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This paper analyzes the Energy Efficiency (EE) investment decisions of a capital-constrained manufacturer that competes with an alternate supplier for the business of a large industrial buyer. Through a series of game theoretic models, we characterize when it is beneficial for the buyer to offer EE instruments, including assessment assistance and procurement commitment, and how these interact with third-party assessment assistance to impact the supplier's EE investment level. We find that assessment assistance helps reduce the EE gap but procurement commitment is required to eliminate it. We also find that the availability of third-party assessment assistance reduces the buyer's incentive to offer both of its instruments, potentially lowering the supplier's EE investment level. Our findings provide insights for buyers and policy makers interested in improving supply chain EE.

Key words: Energy Efficiency, Supplier Development, Supply Chain Sustainability, Buyer-supplier Interactions, Energy Efficiency Assessment, Energy Audit

1. Introduction

Improving Energy Efficiency (EE) has emerged as an effective mean to reduce Green House Gas emissions in industrial settings, due to its combined environmental and economic benefits.[1] The Alliance to Save Energy estimates that doubling energy productivity by 2030 could save the U.S. $327 billion annually in energy cost.[2] From a business standpoint, investing in EE also reduces budget risks associated with rising and volatile energy costs. Despite these benefits, it is well documented that significant EE opportunities remain unrealized in every industrial sector (Kleindorfer 2010). This results in *"a significant gap between the current and optimum levels of energy efficiency,"* a phenomenon known as the "EE gap" (Hirst and Brown 1990).

The manufacturing sector is the world's largest energy consumer, responsible for more than a third of the total global energy consumption (Saygin et al. 2010). Since this sector is comprised of many small and medium-sized manufacturers (SMMs), it is essential for policy makers wishing to reduce the EE gap to understand the challenges faced by these SMMs in making their EE investment

[1] Improving EE is defined as using less energy to provide the same service (The Lawrence Berkeley National Lab.).
[2] http://www.ase.org/policy/energy2030 (accessed August 21, 2017)

decisions. Unlocking the potential for EE improvement at SMMs usually begins with an initial assessment (energy audit) conducted by EE experts. This assessment provides a baseline understanding of energy use and identifies potential investments that could be made to improve EE. Unfortunately, SMMs *"often focus on the day-to-day tasks of the core business, leaving limited time and resources to investigate EE opportunities"* (International Energy Agency Report 2015). Many SMMs are also reluctant to perform EE audits due to the concern that *"the (subsequent) investment could not lead to the expected savings"* (Tomasi and Morea 2012). Without an initial assessment, EE investment opportunities remain dormant at many SMMs.

To tackle this barrier, assessment assistance providing free or low cost energy audits at SMMs has been established by many non-profit and government funded programs (collectively referred to here as third-party organizations). Notable programs in the U.S. include national Industrial Assessment Centers (IAC) funded by the Department of Energy and local technical assistance programs (e.g. Minnesota Technical Assistance Program). Price and Lu (2011) provide a detailed survey of similar programs globally. Although these programs have achieved remarkable success in identifying profitable EE investments, many remain unimplemented at SMMs. According to the IAC database, more than half of their EE improvement recommendations are not implemented. This is often due to uncertainty in the paybacks of EE improvements, which are realized through future savings in energy costs and depend on continued business with the supplier's key customers. Inhofe and Fannon (2005) point out that when high energy prices overshadow the gains from EE improvements, a buyer might switch to a cheaper competitor, making the delayed benefits of EE investments unattainable. This uncertainty dampens SMMs' incentive to invest.

To reduce this uncertainty, some large buyers (e.g., Wal-mart and Starbucks), offer long-term procurement commitment that provides business security to selected suppliers and encourages longer term investments in EE and other environmental improvements. As Andrew Ruben, Wal-mart's then executive vice president of private brand operations, explained, environmental improvements *"might require an investment that takes two and a half or three years to pay off. Offering a two-year commitment gives a supplier enough incentive to make the investment"* (Plambeck and Denend 2011). Apart from procurement commitment, large buyers have also introduced their own EE assessment assistance programs, independent of those offered by third parties (e.g. Wal-mart's "Supplier Energy Efficiency Program" or Ikea's "Suppliers Go Renewable"). In these programs, buyers initiate and subsidize the costs of EE assessment at suppliers' facilities. This helps them better understand suppliers' EE opportunities and adjust procurement strategies accordingly (Plambeck and Denend 2011).

As more large corporations, including Wal-mart, Ikea, GE and Starbucks, develop interests in improving EE within their supply chains, it is important to understand under what circumstances it is beneficial for a buyer to offer EE instruments, and whether they are helpful in reducing the EE gap. We focus on two instruments, assessment assistance and procurement commitment, since they are gaining traction as potential tools for buyers to help tackle the SMMs' reluctance to conduct EE assessment and the lack of business security. From the perspective of policy makers, it is also crucial to examine the interaction between potential buyer-offered instruments and third-party assistance in reducing the EE gap. As such, we address the following research questions.

1. When is it beneficial for a buyer to offer EE instruments (assessment assistance and/or procurement commitment) to its supplier? Under what conditions do these instruments reduce the EE gap at an SMM?
2. How does the addition of third-party support (i.e., providing free EE assessment) influence the buyer's offerings, and consequently, the supplier's EE investment?
3. How do characteristics of the energy market (prices, volatility, correlation across time) further affect these outcomes?

To answer these questions, we develop a stylized model that captures the EE investment decision of a focal supplier competing with an alternate supplier for the business of a large buyer in a two-period time frame. Our setting is motivated by U.S. suppliers participating in Wal-mart's SEEP.[3] An example of such a supplier is Dana Undies, a small family-owned manufacturer of children's clothes in Georgia (U.S.) with less than 200 employees and a $65,000$-square-foot facility. Most of Dana Undies' competitors are from Eastern Asian countries, including China, Vietnam, Cambodia, Indonesia (Lu 2014). In these regions, local governments established policies to maintain stable local energy prices, shielding businesses from global energy fluctuations (Kojima 2009). In contrast, Dana Undies was exposed to fluctuating energy prices in the U.S. and *"was facing challenges competing on prices with competitors and pointed to energy costs for much of the problem"*, as asserted in Wal-mart's Written Testimony (2007). Wal-mart's assessment assistance through SEEP helped Dana Undies overcome the assessment hurdle and identify EE improvements that significantly reduced its energy expenses.

In line with this example, we focus on manufacturing settings where energy costs are important to an SMM's price competitiveness and so the economics of EE improvements is key to the investment decision. In particular, we assume the production cost of the focal supplier depends on a volatile energy price realized at production time. In contrast, the alternate supplier operates in a region which benefits from stable energy prices due to government intervention, making its production cost more predictable. The focal supplier can explore potential EE improvements to reduce its energy usage (and thus, production cost), beginning with an EE assessment. After the assessment results are known, the supplier selects the level of EE investment, and incurs the associated upfront payment. The supplier's investment reward depends on whether the buyer offers a short- or long- term contract

[3] Wal-mart initially offered the program exclusively to their U.S. suppliers. In 2014, they extended a similar program to Chinese suppliers.

over the payback horizon. Under a short-term contract, the buyer is free to switch to the alternative supplier if the rise in future energy prices overtakes any gains from EE investment, leaving the focal supplier vulnerable to not realizing the full benefit of its EE investment.

