the solution to [RP].[44] As explained further below, the rent arises primarily from the utility's superior knowledge of the fixed cost of implementing SATA.

Fourth, the regulator's expected gain from SATA is considerably lower in the presence of the prevailing information asymmetries than in their absence. As Table 1 reports, information asymmetries reduce the expected gain from SATA by approximately 50% in the baseline setting.[45]

Table 1 also reports that $\widehat{s}$ exceeds s^* in the baseline setting, so SATA is assigned to provide market services for some s realizations ($s \in (s^*, \widehat{s})$) for which expected welfare would be higher if SATA were assigned to provide transmission services. More generally, $\widehat{s}$ can either exceed or be less than s^* at the solution to [RP]. The optimal deviation between $\widehat{s}$ and s^* is designed to render SATA (TCE) implementation relatively profitable for the utility when congestion is relatively unlikely (likely). To illustrate, suppose s realizations just above (below) s^* are more likely when $H_1(s)$ prevails than when $H_3(s)$ prevails. In this case, the regulator often will set $\widehat{s}$ above (below) s^* in order to expand the range of s realizations for which the utility can profit from using SATA to provide market services when $H_1(s)$ prevails more than when $H_3(s)$ prevails.

Tables A1 – A16 in the Appendix record how the optimal regulatory policy and industry

[43] When $\widehat{s}$ is large, the probability that $s \leq \widehat{s}$ can be similar under all $H_i(s)$ distributions. Consequently, revenue sharing may cede rent to the utility without rendering SATA implementation substantially more profitable for the utility when congestion is unlikely (e.g., when $H_1(s)$ prevails) than when congestion is likely (e.g., when $H_3(s)$ prevails). Numerical solutions indicate that f often is close to 0 (and can even be 0) at the solution to [RP] when $\widehat{s}$ is relatively high (which is the case, for instance, when M_0, M_1, R_0, and R_1 are large).

[44] From the last two entries in the last row of Table 1, $\frac{9{,}551}{19{,}103} \approx 0.50$.

[45] From the last two data entries in the last column of Table 1, $\frac{38{,}220 - 19{,}103}{38{,}220} \approx 0.50$.

outcomes change as elements of the baseline setting change. Table A1 reports that the regulator's expected gain from SATA ($\widehat{V}$) and the utility's rent ($E\{\Pi\}$) can both increase substantially as the cost of TCE (K_T) increases. As K_T increases, the regulator induces the utility to implement SATA over a broader range of K_S realizations (i.e., $E\{\widehat{K}_S\} \equiv \sum_{i=1}^{n} \phi_i \widehat{K}_{Si}$ increases), which increases both $\widehat{V}$ and $E\{\Pi\}$.[46]

Tables A2 and A3 report that $\widehat{V}$ and $E\{\Pi\}$ decline as $\underline{K}_S$ increases or $\overline{K}_S$ increases, *ceteris paribus*. A higher fixed cost of SATA tends to limit its implementation, which reduces the regulator's expected gain from SATA and the utility's rent.[47] Perhaps more surprisingly, Table A4 indicates that the regulator's expected payoff from SATA can increase as $\overline{K}_S - \underline{K}_S$ increases, holding the expected value of K_S constant. One might suspect that "increased uncertainty" (i.e., an increase in $\overline{K}_S - \underline{K}_S$) would harm the regulator. However, this is not necessarily the case because increases in $\overline{K}_S - \underline{K}_S$ that entail a reduction in $\underline{K}_S$ lower the expected SATA cost in the "relevant region," i.e., for those $\underline{K}_S$ realizations for which the regulator optimally induces the utility to implement SATA. Corresponding increases in $\overline{K}_S$ are relatively inconsequential because the utility is induced to implement TCE for the higher K_S realizations.

Table A5 illustrates that $\widehat{V}$ and $E\{\Pi\}$ decline modestly as v, the variable cost of SATA, increases.[48] $\widehat{V}$ and $E\{\Pi\}$ also decline modestly as L^e, the expected loss from congestion, increases. (See Table A6.)[49] In both cases, the reduced utility profit reflects reduced implementation of SATA.

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[46] To illustrate, when K_T increases by 25% (from $200,000$ to $250,000$), $\widehat{V}$ increases by approximately 145% (from $7,812$ to $19,103$) and $E\{\Pi\}$ also increases by approximately 145% (from $3,906$ to $9,551$). These substantial increases reflect in part the 17.4% increase in $E\{\widehat{K}_S\}$ (from $143,953$ to $168,953$) that arises when K_T increases from $200,000$ to $250,000$. The utility's rent increases as SATA implementation expands because the utility secures no rent when it implements TCE (because $P_T = K_T$ at the solution to [RP]).

[47] To illustrate, when $\underline{K}_S$ increases from $100,000$ to $125,000$, $\widehat{V}$ declines from $19,103$ to $14,258$ and $E\{\Pi\}$ declines from $9,551$ to $7,129$.

[48] For example, as v increases from $25,000$ to $30,000$, $\widehat{V}$ declines from $19,103$ to $18,301$ and $E\{\Pi\}$ declines from $9,551$ to $9,150$.

[49] To illustrate, as L^e increases from $750,000$ to $800,000$, $\widehat{V}$ declines from $19,103$ to $19,031$ and $E\{\Pi\}$ declines from $9,551$ to $9,515$.

Tables A7 – A9 illustrate the changes that arise as the prevailing $H_i(s)$ distributions change. An increase in the mean of any $H_i(s)$ distribution tends to reduce the expected gain from SATA ($\widehat{V}$), in part by reducing the likelihood that SATA is implemented.[50] Table A10 shows that as high congestion probabilities become systematically more likely, SATA is implemented less often, which reduces $\widehat{V}$ and $E\{\Pi\}$.[51] In contrast, $\widehat{V}$ and $E\{\Pi\}$ increase as the $H_1(s)$ and $H_3(s)$ become more likely and the $H_2(s)$ distribution becomes correspondingly less likely. (See Table A11.)[52] The increases in $\widehat{V}$ and $E\{\Pi\}$ arise in this case primarily because the increased likelihood of the $H_1(s)$ distribution leads to a substantial increase in the probability that SATA is implemented.

Tables A12 – A15 report that $\widehat{V}$ and $E\{\Pi\}$ increase modestly as the revenue or the incremental consumer welfare that arises when SATA supplies market services increases.[53] Larger values of M_0, M_1, R_0, or R_1 promote expanded implementation of SATA (i.e., $E\{\widehat{K}_S\}$ increases) and increased deployment of SATA to deliver market services (i.e., $\widehat{s}$ increases), both of which increase the regulator's expected gain from SATA and the utility's expected profit.[54] Table A16 reports that outcomes similar to those that arise in the baseline setting persist as n, the number of possible distributions of s, increases.

Tables 1 and A1 – A16 indicate that the utility often secures substantial rent under the optimal regulatory policy. To determine the primary source of this rent, it is useful to compare outcomes in the benchmark settings considered in Section 3. Table 2 records the regulator's expected gain from SATA ($\widehat{V}$) and the utility's expected rent ($E\{\Pi\}$) in

[50] To illustrate, when α_1 increases from 1 to 1.5, $E\{\widehat{K}_S\}$ declines from $168,953$ to $167,570$. When α_2 increases from 3 to 4, $E\{\widehat{K}_S\}$ declines from $168,953$ to $168,654$. When α_3 increases from 16 to 17, $E\{\widehat{K}_S\}$ declines from $168,953$ to $168,928$.

[51] For example, as ϕ_3 increases by 0.1 and ϕ_1 declines by 0.1, $\widehat{V}$ declines from $19,103$ to $18,460$ and $E\{\Pi\}$ declines from $9,551$ to $9,230$.

[52] To illustrate, as ϕ_1 and ϕ_3 each increases by 0.1 and ϕ_2 declines by 0.2, $\widehat{V}$ increases from $19,103$ to $19,359$ and $E\{\Pi\}$ increases from $9,551$ to $9,680$.

[53] For example, as M_1 increases from $105,000$ to $120,000$, $\widehat{V}$ increases from $19,103$ to $19,126$ and $E\{\Pi\}$ increases from $9,551$ to $9,563$.

[54] More pronounced, simultaneous increases in M_0, M_1, R_0, and R_1 can lead to substantially higher values of $\widehat{s}$ and lower values of f. To illustrate, if $M_0 = 127,500$, $M_1 = 360,000$, $R_0 = 152,500$, and $R_1 = 385,000$, then $\widehat{s} = 0.9808$ and $f = 0$ (and $\widehat{V} = 53,784$ and $E\{\Pi\} = 26,892$) at the solution to [RP].

five settings. The first and fourth rows of data pertain to the full information setting and the setting in problem [RP], respectively. The second row of data records outcomes in the benchmark setting of Section 3.3 where the regulator and the utility both know K_S and both have the same imperfect knowledge of $H_i(s)$. The third row of data in Table 2 reports outcomes in the benchmark setting of Section 3.4 where the regulator and the utility both know the prevailing $H_i(s)$, but only the utility knows the realization of K_S.

The last row of data in Table 2 records outcomes under what we call a "Rule of Thumb" policy, which is designed to reflect policies that have been proposed in practice and may have intuitive appeal. Under the Rule of Thumb policy, the regulator reimburses the utility for the fixed expected cost of the asset it implements (in addition to reimbursing the variable cost of employing SATA). Thus, $P_T = K_T$ and $P_S = E\{K_S\}$. In addition, the utility is awarded one-half of the revenue it generates when SATA supplies market services (so $f = 0.5$).[55] Furthermore, $\widehat{s}$ is set at 0.05, so SATA is assigned to supply transmission services whenever the realized congestion probability exceeds 5%.[56]

Setting	$\widehat{V}$	$E\{\Pi\}$
Full Information	$38,220$	0
Symmetric Uncertainty about $H_i(s)$ Only	$38,036$	0
Utility has Private Knowledge of K_S Only	$19,110$	$9,555$
[RP]	$19,103$	$9,551$
Rule of Thumb	$5,450$	$31,781$

Table 2. Additional Outcomes in the Baseline Setting

[55] This compensation structure is consistent with the CAISO full cost-of-service plus revenue sharing policy. CAISO observes that a policy of this sort provides "incentives for the [utility] to participate in the market by allowing [it] to retain some percentage of the market revenue" while eliminating the utility's "risk of not being able to at least recover the full cost of the resource" (CAISO, 2018b, p. 17).

[56] When $\widehat{s} = 0.05$, the probability of unmitigated congestion (i.e., the probability that SATA supplies market services and congestion arises), is $\sum_{i=1}^{n} \phi_i H_i(0.05) \approx 0.0327$.

Table 2 reports that limited knowledge of $H_i(s)$ alone is not very constraining for the regulator. The first two rows of data indicate that the regulator's expected gain from SATA declines below the gain achieved in the full information setting by less than 1% when neither the regulator nor the utility know $H_i(s)$, but both know K_S.[57] This relatively small decline arises even though the three possible distributions of s differ substantially in the baseline setting. (Recall Figure 1.) The ability to dictate the deployment of SATA after observing the realized congestion probability helps to limit the losses from having to choose between SATA and TCE without knowing the prevailing $H_i(s)$ distribution.[58] Furthermore, the realization of s serves as an *ex post* signal that is correlated with the utility's privileged knowledge of $H_i(s)$. When the regulator knows K_S, she can employ the signal to induce the utility to implement SATA only when congestion is relatively unlikely without ceding much rent to the utility. She can do so by rewarding the utility only when the realization of s is relatively low following the implementation of SATA (by setting $f > 0$ and assigning SATA to supply market services only when $s < \widehat{s}$).[59]

In contrast, the regulator's expected gain from SATA declines substantially when the utility is privately informed about K_S, even when the regulator and the utility both know the prevailing $H_i(s)$ distribution. The first and third rows of data in Table 2 indicate that asymmetric information about K_S alone reduces the regulator's expected gain from SATA by approximately 50%.[60] The reduction arises from two primary sources. First, the utility secures substantial rent when K_S is low because P_S and f are set to ensure the utility implements SATA for both low and moderate values of K_S. Second, when P_S and f are

[57] $\frac{38{,}220 - 38{,}036}{38{,}220} \approx 0.005$. The limited extent of this decline reflects in part the fact that the regulator can eliminate the utility's rent in this benchmark setting where the utility has no private information. The $\widehat{V}$ entry in the second row of data in Table 2 is the value of V_2 (from Section 3.3) in the baseline setting.

[58] Recall from Section 3.2 that if the utility alone knows $H_i(s)$ but the regulator and utility both know K_S, the regulator can achieve the same expected gain she secures in the full information setting.

[59] Cremér and McLean (1988), Riordan and Sappington (1988), and Gary-Bobo and Spiegel (2006), among others, demonstrate how a principal can employ an *ex post* signal that is correlated with an agent's private information to limit the agent's rent while inducing the agent to reveal the information truthfully.

[60] $\frac{38{,}220 - 19{,}110}{38{,}220} = 0.50$. The $\widehat{V}$ entry in the third row of data in Table 2 is V_3 (from Section 3.4) in the baseline setting.

reduced to limit the utility's rent, the utility often implements TCE when expected welfare would be higher if SATA were implemented.

The regulator's incremental loss from asymmetric knowledge of both $H_i(s)$ and K_S rather than just K_S is limited in the baseline setting (and more generally). The third and fourth rows of data in Table 2 report that the regulator's expected gain from SATA at the solution to [RP] is less than 0.1% below her expected gain from SATA in the benchmark setting where she shares the utility's knowledge of $H_i(s)$ but not its knowledge of K_S.[61] Again, the ability to dictate how SATA is deployed after s is realized helps to limit the regulator's loss from limited knowledge of the prevailing distribution of s.