We find that assessment assistance helps reduce the supplier's EE gap but procurement commitment is required to eliminate it. However, the buyer offers procurement commitment only when the alternate supplier is sufficiently expensive. Not surprisingly, third-party assessment assistance is important for unlocking EE improvement when the assessment cost is high. Nevertheless, when the costs of both the assessment and the alternate supplier are moderate, the addition of third-party assistance can actually *harm* EE investment by deterring the buyer from offering her own instruments. In our numerical study, using data from Industrial Assessment Centers (IAC), we observe this *detrimental* impact of adding third party assistance in more than 50% of the instances, leading to an associated 75% reduction in EE investments relative to the economically optimal level. Energy market characteristics influence these outcomes in several ways. We find that an increase in the volatility or cross period correlation of energy prices reduces the buyer's incentive to offer both assessment assistance and procurement commitment, leading to lower EE investment. However, an increase in the expected energy price generally increases the buyer's incentive to offer both instruments, expanding the regions where the EE gap is reduced or even eliminated.

This study contributes to the sustainable operations literature by analyzing the impact of buyer and third-party offered instruments on the EE investment decision at an SMM. Most papers in this literature stream focus on the decision of a *single* firm to implement EE improvements (e.g., Anderson and Newell 2004, Aflaki et al. 2013 and Muthulingam et al. 2013) or to adopt more general sustainable technologies (see, for example, Krass et al. 2013, Wang et al. 2013, Drake et al. 2016, Kök et al. 2016, Hu et al. 2015 and Raz and Ovchinnikov 2015). Our work differs from these studies in that we are interested in the impact of *supply chain interaction and external assistance* on the firm's EE investment decision.

Since EE investments provide a cost reduction opportunity at the supplier that can also benefit the buyer (Wu et al. 2014), our research is related to the literature on supplier development. This literature, including Bernstein and Kök (2009), Wang et al. (2010), Li (2013), Kim and Netessine (2013) and Tang et al. (2014), investigates the impact of different types of buyer-provided incentives for improving quality and other performance measures within the supplier base. They focus on continuous process improvement decisions that are central to the practice of Lean Production and Six Sigma, but differ from decisions involving a radical change in technology or equipment. In contrast, EE improvements usually require one-shot up-front investments with future rewards (through savings in energy expenses) that are earned over time (Kapur et al. 2011). This motivates our use of a two-period model to capture the decision dynamics. Most of the above cited papers use a single-period model with the exception of Bernstein and Kök (2009), who consider a multi-period model in which the suppliers accumulate cost-reduction investments in each period. In our setting, we assume the supplier makes one investment decision at the beginning of the time horizon. Our study also differs from these papers in focus, as we incorporate the need for an initial EE assessment and the possibility of third party assistance along with buyer-offered instruments. This allows us to derive new insights into how the interaction of these instruments impact the supplier's investment.

2. Model Description

We consider a two-tiered supply chain consisting of a large buyer (she) that has negotiation power and a capital-constrained supplier (he) who considers investing in EE improvements at his production facility. The buyer wishes to procure a mature product with constant demand over a two-period time horizon, which she sells at market price p. Assuming a constant demand allows us to isolate the impact of energy price uncertainty, which affects both the availability and magnitude of the supplier's EE cost savings. We normalize the buyer's demand to one without loss of generality.

The supplier's production cost is divided into a time-dependent energy-related cost component as well as a non-energy cost component that is normalized to zero. We assume the energy-related cost in each period, $\tilde{c}_t$, $t = 1, 2$, follows a Normal distribution with mean μ and standard deviation σ, where $\mu \gg \sigma$ such that the probability of a negative energy cost is negligible. Let $f(\cdot)$ and $F(\cdot)$ denote the p.d.f. and c.d.f. of $\tilde{c}_t$, respectively. We further assume energy costs are correlated across time periods, captured through a bivariate Normal distribution with positive correlation coefficient $\rho \geq 0$. This is consistent with energy price processes examined in prior empirical studies (e.g. Skorodumov 2008). These assumptions imply that the conditional expectation of energy cost in period 2, for a realized cost c_1 in period 1, is $\mathbb{E}_2[\tilde{c}_2|c_1] = \mu(1-\rho) + \rho c_1$.

The supplier can explore potential EE improvements to reduce his energy usage by conducting an EE assessment at a fixed cost A. We assume that prior to the assessment, there exists a range of potential energy savings that could be achieved for different investment levels, although the exact saving is not yet known. Once the assessment is complete, the exact saving for each possible investment level $I \in [0, I_m]$ is revealed, where I_m reflects the most advanced EE technologies available. We capture the pre-assessment uncertainty in the energy savings potential by the saving function $g(I) = \tilde{\alpha}\sqrt{I}$, where the random variable $\tilde{\alpha}$ represents the investment's effectiveness. Before the assessment, only the distribution of $\tilde{\alpha}$ is known. After the assessment, the true value of $\tilde{\alpha}$, which we denote by α, is revealed, and the reduction in energy cost for a given investment level I is given by $c_t\alpha\sqrt{I}$, $t = 1, 2$. We assume $\tilde{\alpha}$ is uniformly distributed over $[\alpha_L, \alpha_H]$, implying that all technologies are equally likely. Furthermore, $\alpha_H\sqrt{I_m} < 1$, implying that the maximum EE investment does not completely eliminate all energy usage.

If an assessment is performed, the supplier can select a level of EE investment, $I \in [0, I_m]$, which he then funds with an external loan. The supplier repays the loan in equal installments βI at the end of each period, where $\beta \geq \frac{1}{2}$. We assume loan financing since the supplier is an SMM with limited capital resources. The single investment assumption reflects the fact that EE financing is often difficult to secure (Palmer et al. 2012) and so a subsequent EE investment might not be possible until the first one is paid off. The supplier's investment choice I has a long-term impact on his cost structure, captured by both the recurrent payment βI, and the uncertain energy cost savings $\tilde{c}_t g(I)$ in period $t = 1, 2$. His total cost in period t is captured by $\tilde{c}_t(1 - \alpha\sqrt{I}) + \beta I$.

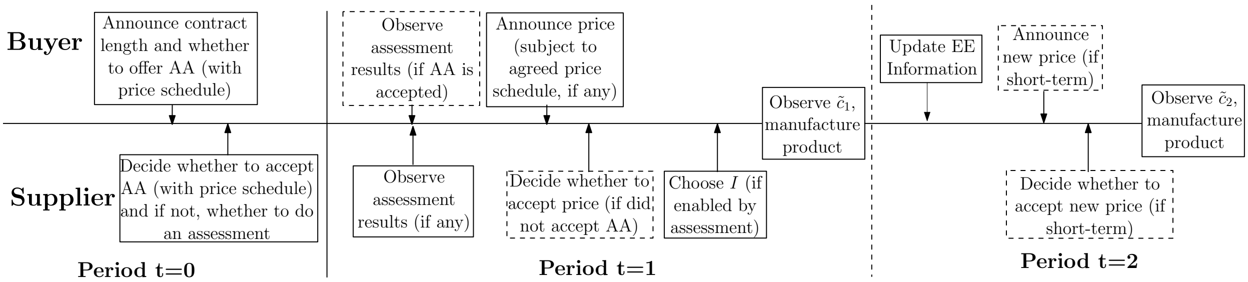


Figure 1 Sequence of events

Figure 1 illustrates the key interactions between the buyer and supplier, which form a Stackelberg game with the buyer as leader and both parties acting to maximize their expected profits.[4] In the pre-assessment phase (period 0), the buyer announces the contract length, either the standard single-period or a longer two-period contract if using Procurement Commitment (PC) and decides whether to offer Assessment Assistance (AA). Under PC (i.e., a long-term contract), the buyer commits to sourcing her entire demand (normalized to size 1) from the supplier at the same price in both periods. Without PC (i.e., a short-term contract), the buyer may switch to the alternate supplier in period 2 after observing the energy cost c_1. Under AA, the buyer incurs the assessment cost A and offers the supplier a scheme to split the EE cost savings after observing the assessment result α. In particular, the buyer commits to a price schedule which depends on the realized α (i.e., $w_1(\alpha)$ in the first period without PC or $w(\alpha)$ in both periods with PC) together with AA.[5] The supplier chooses his EE investment level in period 1 if accepting AA. If AA is either not offered or rejected, the supplier can still decide whether to conduct an assessment and keep the result as his private information. In this case, the buyer sets her price accordingly to the announced contract length (w_1 in the first period under a short- and w in both periods under a long-term contract) after observing

[4] When two strategies lead to the same expected profit, we assume both firms choose the option providing higher EE investment.

[5] This committed price schedule protects the supplier from the possibility that the buyer extracts all the EE cost savings after learning the assessment result.

the supplier's assessment decision. The supplier agrees to any offered price that provides an expected profit no less than his reservation level. After accepting the price in period 1, the supplier chooses an EE investment level I (if enabled by the assessment).

If the buyer's offer is rejected in either period, she purchases from an alternate supplier at a cost c_a, where $p > c_a \geq \mu$.[6] This cost c_a includes the alternative supplier's energy and other production related costs, as well as any additional procurement related costs. For ease of exposition, we assume a deterministic cost c_a, applicable when the alternate supplier is from a region that enjoys stable energy prices, due to government regulation or other market forces, e.g. Bangladesh, India, Indonesia, Vietnam, etc. (Kojima 2009). In Online Appendix B.1, we provide insights into how our model would change when considering price volatility as well as potential correlation between the energy-related component of c_a and the focal supplier's energy cost.

All information is common knowledge in period 1 except for the assessment results (i.e., the true value of α) which the supplier keeps as his private knowledge unless accepting the buyer's AA. In period 2, we assume the buyer can observe the supplier's prior EE investment I (if any) and his energy usage $(1-\alpha\sqrt{I})$ from period 1, allowing her to also discern α. This assumption reflects the fact that buyers often monitor a supplier's energy usage through an information sharing portal managed by a third-party energy management company (e.g. the Foresight portal managed by the Midwest Energy Cooperation) and suppliers report undertaken EE investments upon requested by buyers. It is also consistent with the remark by Jira and Toffel (2013), in their empirical analysis of data from the Carbon Disclosure Project's (CDP) Supply Chain Program,[7] that *"suppliers are increasingly being asked to share information about their vulnerability to climate change and their strategies to reduce greenhouse gas emissions,"* including energy usage and undertaken EE investments. They find that suppliers are willing to share such information for a number of reasons, including green house gas regulations and the buyer's commitment to sustainability. Since the costs of information sharing (e.g. costs of maintaining the information sharing platform and/or reporting) are negligible and often paid by suppliers, we assume the buyer incurs no extra cost for the information update.

Before defining our *benchmark* for measuring the possible EE gap across different scenarios, it is worth acknowledging a few different definitions of the *EE gap* (and the related *energy paradox*) found in extant literature. Gillingham and Palmer (2013) interchangeably use EE gap and EE paradox to refer to the phenomenon that *"individuals make decisions about energy efficiency that leads to a slower penetration of energy efficient products into the market than might be expected if consumers made all positive net present value investments."* Gerarden et al. (2015), on the other hand, distinguish

[6] This assumption ensures the buyer's profitability and rationalizes the focal supplier's EE investment problem.

[7] CDP is a collaboration of multinational corporations requesting environmental information from thousands of suppliers in 49 countries.

between "energy paradox" as the issue of private optimality (i.e., *"the apparent reality that some EE technologies that would pay off for adopters are nevertheless not adopted"*) versus "EE gap" as a broader concept related to social optimality (i.e., *"the apparent reality that some energy-efficiency technologies that would be socially efficient are not adopted"*). In this paper, we follow the EE gap definition by Allcott and Greenstone (2012) as the *"wedge between the cost-minimizing level of energy efficiency and the level actually realized."*

Recall that the supplier's total cost in each period is $\tilde{c}_t(1-\alpha\sqrt{I})+\beta I$, and so his total expected cost across both periods is $2\left[\mu(1-\alpha\sqrt{I})+\beta I\right]$. It is straightforward to show that the most cost effective EE investment level (i.e., the *benchmark*) for a given value of α is then $I^{e^*}(\alpha)=\min\left(I_m,[\mu\alpha/2\beta]^2\right)$, which also represents the channel's optimal investment level if the buyer and supplier were vertically integrated. Hereafter, we focus on parameter ranges such that $\left[\frac{\mu\alpha_H}{2\beta}\right]^2 \leq I_m$, implying that for $\alpha \in [\alpha_L,\alpha_H]$, the interior solution is optimal and so

$$I^{e^*}(\alpha)=\left[\frac{\mu\alpha}{2\beta}\right]^2. \tag{1}$$

Focusing on the interior solution allows us to study the key dynamics while avoiding trivial special cases. This is a reasonable assumption since it is often prohibitively expensive to invest in the most advanced technologies (captured by I_m) which have yet to benefit from scale economies (Sorrell 2015).

3. Impact of Buyer-offered Instruments

In this section, we address our first research question, namely under what conditions it is beneficial for the buyer to offer EE instruments (AA and PC) and whether these instruments reduce the EE gap at an SMM. We begin by establishing the supplier's EE investment level when no external instruments are available. This serves as a baseline for the later quantification of any improvements buyer-offered instruments and third-party assistances may offer.

3.1. The Baseline EE Investment Level

We first analyze the outcomes when the supplier self-funds an assessment without any external assistances. In this case, the assessment result (α) is the supplier's private information until the buyer observes an update of the supplier's operations in period 2. We derive the firms' optimal decisions by backward induction, starting in period 2 with the supplier's decision to accept or reject the buyer's offered price w_2. For an observed energy cost c_1, the supplier's profit when accepting w_2 is $w_2-\mathbb{E}_2[\tilde{c}_2|c_1](1-\alpha\sqrt{I})-\beta I$.

For ease of exposition, we assume the supplier has a zero reservation profit across the planning horizon. However, his reservation profit becomes $-\beta I$ in period 2 if he commits to the investment I in period 1. This is because the installment amount βI is a payable sunk cost whether or not production takes place. It follows that the supplier will accept w_2 if $w_2 \geq \mathbb{E}_2[\tilde{c}_2|c_1](1-\alpha\sqrt{I})$. Knowing this, as well as I and α (through the updated observation of the supplier's operations), the buyer sets w_2 to maximize her profit given by

$$\pi_2(w_2,\alpha,c_1) = \begin{cases} p - w_2, & \text{if } w_2 \geq \mathbb{E}_2[\tilde{c}_2|c_1](1-\alpha\sqrt{I}) \\ p - c_a, & \text{otherwise.} \end{cases} \tag{2}$$

When $\mathbb{E}_2[\tilde{c}_2|c_1](1-\alpha\sqrt{I}) > c_a$, the buyer is better off switching to the alternate supplier and so will offer $w_2 = c_a$ which will be rejected by the focal supplier. When $c_a \geq \mathbb{E}_2[\tilde{c}_2|c_1](1-\alpha\sqrt{I})$, the dynamics reflect an ultimatum game with the buyer as the leader with the power to divide the supply chain savings from using the cheaper focal supplier, i.e., $c_a - \mathbb{E}_2[\tilde{c}_2|c_1](1-\alpha\sqrt{I})$. Since there is no information asymmetry in period 2 (and both players are perfectly rational), the unique sub-game perfect equilibrium is for the supplier to accept the buyer's minimum offer $w_2 = \mathbb{E}_2[\tilde{c}_2|c_1](1-\alpha\sqrt{I})$. Combining the two cases yields $w_2^*(c_1,\alpha) = \min(\mathbb{E}_2[\tilde{c}_2|c_1](1-\alpha\sqrt{I}), c_a)$. This price allows the buyer to extract all EE savings in period 2, leaving the supplier with his reservation profit $-\beta I$. This model structure is similar to that analyzed by Swinney and Netessine (2009), who consider a related Stackelberg setting where the buyer holds negotiation power.