Implementation of the Rule of Thumb policy substantially reduces the regulator's expected gain from SATA ($\widehat{V}$) and generates considerable rent for the utility ($E\{\Pi\}$) in the baseline setting. Under the Rule of Thumb policy, $\widehat{V}$ declines by more than 70% whereas $E\{\Pi\}$ increases by more than 230% relative to their values at the solution to [RP].[62] Table 3 helps to explain these effects. The first column in the table records a single modification of the identified Rule of Thumb policy.[63] The last two columns report the values of $\widehat{V}$ and $E\{\Pi\}$ that arise under the corresponding modified Rule of Thumb policy. The first two rows of data record the effects of changing the critical congestion probability ($\widehat{s}$). In the first row, $\widehat{s}$ is increased to its level (0.1273) at the solution to [RP]. In the second row, $\widehat{s}$ is reduced to 0.01, so SATA is deployed to supply transmission services whenever the realized congestion probability exceeds 1%.[64]

The third and fourth rows of data in Table 3 report the effects of changing the utility's share of the revenue generated when SATA provides market services. In the third row, f

[61] $\frac{19{,}110 - 19{,}103}{19{,}110} \approx 0.0004$. This conclusion implies that the regulator would achieve at most a very small percentage increase in her expected payoff if she were to offer the utility a menu of compensation structures and allow the utility to select its preferred option from the menu, as in Laffont and Tirole (1993), for example. Brown and Sappington (2019) demonstrate that such menus of compensation structures generate relatively little incremental surplus in other settings.

[62] $\frac{19{,}103 - 5{,}450}{19{,}103} \approx 0.715$ and $\frac{31{,}781 - 9{,}551}{9{,}551} \approx 2.33$.

[63] Other elements of the Rule of Thumb policy remain unchanged in each case considered in Table 3.

[64] When $\widehat{s} = 0.01$, the expected probability of unmitigated congestion ($\sum_{i=1}^{n} \phi_i H_i(\widehat{s})$) is 0.0003.

is set at 0.6232, its value at the solution to [RP]. In the fourth row, f is reduced to 0.25. The last three rows in Table 3 consider changes in the base payment for implementing SATA (P_S). In the fifth row of data, P_S is set at $165,542$, its value at the solution to [RP]. In the sixth row, P_S is reduced to $112,500$, one-half of the expected fixed cost of SATA. In the last row, P_S is set at $224,792$, which is the difference between the expected fixed cost of SATA ($E\{K_S\}$) and an approximation of the utility's expected revenue ($E\{R\}$) from employing SATA to supply market services. Formally, $E\{R\} \equiv \sum_{i=1}^{n} \phi_i \int_0^{\widehat{s}} f\,[\,s\,R_1 + (1-s)\,R_0\,]\,dH_i(s)$, where $f = 0.5$ and $\widehat{s} = 0.05$.[65]

Change in Rule of Thumb Policy	$\widehat{V}$	$E\{\Pi\}$
$\widehat{s} \,=\, 0.1273$	$5,277$	$32,660$
$\widehat{s} \,=\, 0.01$	$5,057$	$31,354$
$f \,=\, 0.6232$	$4,497$	$33,450$
$f \,=\, 0.25$	$5,671$	$32,109$
$P_S \,=\, 165,542$	$19,059$	$9,539$
$P_S \,=\, \frac{1}{2}\,E\{K_S\} \,=\, 112,500$	$7,822$	544
$P_S \,=\, E\{K_S\} - E\{R\} \,=\, 224,792$	$5,153$	$31,250$

Table 3. Effects of Modifying Elements of the Rule of Thumb Policy

Table 3 indicates that the base payment for SATA (P_S) plays a central role in determining the performance of the prevailing regulatory policy. When P_S is set at its optimal level (i.e., at its level in the solution to [RP]), the regulator secures nearly the same gain from SATA that she achieves under the optimal policy even though $\widehat{s}$ and f differ significantly from their optimal levels.[66] In contrast, $\widehat{V}$ remains far below its optimal value when either $\widehat{s}$ or f is set

[65] $E\{R\} = 208$ in the baseline setting. $E\{R\}$ overstates the utility's actual expected revenue from supplying market services because it does not account for the fact the utility will sometimes implement TCE rather than SATA.

[66] Under this modified Rule of Thumb policy, f is 19.74% ($\approx \frac{0.6232 - 0.5}{0.6232}$) below and $\widehat{s}$ is 60.72% ($\approx \frac{0.1273 - 0.05}{0.1273}$) below their respective levels at the solution to [RP].

at its optimal value but P_S is set equal to the expected fixed cost of SATA.[67,68]

Table 3 also indicates that the gain from SATA can be relatively low both if P_S is reduced only moderately below the full expected cost of SATA or if P_S is reduced well below $E\{K_S\}$. A moderate reduction in P_S below $E\{K_S\}$ (e.g., $P_S = E\{K_S\} - E\{R\}$) affords the utility considerable rent, thereby reducing $\widehat{V}$. A substantial reduction in P_S can limit the utility's rent. However, it can also induce the utility to implement TCE when expected welfare would be higher if SATA were implemented, thereby foregoing much of the potential increase in surplus that SATA can provide.[69] Specifically, if P_S is reduced to $\frac{1}{2}\, E\{K_S\}$, $\widehat{V}$ under the modified Rule of Thumb policy is only 59% ($\approx \frac{19{,}103\,-\,7{,}822}{19{,}103}$) of its value at the solution to [RP].

Tables A17 – A31 in the Appendix record the value of $r \equiv \frac{P_S}{E\{K_S\}\,-\,E\{R\}}$ that arises at the solution to [RP] for each of the settings considered in Tables A1 – A15. The average value of r is these settings is 0.74, and r varies between 0.52 and 0.86. The smallest value of r arises when K_T is small, so P_S is optimally set at a relatively small level to avoid excessive implementation of SATA.[70] The largest value of r arises when $\overline{K}_S - \underline{K}_S$ is small, so P_S is optimally set relatively close to $E\{K_S\}$ in light of the relatively limited information asymmetry regarding K_S.[71]

5 Conclusions.

We have examined the design of policies to motivate both the appropriate choice between TCE and SATA and subsequent SATA deployment. Our analysis provides four primary con-

[67] The substantial reduction in $\widehat{V}$ arises even though the Rule of Thumb policy often induces the utility to implement the asset that maximizes expected welfare. In the baseline setting, $E\{\widehat{K}_S\} \approx 228,376$ under the Rule of Thumb policy and $E\{\widehat{K}_S\} \approx 237,906$ under the optimal policy in the full information setting. Thus, the expected maximum K_S realization for which SATA is implemented is fairly similar under these two policies. (In contrast, $E\{\widehat{K}_S\} \approx 168,953$ at the solution to [RP] in the baseline setting.)

[68] $\widehat{V}$ also remains well below its optimal value (i.e., its value at the solution to [RP]) if $\widehat{s}$ and f are both set equal to their values at the solution to [RP] but $P_S = \frac{1}{2}\, E\{K_S\}$. In this case, $\widehat{V} = 7,848$ and $E\{\Pi\} = 549$.

[69] $E\{\widehat{K}_S\} = 113,548$ under the modified Rule of Thumb policy with $P_S = \frac{1}{2}\, E\{K_S\}$. $E\{\widehat{K}_S\} = 168,953$ at the solution to [RP].

[70] See the first row of data in Table A17.

[71] See the first row of data in Table A20.

clusions. First, the optimal payment to the utility for implementing SATA typically is substantially below the expected cost of acquiring, installing, and integrating SATA. The relatively modest compensation reduces the rent the utility secures from its privileged knowledge of this cost.