Now considering period 1, recall that the buyer does not yet know the exact value of α and so she chooses w_1 to maximize $\mathbb{E}_0[\pi_1(w_1,\alpha)]$ with

$$\pi_1(w_1,\alpha) = \begin{cases} p - w_1 + \mathbb{E}_1\left[p - w_2^*(c_1,\alpha)\right], & \text{if } \psi_1^*(w_1,\alpha) \geq 0 \\ 2(p-c_a), & \text{otherwise,} \end{cases} \tag{3}$$

where

$$\psi_1^*(w_1,\alpha) = \max_{0\leq I\leq I_m} w_1 - \mu(1-\alpha\sqrt{I}) - 2\beta I, \tag{4}$$

is the supplier's optimal expected profit from period 1 onward if he accepts w_1. In (4), w_1 denotes the revenue offered from the buyer while $\mu(1-\alpha\sqrt{I})$ captures the expected total energy costs, including any savings from the EE investment. The last term represents the total cost of EE investments, consisting of the payable loan installment in period 1 ($-\beta I$) and the supplier's expected earning in period 2 ($-\beta I$) when the profit is entirely extracted by the buyer. Let $I^{e1}(\alpha)$ denote the optimal solution to (4), which can be easily derived as

$$I^{e1}(\alpha) = \left[\frac{\mu\alpha}{4\beta}\right]^2. \tag{5}$$

Note that $I^{e1}(\alpha)$ also reflects the optimal EE investment level when the supplier takes a short-term view, assuming the buyer always switches in the second period. Substituting (5) into (4), we have $\psi_1^*(w_1,\alpha) = w_1 - \mu + \frac{(\mu\alpha)^2}{8\beta}$. The supplier accepts w_1 only if $\psi_1^*(w_1,\alpha) \geq 0$, which occurs when

$$w_1 \geq \mu - \frac{(\mu\alpha)^2}{8\beta}. \tag{6}$$

We make the following observations that facilitate our further analysis. On one hand, the supplier always rejects any w_1 lower than $\underline{w}_1 = \mu - \frac{(\mu\alpha_H)^2}{8\beta}$. Thus, offering $w_1 < \underline{w}_1$ results in the buyer sub-optimally earning $2(p-c_a)$ since she relinquishes any potential EE cost savings. On the other hand, the supplier will accept any w_1 that is at least $\bar{w}_1 = \mu - \frac{(\mu\alpha_L)^2}{8\beta}$. This implies that offering $w_1 > \bar{w}_1$ is also sub-optimal for the buyer as she unnecessarily yields extra profits to the supplier. It follows from the above two arguments that $w_1^* \in [\underline{w}_1, \bar{w}_1]$. Within this range of w_1, the condition in (6) implies that there exists an EE effectiveness threshold $\alpha_s(w_1) \in [\alpha_L, \alpha_H]$ where $\alpha_s(w_1) = \frac{\sqrt{8\beta(\mu - w_1)}}{\mu}$, such that the supplier accepts w_1 only if the realized $\alpha \geq \alpha_s(w_1)$. This results in the following characterization of the buyer's optimization problem.

$$\pi_1^* = \max_{\underline{w}_1 \leq w_1 \leq \bar{w}_1} \int_{\alpha_L}^{\alpha_s(w_1)} 2(p-c_a) f(\tilde{\alpha}) d\tilde{\alpha} + \int_{\alpha_s(w_1)}^{\alpha_H} \left[2p - w_1 - \mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde{c}_2|c_1] \left(1 - \frac{\mu\tilde{\alpha}^2}{4\beta}\right), c_a \right) \right] f(\tilde{\alpha}) d\tilde{\alpha}. \quad (7)$$

By lowering her offered price w_1 (i.e., increasing $\alpha_s(w_1)$), the buyer benefits from a cheaper procurement cost but bears a higher risk of being rejected and having to source from the costlier alternate supplier. The buyer balances this tradeoff in choosing the optimal w_1^*, which is equivalent to identifying the optimal threshold α_s^*. As we show in the technical proofs provided in Online Appendix A, $\frac{\partial \pi_1}{\partial \alpha_s}$ has at most two real roots, where α_2 denotes the larger one (if any). Lemma 1 uses this terminology to characterize the buyer's and supplier's optimal decisions.

LEMMA 1. *When no external instruments are available and if an EE assessment is performed by the supplier, the buyer offers* $w_1^* = \mu - \frac{(\mu\alpha_s^*)^2}{8\beta}$, *where*

$$\alpha_s^* = \begin{cases} \alpha_L, & \text{if } \frac{\partial \pi_1}{\partial \alpha_s} < 0, \ \forall \alpha \in [\alpha_L, \alpha_H] \text{ or } \pi_1(\alpha_L) > \pi_1(\alpha_2) \\ \alpha_2, & \text{otherwise,} \end{cases} \quad (8)$$

and $\alpha_L \leq \alpha_s^* \leq \frac{2}{3}\alpha_H$. *If* $\alpha < \alpha_s^*$, *the supplier rejects the offer and sets* $I^*(\alpha) = 0$. *Otherwise, he accepts* w_1^* *and sets* $I^*(\alpha) = I^{e1}(\alpha)$, *where* $I^{e1}(\alpha)$ *is defined in (5), the buyer then offers* $w_2^*(c_1, \alpha) = \min\left(\mathbb{E}_2[\tilde{c}_2|c_1]\left(1 - \frac{\mu\alpha^2}{4\beta}\right), c_a\right)$ *in period 2.*

By substituting w_1^* and $I^*(\alpha)$ into (4), the supplier's optimal profit in period 1 when conducting the EE assessment is given by

$$\psi_1^*(w_1^*, \alpha) = \begin{cases} 0, & \text{if } \alpha < \alpha_s(w_1^*) = \alpha_s^*; \\ \frac{\mu^2(\alpha^2 - \alpha_s^{*2})}{8\beta}, & \text{if } \alpha \geq \alpha_s(w_1^*) = \alpha_s^*. \end{cases}$$

When the supplier accepts the offered price w_1^*, he earns a portion of the EE investment benefit in period 1, $\frac{\mu^2(\alpha^2 - \alpha_s^{*2})}{8\beta}$, as information rent from privately knowing α. The supplier's expected profit across the planning horizon is then given by $\psi_0 = -A + \mathbb{E}_0[\psi_1^*(w_1^*, \tilde{\alpha})] = -A + \int_{\alpha_s^*}^{\alpha_H} \frac{\mu^2(\tilde{\alpha}^2 - \alpha_s^{*2})}{8\beta} f(\tilde{\alpha}) d\tilde{\alpha}$.

When the supplier does not perform an EE assessment, the investment level is zero by definition. It is easy to show that the buyer offers $w_1^* = \mu$, $w_2^*(c_1) = \min(\mathbb{E}_2[\tilde{c}_2|c_1], c_a)$ and the supplier's expected profit across the planning horizon is zero. Comparing the supplier's expected profits across the two cases suggests that the supplier self-funds the assessment only when the assessment cost A is sufficiently low. Before formalizing that result in Proposition 1, we introduce in Table 1 the notational convention for the assessment cost threshold A^i, where the superscript i represents different scenarios. Also, A^i_{3p} represents the corresponding counterpart of A^i when the third-party assistance is available.

Superscript i	**Representing**
S	Supplier's threshold when there is no external assistance
S_p	Supplier's threshold when there is Procurement Commitment
B_a	Buyer's threshold when offering only Assessment Assistance
B_p	Buyer's threshold when offering *both* Procurement Commitment and Assessment Assistance
B^*	Buyer's threshold under her optimal strategy

Table 1 Notational convention for A^i.

Proposition 1. *Without any external instruments, the supplier performs an EE assessment iff the assessment cost* $A \le A^S(c_a) = \int_{\alpha_s^*}^{\alpha_H} \frac{\mu^2(\tilde\alpha^2 - \alpha_s^{*2})}{8\beta} f(\tilde\alpha)d\tilde\alpha$ *where* $A^S(c_a)$ *increases in* c_a.

As the cost of the alternate supplier increases, the buyer is willing to surrender a higher information rent, thus increasing the supplier's assessment threshold, i.e., $A^S(c_a)$ increases in c_a.

The supplier's ($\psi^*_{0_b}$) and buyer's ($\pi^*_{0_b}$) expected profits in period 0 are then given by

$$\psi^*_{0_b} = \left(-A + \int_{\alpha_s^*}^{\alpha_H} \frac{\mu^2(\tilde\alpha^2 - \alpha_s^{*2})}{8\beta} f(\tilde\alpha)d\tilde\alpha\right)^+ = (A^S(c_a) - A)^+, \tag{9}$$

$$\pi^*_{0_b} = \begin{cases} 2p - \left[\int_{\alpha_L}^{\alpha_s^*} 2c_a f(\tilde\alpha)d\tilde\alpha + \int_{\alpha_s^*}^{\alpha_H} \left[\mu - \frac{(\mu\alpha_s^*)^2}{8\beta} + \mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde c_2|c_1]\left(1 - \frac{\mu\alpha^2}{4\beta}\right), c_a\right)\right] f(\tilde\alpha)d\tilde\alpha\right], & \text{if } A \le A^S(c_a); \\ 2p - [\mu + \mathbb{E}_1 \min(\mathbb{E}_2[\tilde c_2|c_1], c_a)]. & \text{otherwise} \end{cases} \tag{10}$$

Combining the results of Lemma 1 and Proposition 1 allows us to characterize the corresponding baseline EE gap, defined as $\Delta^S(\alpha) = I^{e^*}(\alpha) - I^*(\alpha)$, where $I^{e^*}(\alpha)$ is given in (1).

$$\Delta^S(\alpha) = \begin{cases} \Delta^{e1}(\alpha) \doteq \frac{3}{16}\left[\frac{\mu\alpha}{\beta}\right]^2, & \text{if } A \le A^S(c_a) \text{ and } \alpha \ge \alpha_s^*; \\ \Delta^0(\alpha) \doteq \frac{1}{4}\left[\frac{\mu\alpha}{\beta}\right]^2, & \text{otherwise.} \end{cases} \tag{11}$$

Equation (11) shows that without any external instruments, EE investment occurs only when the assessment cost is sufficiently low and the realized EE investment effectiveness is sufficiently high. However, this EE investment still results in a sizeable EE gap. We next investigate the impact of the buyer-offered instruments on reducing this EE gap.

3.2. Impact of Assessment Assistance

Similar to the previous analysis, we derive the buyer's decision whether to offer AA by comparing her expected profits with and without the offer. When AA is offered and subsequently accepted by the supplier, the dynamics in period 2 follow the previous case where the assessment was performed by the supplier without external support. However, the buyer now has to commit to a first-period price schedule $w_1(\alpha)$ when offering AA in order to satisfy the supplier's participation constraint and convince him to accept her offer in period 0. The supplier's participation constraint represents the expected profit he would earn if rejecting the buyer's assistance and (possibly) self-performing an assessment, i.e., his expected profit in the baseline scenario given in (9).

Assuming that the supplier accepts the buyer's AA offer, we characterize the firms' optimal decisions by backward induction, starting from the supplier's EE investment decision in period 1 (since the decisions in period 2 are the same as in the baseline scenario). For an agreed price schedule $w_1(\alpha)$, the supplier's optimization problem in period 1 is given by $\psi_1^*(\alpha) = \max_{0\le I\le I_m} w_1(\alpha) - \mu(1-\alpha\sqrt{I}) - 2\beta I$. It is straightforward to show that the supplier's optimal EE investment $I^*(\alpha)$ is given by $I^*(\alpha) = I^{e1}(\alpha) = \left[\frac{\mu\alpha}{4\beta}\right]^2$ and it follows that $\psi_1^*(\alpha) = w_1(\alpha) - \mu + \frac{(\mu\alpha)^2}{8\beta}$. Anticipating this response by the supplier, the buyer's optimal price schedule $w_1^*(\alpha)$ to offer along with AA is determined by the solution to the following problem.

$$\pi_0 = \max_{w_1(\alpha)} -A + \mathbb{E}_0\left[2p - w_1(\alpha) - \mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde{c}_2|c_1]\left(1-\frac{(\mu\alpha)^2}{4\beta}\right), c_a\right)\right] \tag{12}$$
$$\text{s.t.}\quad \mathbb{E}_0\left[\psi_1^*(\alpha)\right] = \mathbb{E}_0\left[w_1(\alpha) - \mu + \frac{(\mu\alpha)^2}{8\beta}\right] \ge \psi_{0_b}^*.$$

The buyer's and supplier's optimal decisions are then characterized in the following lemma.

LEMMA 2. *The buyer's optimal solution to (12) is to offer $w_1^*(\alpha) = \mu - \frac{(\mu\alpha)^2}{8\beta} + \psi_{0_b}^*$ together with AA, which the supplier accepts. The supplier then sets $I^*(\alpha) = I^{e1}(\alpha)$, where $I^{e1}(\alpha)$ is defined in (5). In period 2, the buyer offers $w_2^*(c_1,\alpha) = \min\left(\mathbb{E}_2[\tilde{c}_2|c_1]\left(1-\frac{\mu\alpha^2}{4\beta}\right), c_a\right)$.*

By committing to the price schedule $w_1^*(\alpha)$ that guarantees the supplier's expected reservation profit, the buyer is able to benefit from the EE cost savings under all realizations of α. This is unlike the previous scenario where the supplier accepts the buyer's offer (and makes subsequent EE investments) only for sufficiently high α (i.e. $\alpha \ge \alpha_s^*$). It follows from Lemma 2 that the buyer's optimal expected profit across the planning horizon when offering AA is given as

$$\pi_0 = 2p - \left[\mu + \int_{\alpha_L}^{\alpha_H}\left[\mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde{c}_2|c_1]\left(1-\frac{\mu\tilde{\alpha}^2}{4\beta}\right), c_a\right) - \frac{(\mu\tilde{\alpha})^2}{8\beta}\right] f(\tilde{\alpha})d\tilde{\alpha}\right] - A - \psi_{0_b}^*. \tag{13}$$

Comparing the two expressions in (10) and (13) yields the following result.