Second, the optimal policy often awards the utility a substantial share of the revenue it derives from employing SATA to supply market services.[72] Because revenue sharing serves to reward the utility when SATA is ultimately deployed to supply market services, it can help to motivate the utility to employ its superior knowledge of local industry conditions to implement SATA only when congestion is relatively unlikely and SATA costs are relatively low. Third, limited knowledge of the utility's cost of implementing SATA is particularly constraining for the regulator. Her limited knowledge of the probability of local congestion (s) typically is substantially less constraining. The relatively small losses from limited *ex ante* knowledge of s stem in part from the fact that the relevant local congestion probability is observed publicly before SATA must be assigned to deliver either market services or transmission services.

Fourth, it is not possible to specify a single, simple policy that is optimal in all settings. Even in our streamlined model, the various elements of the regulatory environment interact in complex ways, thereby precluding a simple characterization of the optimal policy. However, we found that the performance of the regulatory policy is particularly sensitive to the specified payment (P_S) for implementing SATA. It is often optimal to reduce P_S well below the expected cost of implementing SATA ($E\{K_S\}$). Although small values of P_S can induce the utility to implement TCE when welfare would be higher if SATA were implemented, small values of P_S enable consumers to secure the benefits of SATA at relatively low cost when K_S is relatively small. Substantial reductions in P_S below $E\{K_S\}$ can be particularly advantageous when substantial revenue sharing is implemented and considerable revenue

[72] The utility is optimally awarded more than half of the revenue it generates in each of the settings considered in Tables A1 – A14 in the Appendix. Smaller values of f can be optimal if s^* is relatively high, so SATA is often employed to deliver market services.

from employing SATA to supply market services is anticipated.

These conclusions have three primary implications for regulatory policy design. First, policies that set compensation for SATA (P_S) equal to its expected cost ($E\{K_S\}$) can deliver substantial rent to utilities and thereby diminish consumer welfare. Even policies that reduce P_S below $E\{K_S\}$ by the amount of the utility's expected revenue from employing SATA to supply market services typically afford substantial rent to the utility. Larger reductions in P_S can benefit consumers even though they sometimes induce the utility to implement TCE when welfare would be higher if SATA were implemented.

Second, revenue sharing often serves consumers well. As noted above, compensation for implementing SATA (P_S) can be reduced by (at least) the amount of revenue the utility expects to secure via revenue sharing. This reduction in P_S ensures that revenue sharing does not automatically deliver excessive rent to the utility. In addition, revenue sharing can help to induce the utility to implement SATA only when local congestion is relatively unlikely (so SATA is likely to be deployed to supply market services) and the cost of SATA is relatively low.

Third, efforts by regulators to improve their knowledge of prevailing industry conditions typically is best directed at reducing uncertainty about the utility's cost of acquiring, installing, and integrating SATA. For example, regulators might require utilities to file carefully-documented studies of the cost of SATA implementation. Regulators might also encourage corresponding studies by independent experts, and share available studies across regulatory jurisdictions.

Conceivably, our primary findings could reflect the relatively simple regulatory policies we analyzed. It is possible, for instance, that the regulator might be able to secure substantially greater gains for consumers if the fixed payment for implementing SATA could be higher when SATA delivers market services than when it is ultimately deployed to provide transmission services. Although such a reward structure can increase consumer welfare by helping to induce the utility to implement SATA only when congestion is relatively unlikely and the cost of SATA is low, consumer gains from the policy typically are very small.[73] To illustrate, the regulator's ability to implement this more general reward structure increases expected consumer welfare by less than 1% in the baseline setting.[74]

In closing, we suggest four extensions of our study that merit further analysis. First, the effects of utility risk aversion should be analyzed. It seems likely that when the utility is averse to risk, the regulator will optimally increase the utility's fixed compensation for implementing SATA and reduce revenue sharing. Second, variation in the severity of congestion and in the amount of SATA that can be implemented should be considered. Under such conditions, the welfare-maximizing policy may entail simultaneous investment in TCE and SATA. Third, policies that encourage competitive deployment of SATA deserve further study. Such policies have the potential to help to limit utility rent and reduce expected energy costs. Fourth, the full impact of expanded SATA participation in wholesale electricity and ancillary services markets warrants further research. Issues that may merit particular attention include the effects of expanded SATA activity on the earnings (and thus on the investment and participation decisions) of natural gas generators.

[73] The corresponding gains that arise if the regulator is not required to reimburse the utility's variable SATA cost also tend to be very small.

[74] Specifically, the regulator's expected gain from SATA increases by approximately 0.004% ($\approx \frac{19{,}180 - 19{,}103}{19{,}103}$). The limited extent of this gain reflects the fact that f can be employed to deliver much the same incentive that differential fixed SATA payments can provide. Numerical solutions also indicate that only very small gains arise if the regulator can explicitly penalize the utility when it implements SATA and congestion occurs.

Appendix

Section I of this appendix presents additional numerical solutions to [RP]. Section II presents the proofs of the formal conclusions in the text.

I. Additional Numerical Solutions.

The tables that follow record outcomes at the solution to [RP] as parameters in the baseline setting change. The first column in each table identifies the values of the single parameter that changes. (All other parameters remain at their levels in the baseline setting.) The variables whose values are recorded in the tables are those reported in Table 1 in the text.[75]

K_T	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
150,000	115,541	0.6213	0.1277	125,454	115,864	115,541	761	1,521
175,000	128,041	0.6223	0.1275	137,954	128,363	128,041	2,021	4,042
200,000	140,542	0.6228	0.1274	150,454	140,863	140,542	3,906	7,812
225,000	153,042	0.6230	0.1274	162,954	153,363	153,042	6,416	12,832
250,000	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103

Table A1. Outcomes at the Solution to [RP] as K_T Changes.[76]

$\underline{K}_S$	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
50,000	140,542	0.6235	0.1273	150,454	140,863	140,542	14,747	29,494
75,000	153,042	0.6234	0.1273	162,954	153,363	153,042	12,101	24,203
100,000	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
125,000	178,042	0.6230	0.1274	187,954	178,363	178,042	7,129	14,258
150,000	190,542	0.6228	0.1274	200,454	190,863	190,542	4,882	9,765

Table A2. Outcomes at the Solution to [RP] as $\underline{K}_S$ Changes.

$\overline{K}_S$	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
300,000	165,542	0.6232	0.1273	175,454	165,863	165,542	11,939	23,878
325,000	165,542	0.6232	0.1273	175,454	165,863	165,542	10,613	21,225
350,000	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
375,000	165,542	0.6232	0.1273	175,454	165,863	165,542	8,683	17,366
400,000	165,542	0.6232	0.1273	175,454	165,863	165,542	7,959	15,919

Table A3. Outcomes at the Solution to [RP] as $\overline{K}_S$ Changes.

[75] P_T is always set equal to K_T at the solution to [RP], so the value of P_T is not reported in the tables that follow.

[76] Values of K_T above 250,000 violate the maintained assumption that $E_1\{s\}\,L^e \geq K_T$. However, larger values of K_T can be considered without violating this assumption if, say, K_T and L^e are increased proportionately. To illustrate, if $K_T = 400,000$ and $L^e = 1,200,000$, then $P_S = 240,651$, $f = 0.8685$, $\widehat{s} = 0.0721$, $E\{\Pi\} = 41,092$, and $\widehat{V} = 82,184$ at the solution to [RP].