Proposition 2. *With no other instruments available, the buyer offers AA iff the assessment cost A satisfies*

$$A \leq A^{B_a}(c_a) = \int_{\alpha_L}^{\alpha_H} \left[\frac{(\mu\tilde{\alpha})^2}{8\beta} - \mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde{c}_2|c_1] \left(1 - \frac{\mu\tilde{\alpha}^2}{4\beta}\right), c_a \right) \right] f(\tilde{\alpha}) d\tilde{\alpha} + \mathbb{E}_1 \left[\min\left(\mathbb{E}_2[\tilde{c}_2|c_1], c_a \right) \right],$$

where $A^{B_a}(c_a) > A^S(c_a)$ *and* $A^{B_a}(c_a)$ *increases in* c_a.

Proposition 2 suggests that when it would be beneficial for the supplier to self-perform the assessment (i.e., when $A \leq A^S(c_a)$), it is optimal for the buyer to cover his participation constraint and offer AA herself. In this case, the buyer enables EE investment for all realizations of α, even when $\alpha < \alpha_s^*$. She can therefore extract more benefits than when the supplier self-performs the assessment. It may also be advantageous for the buyer to offer assistance in cases where the supplier would not be willing to self-fund an assessment (i.e., $A > A^S(c_a)$). In such cases, the supplier's baseline expected profit is zero and so the buyer can extract all the EE benefit by offering assistance herself. The above results suggest that AA increases the buyer's power to some extent, allowing her to afford a more expensive assessment cost than the self-funding supplier. This implies that buyer-offered AA widens the range of affordable assessment costs to identify EE improvement opportunities. When the alternate supplier is more expensive, the buyer is more inclined to stay with the focal supplier to benefit from his EE cost savings, and thus her assessment threshold $A^{B_a}(c_a)$ increases in c_a.

It follows from Propositions 1 and 2 that the buyer's optimal expected profit across the planning horizon, taking into account his optimal AA decision, is given by

$$\pi_0^* = \begin{cases} \pi_0^a = 2p - \left[\mu + \int_{\alpha_L}^{\alpha_H} \left[\mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde{c}_2|c_1] \left(1 - \frac{\mu\tilde{\alpha}^2}{4\beta}\right), c_a \right) - \frac{(\mu\tilde{\alpha})^2}{8\beta} \right] f(\tilde{\alpha}) d\tilde{\alpha} \right] - A^S(c_a), & \text{if } A \leq A^S(c_a) \\ \pi_0^b = 2p - \left[\mu + \int_{\alpha_L}^{\alpha_H} \left[\mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde{c}_2|c_1] \left(1 - \frac{\mu\tilde{\alpha}^2}{4\beta}\right), c_a \right) - \frac{(\mu\tilde{\alpha})^2}{8\beta} \right] f(\tilde{\alpha}) d\tilde{\alpha} \right] - A, & \text{if } A^S(c_a) < A \leq A^{B_a}(c_a) \\ \pi_0^c = 2p - \left[\mu + \mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde{c}_2|c_1], c_a \right) \right], & \text{if } A^{B_a}(c_a) < A. \end{cases} \tag{14}$$

The EE gap $\Delta^{B_a}(\alpha)$ in this case is

$$\Delta^{B_a}(\alpha) = \begin{cases} \Delta^{e1}(\alpha), & \text{if } A \leq A^{B_a}(c_a); \\ \Delta^0(\alpha), & \text{otherwise,} \end{cases}$$

where $\Delta^{e1}(\alpha)$ and $\Delta^0(\alpha)$ are defined in (11). Although the EE gap is reduced when the assessment cost is moderately high ($A^S(c_a) < A \leq A^{B_a}(c_a)$), it is not eliminated. This is because the supplier still takes a short-term view of the investment benefits.

3.3. Impact of Procurement Commitment

We now investigate the sole impact of PC where the buyer commits to source her entire demand from the focal supplier at a fixed price w across both periods. We follow the same approach as in

Section 3.1 to explore when it is beneficial for the supplier to self-perform an assessment under this long-term contract. For brevity, we omit similar analysis and focus on the results, starting with the firms' optimal decisions after an assessment is conducted by the supplier as defined in Lemma 3.

LEMMA 3. *Under PC and when an assessment is performed by the supplier, the buyer offers* $w^* = \mu - \frac{(\mu\alpha_p^*)^2}{4\beta}$, *where*

$$\alpha_p^* = \begin{cases} \alpha_L, & \text{if } \frac{\partial \pi_{1_{pb}}}{\partial \alpha_p} < 0,\ \forall \alpha \in [\alpha_L, \alpha_H] \text{ or } \pi_{1_{pb}}(\alpha_L) > \pi_{1_{pb}}(\alpha_{2_p}) \\ \alpha_{2_p}, & \text{otherwise,} \end{cases} \tag{15}$$

$$\pi_{1_{pb}} = \int_{\alpha_L}^{\alpha_p} 2(p - c_a) f(\tilde{\alpha}) d\tilde{\alpha} + \int_{\alpha_p}^{\alpha_H} 2\left(p - \mu + \frac{(\mu\alpha_{c_p})^2}{4\beta}\right) f(\tilde{\alpha}) d\tilde{\alpha},$$

and α_{2_p} *is the larger real root (if any) to* $\frac{\partial \pi_{1_{pb}}}{\partial \alpha_p} = 0$. *We have* $\alpha_L \le \alpha_p^* \le \frac{2}{3}\alpha_H$. *If* $\alpha < \alpha_p^*$, *the supplier rejects the offer and sets* $I^*(\alpha) = 0$. *Otherwise, he accepts* w_1^* *and sets* $I^*(\alpha) = I^{e^*}(\alpha)$, *where* $I^{e^*}(\alpha)$ *is defined in (1).*

Similar to the baseline scenario (Section 3.1), the supplier accepts the buyer's price when his realized EE effectiveness parameter is sufficiently high (i.e. $\alpha \ge \alpha_p^*$). In this case, the supplier chooses the most cost-effective investment level $I^{e^*}(\alpha)$ that maximizes his total information rent (from privately knowing α) across *both* periods, unlike in the baseline scenario where he can only earn information rent in period 1.

It follows that the supplier's optimal total profit from period 1 onward for a given α is

$$\psi_{1_{pb}}^*(w^*, \alpha) = \begin{cases} 0, & \text{if } \alpha < \alpha_p^* \\ \frac{\mu^2(\alpha^2 - \alpha_p^{*2})}{2\beta}, & \text{otherwise.} \end{cases}$$

His associated profit across the planning horizon is then given by $\psi_{0_{pb}} = -A + \int_{\alpha_p^*}^{\alpha_H} \frac{\mu^2(\tilde{\alpha}^2 - \alpha_p^{*2})}{2\beta} f(\tilde{\alpha}) d\tilde{\alpha}$.

Now considering the case where the supplier does not perform an EE assessment, the EE investment is then zero by definition and it is easy to show that the buyer offers $w^* = \mu$ which is accepted by the supplier. In this case, the supplier's expected profit across the planning horizon is zero. The following proposition summarizes the supplier's optimal assessment decision.

PROPOSITION 3. *Under PC and no other instruments, the supplier performs an EE assessment iff the assessment cost* $A \le A^{S_p}(c_a) = \int_{\alpha_p^*}^{\alpha_H} \frac{\mu^2(\tilde{\alpha}^2 - \alpha_p^{*2})}{2\beta} f(\tilde{\alpha}) d\tilde{\alpha}$, *where* $A^{S_p}(c_a)$ *increases in* c_a.