$\overline{K}_S - \underline{K}_S$	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
150,000	190,542	0.6228	0.1274	200,454	190,863	190,542	6,510	13,020
200,000	178,042	0.6230	0.1274	187,954	178,363	178,042	8,020	16,040
250,000	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
300,000	153,042	0.6234	0.1273	162,954	153,363	153,042	11,093	22,186
350,000	140,542	0.6235	0.1273	150,454	140,863	140,542	12,640	25,281

Table A4. Outcomes at the Solution to [RP] as $\overline{K}_S - \underline{K}_S$ Changes.[77]

v	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
10,000	171,198	0.5509	0.1240	177,811	171,403	171,198	10,815	21,629
20,000	167,428	0.6042	0.1262	176,238	167,709	167,428	9,962	19,924
25,000	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
30,000	163,655	0.6385	0.1285	174,670	164,017	163,655	9,150	18,301
40,000	159,878	0.6608	0.1309	173,105	160,327	159,878	8,379	16,759

Table A5. Outcomes at the Solution to [RP] as v Changes.

L^e	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
750,000	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
800,000	165,568	0.6502	0.1174	175,104	165,830	165,568	9,515	19,031
850,000	165,587	0.6773	0.1088	174,803	165,805	165,587	9,485	18,970
1,000,000	165,625	0.7589	0.0894	174,110	165,761	165,625	9,416	18,831
1,250,000	165,655	0.8955	0.0689	173,371	165,728	165,655	9,343	18,686

Table A6. Outcomes at the Solution to [RP] as L^e Changes.[78]

α_1	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
1.0	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
1.25	165,509	0.6992	0.1274	172,982	165,869	165,509	9,304	18,609
1.5	165,454	0.8340	0.1274	171,372	165,884	165,454	9,146	18,292
2.0	165,701	1.0000	0.1294	168,835	166,241	165,701	8,962	17,930
2.5	165,937	1.0000	0.1307	167,285	166,494	165,937	8,864	17,734

Table A7. Outcomes at the Solution to [RP] as α_1 Changes.[79]

[77] $E\{\overline{K}_S - \underline{K}_S\} = 225,000$ in all cases in Table A4.

[78] Values of L^e below 750,000 violate the maintained assumption that $E_1\{s\}\, L^e \geq K_T$. However, smaller values of L^e can be considered without violating this assumption if, say, K_T and L^e are reduced proportionately. To illustrate, if $L^e = 500,000$ and $K_T = 166,666.67$, then $P_S = 123,476$, $f = 0.4905$, $\widehat{s} = 0.2220$, $E\{\Pi\} = 1,688$, and $\widehat{V} = 3,376$ at the solution to [RP].

[79] Values of α_1 below 1 violate the maintained assumption that $E_1\{s\}\, L^e \geq K_T$. However, smaller values of α_1 can be considered without violating this assumption if, say, K_T and α_1 are reduced commensurately. To illustrate, if $\alpha_1 = 0.75$ and $K_T = 200,000$, then $P_S = 140,559$, $f = 0.5909$, $\widehat{s} = 0.1274$, $E\{\Pi\} = 4,178$, and $\widehat{V} = 8,356$ at the solution to [RP].

α_2	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
2	165,432	0.6478	0.1277	175,763	167,409	165,432	9,710	19,421
2.5	165,603	0.6244	0.1275	175,546	166,394	165,603	9,613	19,226
3	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
3.5	165,405	0.6302	0.1272	175,418	165,535	165,405	9,507	19,014
4	165,253	0.6392	0.1272	175,405	165,305	165,253	9,472	18,945
8	164,444	0.6899	0.1271	175,398	164,444	164,444	9,327	18,655

Table A8. Outcomes at the Solution to [RP] as α_2 Changes.

α_3	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
5	166,667	0.5508	0.1272	175,418	166,950	166,674	9,744	19,487
10	165,901	0.6002	0.1273	175,442	166,209	165,901	9,612	19,224
12	165,747	0.6101	0.1273	175,447	166,061	165,747	9,586	19,172
15	165,584	0.6205	0.1273	175,452	165,903	165,584	9,558	19,117
16	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
17	165,504	0.6257	0.1273	175,455	165,826	165,504	9,545	19,090
22	165,363	0.6347	0.1273	175,459	165,689	165,363	9,521	19,042

Table A9. Outcomes at the Solution to [RP] as α_3 Changes.

In Table A10, Δ_1 is the amount by which ϕ_1 is reduced below $\frac{1}{3}$ and ϕ_3 is increased above $\frac{1}{3}$.

Δ_1	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
-0.2	166,286	0.5749	0.1272	175,418	166,580	166,286	10,194	20,388
-0.1	165,846	0.6032	0.1272	175,433	166,156	165,846	9,873	19,745
0	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
0.1	165,319	0.6387	0.1274	175,487	165,649	165,319	9,230	18,460
0.2	165,149	0.6532	0.1277	175,568	165,488	165,149	8,909	17,818

Table A10. Outcomes at the Solution to [RP] as Δ_1 Changes.

In Table A11, Δ_2 is the amount by which ϕ_1 and ϕ_3 are increased above $\frac{1}{3}$.[80]

Δ_2	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
-0.2	166,750	0.5497	0.1273	175,494	167,033	166,750	9,298	18,597
-0.1	166,218	0.5820	0.1274	175,476	166,518	166,218	9,424	18,849
0	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
0.1	164,654	0.6777	0.1272	175,424	165,002	164,654	9,680	19,359

Table A11. Outcomes at the Solution to [RP] as Δ_2 Changes.

[80] $\Delta_2 = 0.2$ is not considered in Table A11 because $\phi_2 < 0$ if $\Delta_2 = 0.2$.

M_0	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
20,000	165,609	0.6401	0.1006	173,660	165,772	165,609	9,371	18,742
30,000	165,574	0.6251	0.1161	174,640	165,817	165,574	9,469	18,937
37,500	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
40,000	165,530	0.6239	0.1310	175,739	165,880	165,530	9,581	19,161
50,000	165,479	0.6319	0.1455	176,950	165,963	165,479	9,706	19,413

Table A12. Outcomes at the Solution to [RP] as M_0 Changes.

M_1	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
75,000	165,558	0.6394	0.1211	175,237	165,842	165,558	9,529	19,058
90,000	165,550	0.6313	0.1242	175,343	165,852	165,550	9,540	19,080
105,000	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
120,000	165,533	0.6152	0.1307	175,570	165,875	165,533	9,563	19,126
150,000	165,512	0.5990	0.1379	175,821	165,903	165,512	9,589	19,178

Table A13. Outcomes at the Solution to [RP] as M_1 Changes.

R_0	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
37,500	165,733	1.0000	0.0890	172,804	165,848	165,733	9,305	18,614
50,000	165,591	0.7681	0.1084	174,135	165,794	165,591	9,418	18,836
62,500	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
75,000	165,482	0.5387	0.1455	176,949	165,960	165,482	9,706	19,413
87,500	165,409	0.4854	0.1629	178,606	166,091	165,409	9,883	19,667

Table A14. Outcomes at the Solution to [RP] as R_0 Changes.

R_1	P_S	f	$\widehat{s}$	$\widehat{K}_{S1}$	$\widehat{K}_{S2}$	$\widehat{K}_{S3}$	$E\{\Pi\}$	$\widehat{V}$
78,000	165,572	0.6816	0.1170	175,090	165,826	165,572	9,514	19,028
104,000	165,558	0.6523	0.1219	175,264	165,843	165,558	9,532	19,064
130,000	165,542	0.6232	0.1273	175,454	165,863	165,542	9,551	19,103
156,000	165,523	0.5944	0.1332	175,660	165,886	165,523	9,572	19,145
182,000	165,501	0.5658	0.1397	175,885	165,914	165,501	9,596	19,191

Table A15. Outcomes at the Solution to [RP] as R_1 Changes.

n		P_T	P_S	f	$\widehat{s}$	$\widehat{K}_{S1} - \widehat{K}_{Sn}$	$E\{\Pi\}$	$\widehat{V}$
5	FI	250,000	K_S	0	0.1271	23,019	0	37,872
	RP	250,000	165,641	0.6447	0.1275	10,268	9,465	18,931
20	FI	250,000	K_S	0	0.1271	19,345	0	34,559
	RP	250,000	166,724	0.5869	0.1274	9,340	9,287	18,574

Table A16. Outcomes in the Baseline Setting with n = 5 and n = 20.[81]

The following tables report the values of P_S and $r \equiv \frac{P_S}{E\{K_S\} - E\{R\}}$ at the solution to [RP].[82] All parameters other than the one identified in the first column of a table are set at their values in the baseline setting.

K_T	P_S	r
150,000	115,541	0.5214
175,000	128,041	0.5778
200,000	140,542	0.6342
225,000	153,042	0.6907
250,000	165,542	0.7471

Table A17. Variations in K_T.

$\underline{K}_S$	P_S	r
50,000	140,542	0.7149
75,000	153,042	0.7319
100,000	165,542	0.7471
125,000	178,042	0.7606
150,000	190,542	0.7727

Table A18. Variations in $\underline{K}_S$.

$\overline{K}_S$	P_S	r
300,000	165,542	0.8421
325,000	165,542	0.7917
350,000	165,542	0.7471
375,000	165,542	0.7072
400,000	165,542	0.6713

Table A19. Variations in $\overline{K}_S$.

$\overline{K}_S - \underline{K}_S$	P_S	r
150,000	190,542	0.8599
200,000	178,042	0.8035
250,000	165,542	0.7471
300,000	153,042	0.6907
350,000	140,542	0.6342

Table A20. Variations in $\overline{K}_S - \underline{K}_S$.[83]

[81] The first and third rows of data in Table A14 report outcomes in the full information (FI) setting. $\phi_i = \frac{1}{n}$ for $i = 1, ..., n$ in all settings considered in the table. For the setting with $n = 5$, $\alpha_1 = 1$, $\alpha_2 = 1.5$, $\alpha_3 = 3$, $\alpha_4 = 7$, and $\alpha_5 = 16$. For the setting with $n = 20$, $\alpha_1 = 1$ and $\alpha_i = \alpha_{i-1} + 0.25$ for $i = 2, ..., n$. These parameter values ensure the expected probability of congestion, $\sum_{i=1}^{n} \phi_i E_i\{s\}$, is similar when $n = 3$ (0.6074), $n = 5$ (0.6057), and $n = 20$ (0.5971).

[82] Recall that $E\{R\} \equiv \sum_{i=1}^{n} \phi_i \int_0^{\widehat{s}} f\,[\,s\,R_1 + (1-s)\,R_0\,]\,dH_i(s)$, where $f = 0.5$ and $\widehat{s} = 0.05$.

[83] $E\{\,\overline{K}_S - \underline{K}_S\} = 225,000$ in all cases in Table A18.

v	P_S	r
10,000	171,198	0.7686
20,000	167,428	0.7543
25,000	165,542	0.7471
30,000	163,655	0.7398
40,000	159,878	0.7253

Table A21. Variations in v.

L^e	P_S	r
750,000	165,542	0.7471
800,000	165,568	0.7467
850,000	165,587	0.7464
1,000,000	165,625	0.7456
1,250,000	165,655	0.7448

Table A22. Variations in L^e.

α_1	P_S	r
1.0	165,542	0.7471
1.25	165,509	0.7442
1.5	165,454	0.7423
2.0	165,701	0.7405
2.5	165,937	0.7396

Table A23. Variations in α_1.

α_2	P_S	r
2	165,432	0.7489
2.5	165,603	0.7479
3	165,542	0.7471
3.5	165,405	0.7463
4	165,253	0.7457
8	164,444	0.7429

Table A24. Variations in α_2.

α_3	P_S	r
5	166,667	0.7508
10	165,901	0.7483
12	165,747	0.7477
15	165,584	0.7472
16	165,542	0.7471
17	165,504	0.7469
22	165,363	0.7465

Table A25. Variations in α_3.

Δ_1	P_S	r
-0.2	166,286	0.7557
-0.1	165,846	0.7513
0	165,542	0.7471
0.1	165,319	0.7429
0.2	165,149	0.7389

Table A26. Variations in Δ_1.

Δ_2	P_S	r
-0.2	166,750	0.7457
-0.1	166,218	0.7464
0	165,542	0.7471
0.1	164,654	0.7475

Table A27. Variations in Δ_2.

M_0	P_S	r
20,000	165,609	0.7451
30,000	165,574	0.7462
37,500	165,542	0.7471
40,000	165,530	0.7474
50,000	165,479	0.7487

Table A28. Variations in M_0.

M_1	P_S	r
75,000	165,558	0.7468
90,000	165,550	0.7469
105,000	165,542	0.7471
120,000	165,533	0.7472
150,000	165,512	0.7475

Table A29. Variations in M_1.

R_0	P_S	r
37,500	165,733	0.7445
50,000	165,591	0.7456
62,500	165,542	0.7471
75,000	165,482	0.7487
87,500	165,409	0.7506

Table A30. Variations in R_0.

R_1	P_S	r
78,000	165,572	0.7467
104,000	165,558	0.7469
130,000	165,542	0.7471
156,000	165,523	0.7473
182,000	165,501	0.7475

Table A31. Variations in R_1.

II. Proofs of Findings 1 – 3.

Proof of Finding 1

The proof parallels the proof of Finding 3, and so is omitted.