The supplier's and the buyer's optimal profits are respectively given by

$$\psi_{0_{pb}}^* = \left(-A + \int_{\alpha_p^*}^{\alpha_H} \frac{\mu^2(\tilde{\alpha}^2 - \alpha_p^{*2})}{2\beta} f(\tilde{\alpha}) d\tilde{\alpha}\right)^+ = (A^{S_p}(c_a) - A)^+, \tag{16}$$

$$\pi^*_{0_{pb}} = \begin{cases} 2p - \left[\int_{\alpha_L}^{\alpha_p^*} 2c_a f(\tilde{\alpha})d\tilde{\alpha} + \int_{\alpha_p^*}^{\alpha_H} \left[2\mu - \frac{(\mu\alpha_s^*)^2}{2\beta}\right] f(\tilde{\alpha})d\tilde{\alpha}\right], & \text{if } A \leq A^{S_p}(c_a); \\ 2p - 2\mu, & \text{otherwise} \end{cases} \tag{17}$$

The EE gap in this scenario, $\Delta^{S_p}(\alpha)$, is eliminated when the investment is enabled (i.e., when $A \leq A^{S_p}(c_a)$ and $\alpha \geq \alpha_p^*$), as we formalize below.

$$\Delta^{S_p}(\alpha) = \begin{cases} 0, & \text{if } A \leq A^{S_p}(c_a) \text{ and } \alpha \geq \alpha_p^* \\ \Delta^0(\alpha), & \text{otherwise.} \end{cases}$$

PC helps completely close the EE gap when $A \leq \min(A^S(c_a), A^{S_p}(c_a))$ and $\alpha \geq \max(\alpha_s^*, \alpha_p^*)$, but does not improve the EE gap when $A \geq \max(A^S(c_a), A^{S_p}(c_a))$ and $\alpha \leq \min(\alpha_s^*, \alpha_p^*)$. It is, however, difficult to delineate the impact of PC when $\min(A^S(c_a), A^{S_p}(c_a)) < A \leq \max(A^S(c_a), A^{S_p}(c_a))$ and $\min(\alpha_s^*, \alpha_p^*) \leq \alpha < \max(\alpha_s^*, \alpha_p^*)$ since there are no closed-form solutions for α_s^* and α_p^*. To facilitate the comparison between $A^S(c_a)$ and $A^{S_p}(c_a)$ (as well as between α_s^* and α_p^*) so that a full understanding of PC's impact can be developed, we make a technical assumption on the range of the alternate supplier's cost c_a and resort to numerical study in Section 6 for the general case. We begin by defining the following assumption

Assumption 1. $c_a \geq c_{a_L} = \mu + \frac{(\mu\alpha_H)^2}{12\beta}$,

which implies that the alternate supplier is relatively expensive, making the focal supplier's EE investment sufficiently attractive for the buyer. Applying this assumption allows us to develop closed form expressions for α_s^* and α_p^* and derive the order between $A^S(c_a)$ and $A^{S_p}(c_a)$ as follows.

Corollary 1. *Under Assumption 1,* $\alpha_s^* = \alpha_p^* = \alpha_L$. *It follows that* $A^S(c_a) = A^S = \int_{\alpha_L}^{\alpha_H} \frac{\mu^2(\tilde{\alpha}^2 - \alpha_L{}^2)}{8\beta} f(\tilde{\alpha})d\tilde{\alpha}$, $A^{S_p}(c_a) = A^{S_p} = \int_{\alpha_L}^{\alpha_H} \frac{\mu^2(\tilde{\alpha}^2 - \alpha_L{}^2)}{2\beta} f(\tilde{\alpha})d\tilde{\alpha}$ *and* $A^S < A^{S_p}$.

When the alternate supplier is sufficiently expensive, the buyer's optimal EE effectiveness threshold is α_L irrespective of whether PC is used. This threshold implies that the supplier will always accept the contract in period 1 under all realization of α. Here, PC empowers the supplier to retain information rent in both periods and earn a higher profit over the long run. This implies two beneficial impacts of PC. First, it allows the supplier to afford the assessment over a wider range of costs, i.e., $A^{S_p} > A^S$. Second, it encourages the supplier to increase his investment and completely close the EE gap when an assessment is performed. We next investigate the impact of the buyer's joint use of AA and PC.

3.4. Joint Impact of Assessment Assistance and Procurement Commitment

Similar to Lemma 2, Lemma 4 characterizes the firms' optimal decisions when the buyer offers both AA and PC.

Lemma 4. *Under PC, the buyer optimally offers the price schedule* $w^*(\alpha) = \mu - \frac{(\mu\alpha)^2}{4\beta} + \frac{\psi^*_{0_{pb}}}{2}$ *(where* $\psi^*_{0_{pb}}$ *is defined in (16)) together with AA, which the supplier accepts. The supplier then sets* $I^*(\alpha) = I^{e^*}(\alpha)$*, where* $I^{e^*}(\alpha)$ *is defined in (1).*

It follows from Lemma 4 that the buyer's expected profit across the planning horizon in this case is given by

$$\pi_{0_p} = 2p - \left[2\mu - \int_{\alpha_L}^{\alpha_H} \frac{\mu^2\tilde{\alpha}^2}{2\beta} f(\tilde{\alpha})d\tilde{\alpha}\right] - A - \psi^*_{0_{pb}}. \tag{18}$$

Without AA, the buyer's profit depends on the supplier's decision to self-conduct the assessment and is given by (17). Comparing (17) and (18) yields the following proposition.

PROPOSITION 4. *Under PC, the buyer offers AA iff the assessment cost* $A \le A^{B_p} = \int_{\alpha_L}^{\alpha_H} \frac{\mu^2\tilde{\alpha}^2}{2\beta} f(\tilde{\alpha})d\tilde{\alpha}$, *where* $A^{B_p} > A^{B_a}(c_a)$ *and* $A^{B_p} > A^{S_p}(c_a)$, *where* $A^{B_a}(c_a)$ *and* $A^{S_p}(c_a)$ *are respectively defined in Propositions 2 and 3.*

The EE gap in this case is

$$\Delta^{B_p}(\alpha) = \begin{cases} 0, & \text{if } A \le A^{B_p}; \\ \Delta^0(\alpha), & \text{otherwise.} \end{cases}$$

Similar to our results in Proposition 2 when there is no PC, the buyer's AA also widens the range of affordable assessment costs when offered together with PC, i.e., $A^{B_p} > A^{S_p}(c_a)$. Furthermore, PC induces the supplier to increase his investments as discussed in the previous section. The resulting higher EE cost savings also benefit the buyer, making AA more attractive to her, i.e., $A^{B_p} > A^{B_a}(c_a)$. These results highlight the complementarity of AA and PC in that together they help 1) extend the range of affordable assessment costs to identify potential EE improvements and 2) fully capitalize these opportunities, i.e., the channel's optimal EE investment level is achieved and the EE gap is eliminated. It follows from Propositions 3 and 4 that the buyer's optimal expected profit in period 0 under PC is given by

$$\pi^*_{0_p} = \begin{cases} \pi^a_{0_p} = 2p - \left[2\mu - \int_{\alpha_L}^{\alpha_H} \frac{(\mu\alpha)^2}{2\beta} f(\tilde{\alpha})d\tilde{\alpha}\right] - A^{S_p}(c_a), & \text{if } A \le A^{S_p}(c_a) \\ \pi^b_{0_p} = 2p - \left[2\mu - \int_{\alpha_L}^{\alpha_H} \frac{(\mu\alpha)^2}{2\beta} f(\tilde{\alpha})d\tilde{\alpha}\right] - A, & \text{if } A^{S_p}(c_a) < A \le A^{B_p}(c_a) \\ \pi^c_{0_p} = 2p - 2\mu, & \text{if } A^{B_p}(c_a) < A. \end{cases} \tag{19}$$

3.5. The Buyer's Choice of EE Instruments

Our results so far outline how buyer-offered instruments can help reduce/eliminate the EE gap. In addition, Propositions 2 and 4 show when it is optimal for the buyer to offer AA under a short- (without PC) and a long-term contract (with PC), respectively. We now analyze when the buyer should offer PC to maximize her own profit. Let $d = \pi^*_0 - \pi^*_{0_p}$ denote the difference in the buyer's expected profit without and with PC, where π^*_0 and $\pi^*_{0_p}$ are respectively given in (14) and (19). When $d > 0$, it is optimal for the buyer to use a short-term contract (no PC); otherwise, PC is optimal.