Proof of Finding 2

(15) implies that when $G(K_S)$ is the uniform distribution, SATA is optimally implemented whenever:

$$K_S + \frac{G(K_S)}{g(K_S)} - W^e_{Si}(s^*) \;\leq\; K_T \quad\Leftrightarrow\quad K_S + \frac{G(K_S)}{g(K_S)} - W^e_{Si}(s^*) \;\leq\; \frac{1}{2}\left[\,\underline{K}_S + \overline{K}_S\,\right] - W^e_{Si}(s^*)$$

$$\Leftrightarrow\quad K_S + \frac{G(K_S)}{g(K_S)} \;\leq\; \frac{1}{2}\left[\,\underline{K}_S + \overline{K}_S\,\right] \quad\Leftrightarrow\quad K_S + K_S - \underline{K}_S \;\leq\; \frac{1}{2}\left[\,\underline{K}_S + \overline{K}_S\,\right]$$

$$\Leftrightarrow\quad 2\,K_S \;\leq\; \frac{3}{2}\,\underline{K}_S + \frac{1}{2}\,\overline{K}_S \quad\Leftrightarrow\quad K_S \;\leq\; \frac{3}{4}\,\underline{K}_S + \frac{1}{4}\,\overline{K}_S\,. \tag{17}$$

(9) and (17) imply that for $K_S \in \left[\,\frac{3}{4}\,\underline{K}_S + \frac{1}{4}\,\overline{K}_S\,,\, \frac{1}{2}\,\underline{K}_S + \frac{1}{2}\,\overline{K}_S\,\right]$, TCE is implemented in the presence of asymmetric knowledge of K_S whereas SATA would be implemented in the presence of symmetric knowledge of K_S. The length of this interval is:

$$\frac{1}{2}\,\underline{K}_S + \frac{1}{2}\,\overline{K}_S - \left(\frac{3}{4}\,\underline{K}_S + \frac{1}{4}\,\overline{K}_S\right) \;=\; \frac{1}{4}\left[\,\overline{K}_S - \underline{K}_S\,\right]. \quad \blacksquare$$

Proof of Finding 3

Lemma 1 ensures the regulator's problem is as formulated in [RP], provided $\widehat{K}_{Si} \in \left[\,\underline{K}_S, \overline{K}_S\,\right]$ for all $i \in \{1, ..., n\}$ at the solution to [RP].

Lemma 1. *Suppose* $E\{\,\Pi_T\,\} \geq 0$ *and* $\widehat{K}_{Si} \in \left[\,\underline{K}_S, \overline{K}_S\,\right]$*. Then for all* $K_S \in \left[\,\underline{K}_S, \overline{K}_S\,\right]$, $\max\{\,E\{\,\Pi_T\,\},\, E_i\{\,\Pi_S(\,K_S)\,\}\,\} \geq 0$.

Proof. By construction, $E_i\{\,\Pi_S(\,\widehat{K}_{Si})\,\} = E\{\,\Pi_T\,\} \geq 0$. Furthermore, from (2), using (1) and (3):

$$E_i\{\,\Pi_S(\,K_S)\,\} \;\gtreqless\; E\{\,\Pi_T\,\}$$

$$\Leftrightarrow\quad P_S + f\int_0^{\widehat{s}} (\,s\,R_1 + [\,1 - s\,]\,R_0\,)\,dH_i(s) - K_S \;\gtreqless\; E\{\,\Pi_T\,\}$$

$$\Leftrightarrow\quad \widehat{K}_{Si} - K_T + P_T - K_S \;\gtreqless\; E\{\,\Pi_T\,\}$$

$$\Leftrightarrow\quad \widehat{K}_{Si} + E\{\,\Pi_T\,\} - K_S \;\gtreqless\; E\{\,\Pi_T\,\} \quad\Leftrightarrow\quad K_S \;\lesseqgtr\; \widehat{K}_{Si}\,.$$

Therefore:

$$\max\{\,E\{\,\Pi_T\,\},\,E_i\{\,\Pi_S(\,K_S\,)\,\}\,\} \;=\; E_i\{\,\Pi_S(\,K_S\,)\,\} \;\geq\; E_i\{\,\Pi_S(\,\widehat{K}_{Si}\,)\,\} \;\geq\; 0$$

$$\text{for all } \; K_S \;\leq\; \widehat{K}_{Si}\,, \text{ and}$$

$$\max\{\,E\{\,\Pi_T\,\},\,E_i\{\,\Pi_S(\,K_S\,)\,\}\,\} \;=\; E\{\,\Pi_T\,\} \;\geq\; 0. \quad \square$$

Define $J \equiv \sum_{i=1}^{n} J_i$. Also let λ_T and λ_f denote the Lagrange multipliers associated with the first and second constraints in (5), respectively. Then the necessary conditions for a solution to [RP] include:

$$P_T: \quad \sum_{i=1}^{n} \left[\frac{\partial J}{\partial \widehat{K}_{Si}} \, \frac{\partial \widehat{K}_{Si}}{\partial P_T} - \phi_i \left(1 - G(\,\widehat{K}_{Si}\,) \right) \right] + \lambda_T \;=\; 0\,. \tag{18}$$

$$P_S: \quad \sum_{i=1}^{n} \left[\frac{\partial J}{\partial \widehat{K}_{Si}} \, \frac{\partial \widehat{K}_{Si}}{\partial P_S} - \phi_i \, G(\,\widehat{K}_{Si}\,) \right] \;=\; 0\,. \tag{19}$$

$$f: \quad \sum_{i=1}^{n} \frac{\partial J}{\partial \widehat{K}_{Si}} \, \frac{\partial \widehat{K}_{Si}}{\partial f} - \sum_{i=1}^{n} \phi_i \, G(\widehat{K}_{Si}) \int_0^{\widehat{s}} (\, s\, R_1 + [\,1 - s\,]\, R_0\,)\, dH_i(s) - \lambda_f \;\leq\; 0\,;$$

$$\text{and } \; f\,[\,\cdot\,] \;=\; 0\,. \tag{20}$$

$$\begin{aligned} \widehat{s}: \quad & \sum_{i=1}^{n} \frac{\partial J}{\partial \widehat{K}_{Si}} \, \frac{\partial \widehat{K}_{Si}}{\partial \,\widehat{s}} + \sum_{i=1}^{n} \phi_i \, G(\,\widehat{K}_{Si}\,)\, h_i(\widehat{s})\,\{\,\widehat{s}\,[\,M_1 + (\,1 - f\,)\,R_1 - L^e\,] \\ & \qquad + [\,1 - \widehat{s}\,]\,[\,M_0 + (\,1 - f\,)\,R_0 - v\,]\,\} \;=\; 0\,. \end{aligned} \tag{21}$$

Differentiating (4), using (6) and (10), provides:

$$\frac{\partial J}{\partial \widehat{K}_{Si}} \;=\; \phi_i \; g(\widehat{K}_{Si})\, \Psi_i^0\,, \tag{22}$$

where

$$\begin{aligned} \Psi_i^0 \;\equiv\; & \int_0^{\widehat{s}} (\, s\,[\,M_1 + (1 - f)\,R_1 - L^e\,] + [\,1 - s\,]\,[\,M_0 + (\,1 - f\,)\,R_0\,] - v\,)\, dH_i(s) \\ & - P_S \;+\; P_T \;-\; v \int_{\widehat{s}}^{1} s\, dH_i(s) \\ =\; & \int_0^{\widehat{s}} (\, s\,[\,M_1 + R_1 - L^e\,] + [\,1 - s\,]\,[\,M_0 + R_0\,] - v\,)\, dH_i(s) - \; v \int_{\widehat{s}}^{1} s\, dH_i(s) \end{aligned}$$

$$- \, f \int_0^{\widehat{s}} (\, s\, R_1 + [\, 1 - s\,]\, R_0\,)\, dH_i(s) - \, P_S \, + P_T$$

$$= \; W_i^e(\widehat{s}) - \left(P_S \, - P_T + f \int_0^{\widehat{s}} (\, s\, R_1 + [\, 1 - s\,]\, R_0\,)\, dH_i(s) \right)$$

$$= \; W_i^e(\widehat{s}) - \left(\widehat{K}_{Si} - K_T \right) \; = \; W_i^e(\widehat{s}) + K_T - \, \widehat{K}_{Si} \,. \tag{23}$$

The conclusion in (23) reflects (3).

(22) and (23) imply:

$$\frac{\partial J}{\partial \widehat{K}_{Si}} - \phi_i \, G(\, \widehat{K}_{Si}) \; = \; \phi_i \; g(\widehat{K}_{Si}) \, \Psi_i^0 \, - \phi_i \, G(\, \widehat{K}_{Si}) \; = \; \phi_i \; g(\widehat{K}_{Si}) \left[\Psi_i^0 \, - \frac{G(\, \widehat{K}_{Si})}{g(\widehat{K}_{Si})} \right]$$

$$= \; \phi_i \; g(\widehat{K}_{Si}) \left[W_i^e(\widehat{s}) + K_T - \, \widehat{K}_{Si} \, - \frac{G(\, \widehat{K}_{Si})}{g(\widehat{K}_{Si})} \right] . \tag{24}$$

Differentiating (3) provides:

$$\frac{\partial \widehat{K}_{Si}}{\partial P_S} \; = \; 1 \, ; \quad \frac{\partial \widehat{K}_{Si}}{\partial P_T} \; = \; - \, 1 \, ; \quad \frac{\partial \widehat{K}_{Si}}{\partial f} \; = \; \int_0^{\widehat{s}} (\, s\, R_1 + [\, 1 - s\,]\, R_0\,)\, dH_i(s) \, ; \; \text{ and}$$

$$\frac{\partial \widehat{K}_{Si}}{\partial \, \widehat{s}} \; = \; f \; h_i(\widehat{s}) \, [\; \widehat{s} \, R_1 \; + (\, 1 - \widehat{s}\,) \, R_0 \,] \, . \tag{25}$$

(25) implies that (18) – (21) can be written as:

$$- \sum_{i=1}^{n} \left[\frac{\partial J}{\partial \widehat{K}_{Si}} \; - \phi_i \, G(\, \widehat{K}_{Si}) \right] - \sum_{i=1}^{n} \phi_i + \lambda_T \; = \; 0 \, . \tag{26}$$

$$\sum_{i=1}^{n} \left[\frac{\partial J}{\partial \widehat{K}_{Si}} \; - \phi_i \, G(\, \widehat{K}_{Si}) \right] \; = \; 0 \, . \tag{27}$$

$$\sum_{i=1}^{n} \left[\frac{\partial J}{\partial \widehat{K}_{Si}} \; - \; \phi_i \, G(\widehat{K}_{Si}) \right] \int_0^{\widehat{s}} (s\, R_1 + [\, 1 - s\,]\, R_0) \, dH_i(s) - \lambda_f \; \leq \; 0 \, ;$$

$$\text{and} \quad f \, [\, \cdot \,] \; = \; 0 \, . \tag{28}$$

$$\sum_{i=1}^{n} \left[\frac{\partial J}{\partial \widehat{K}_{Si}} - \phi_i \, G(\, \widehat{K}_{Si}\,) \right] h_i(\widehat{s}) \, f \, [\, \widehat{s} \, R_1 \; + (\, 1 - \widehat{s}\,) \, R_0 \,]$$

$$+ \sum_{i=1}^{n} \phi_i \, G(\widehat{K}_{Si}) \, h_i(\widehat{s}) \cdot \{ \widehat{s} \, [\, M_1 + R_1 - L^e \,] + [\, 1 - \widehat{s} \,] \, [\, M_0 + R_0 - v \,] \} \;=\; 0\,. \qquad (29)$$

(29) reflects the fact that:

$$\widehat{s} \, [\, M_1 + (1-f) \, R_1 - L^e \,] + [\, 1 - \widehat{s} \,] \, [\, M_0 + (1-f) \, R_0 - v \,]$$

$$= \widehat{s} \, [\, M_1 + R_1 - L^e \,] + [\, 1 - \widehat{s} \,] \, [\, M_0 + R_0 - v \,] - \; f \, [\, \widehat{s} \, R_1 \, + (\, 1 - \widehat{s} \,) \, R_0 \,] \qquad (30)$$

Conclusion (iii) in the Finding follows from (24) and (27).

Conclusion (i) follows from (1) and (5) if $\lambda_T > 0$. Summing (26) and (27) provides:

$$- \sum_{i=1}^{n} \phi_i + \lambda_T \;=\; 0 \quad \Rightarrow \quad \lambda_T \;=\; \sum_{i=1}^{n} \phi_i \;=\; 1 \;>\; 0\,.$$

To prove Conclusion (ii) in the Finding, observe from (29) that if $f = 0$:

$$\widehat{s} \, [\, M_1 + R_1 - L^e \,] + [\, 1 - \widehat{s} \,] \, [\, M_0 + R_0 - v \,]$$

$$\Leftrightarrow \;\; \widehat{s} \, [\, M_1 + R_1 + v - L^e - (M_0 + R_0) \,] + M_0 + R_0 - v \;=\; 0$$

$$\Leftrightarrow \;\; \widehat{s} \;=\; \frac{M_0 + R_0 - v}{M_0 + R_0 + L^e - (M_1 + R_1 + v)} \;=\; s^*. \quad \blacksquare$$

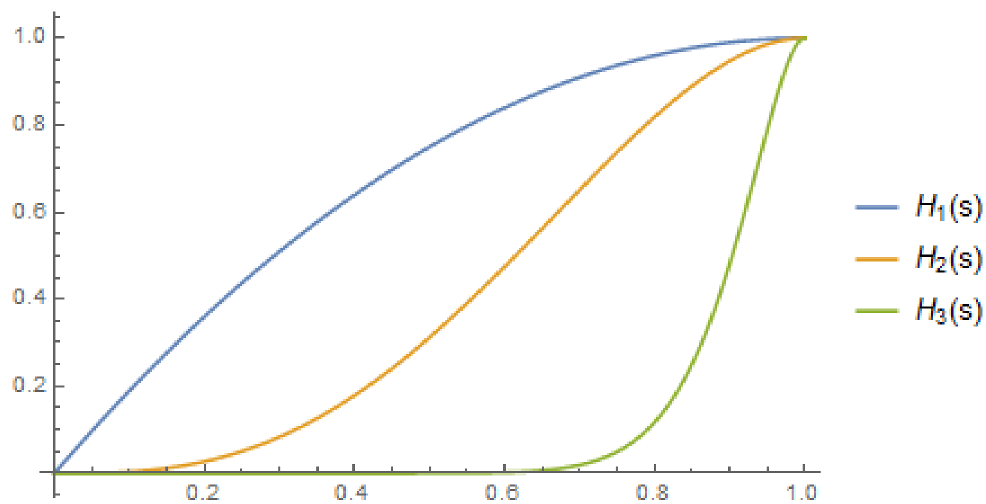

Figure 1. The Cumulative Distribution Functions for *s* in the Baseline Setting.

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