Recall that π_0^* and $\pi_{0_p}^*$ depend on the order of the assessment cost A with respect to both the buyer's respective assessment thresholds ($A^{B_a}(c_a)$ and A^{B_p}) and the supplier's self-assessment thresholds ($A^S(c_a)$ and $A^{S_p}(c_a)$). Since closed-form solutions for α_s^* and α_p^* are necessary for the comparison between $A^S(c_a)$ and $A^{S_p}(c_a)$, we develop our insights under Assumption 1 and discuss in Section 6 the results when the assumption is not satisfied . As follows from Corollary 1, $A^S(c_a)$ and $A^{S_p}(c_a)$ do not depend on c_a under Assumption 1 and so we skip their arguments (c_a) in our subsequent discussion. Note that $A^S < A^{B_a}(c_a) < A^{B_p}$ and $A^{S_p} < A^{B_p}$, as follows from Propositions 2 and 4. However, the ordering between $A^{B_a}(c_a)$ and A^{S_p} is not consistent and so we consider two cases as illustrated in Figure 2, which summarizes the expressions of π_0^* and $\pi_{0_p}^*$ in regions of A defined by the four aforementioned thresholds.

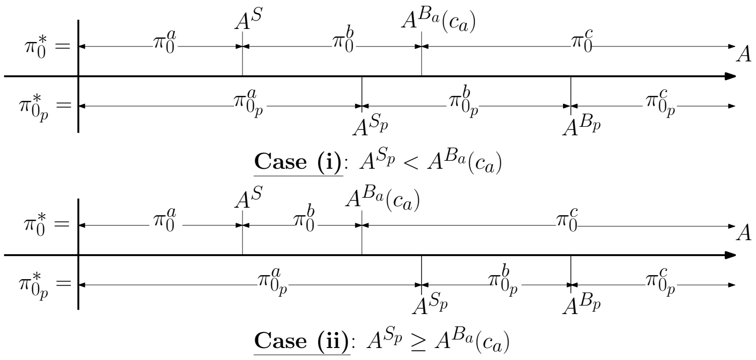


Figure 2 **Summary of π_0^* and $\pi_{0_p}^*$ expressions in regions of A**

The expression of d can then be characterized as follows

$$d = \begin{cases} d^1 = \pi_0^a - \pi_{0_p}^a, & \text{if } A \leq A^S \\ d^2 = \pi_0^b - \pi_{0_p}^a, & \text{if } A^S < A \leq \min(A^{B_a}(c_a), A^{S_p}) \\ d^3 = \begin{cases} d^{3_i} = \pi_0^b - \pi_{0_p}^b, & \text{if } A^{S_p} < A^{B_a}(c_a) \\ d^{3_{ii}} = \pi_0^c - \pi_{0_p}^{B_a}, & \text{otherwise.} \end{cases}, & \text{if } \min(A^{B_a}(c_a), A^{S_p}) < A \leq \max(A^{B_a}(c_a), A^{S_p}) \\ d^4 = \pi_0^c - \pi_{0_p}^b, & \text{if } \max(A^{B_a}(c_a), A^{S_p}) < A \leq A^{B_p} \\ d^5 = \pi_0^c - \pi_{0_p}^c, & \text{if } A^{B_p} < A, \end{cases}$$

Note that d^{3_i} and $d^{3_{ii}}$ correspond to Case (i) and (ii) in Figure 2, respectively. Since the buyer's expected profit in each of these cases depends on the alternate supplier's cost c_a, each d^j ($j = 1, 2, 3_i, 3_{ii}, 4, 5$) is also a function of c_a. It is easy to show that d^j ($j = 1, 2, 3_i, 3_{ii}, 4$) is strictly decreasing in c_a and, for each d^j, there exists a unique c_a^j such that $d^j > 0$ for $\underline{c}_a \leq c_a < c_a^j$ and $d^j \leq 0$ for $c_a^j \leq c_a \leq p$. It is also straightforward to show that $d^5 \geq 0$, $\forall c_a$. Proposition 5 uses these relationships to characterize the buyer's optimal choice of instruments.

Proposition 5. *Under Assumption 1, the buyer offers*
- *PC and AA iff $A \leq A^{B^*}(c_a)$ and $c_a \geq c_a^B(A)$;*
- *Only AA iff $A \leq A^{B^*}(c_a)$ and $c_a < c_a^B(A)$;*

– *No instruments, otherwise.*

The AA threshold $A^{B^*}(c_a)$ and the PC threshold $c_a^B(A)$ are given by

$$A^{B^*}(c_a) = \begin{cases} A^{B_a}(c_a), & \text{if } c_a < c_a^3 = \max(c_a^{3_i}, c_a^{3_{ii}}); \\ A^{B_p} + \mu - \mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde{c}_2|c_1], c_a\right), & \text{otherwise.} \end{cases} \tag{20}$$

$$c_a^B(A) = \begin{cases} c_a^1, & \text{if } A \le A^S, \\ c_a^2(A), & \text{if } A^S < A \le \min\left(A^{B_a}(c_a^3), A^{S_p}\right), \\ c_a^3, & \text{if } \min\left(A^{B_a}(c_a^3), A^{S_p}\right) < A \le \max\left(A^{B_a}(c_a^3), A^{S_p}\right); \end{cases} \tag{21}$$

where $A^{B^*}(c_a)$ increases in c_a and $c_a^B(A)$ decreases in A.

A higher cost of the alternate supplier increases the buyer's incentive to offer AA and gain from the focal supplier's EE investment (i.e., $A^{B^*}(c_a)$ increases in c_a). When the buyer offers AA, a higher assessment cost A increases the buyer's incentive to use PC (i.e., $c_a^B(A)$ decreases in A). To explain this interesting dynamic, recall that the buyer's total costs of offering AA are $A + \psi_{0_b}^* = \max(A, A^S)$ without PC and $A + \psi_{0_{pb}}^* = \max(A, A^{S_p})$ with PC.[8] Since $A^S < A^{S_p}$ (as follows from Corollary 1), a higher A reduces the difference in these costs and thus makes PC more attractive to the buyer.

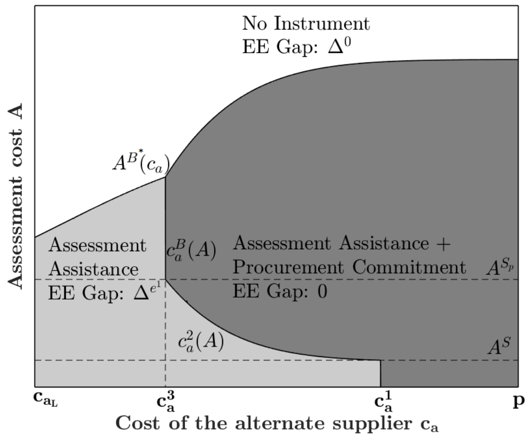


Figure 3 The buyer's optimal choice of EE instruments and the corresponding EE gap in Case (i)

Figure 3 illustrates the results of Proposition 5 when $\max(c_a^{3_i}, c_a^{3_{ii}}) = c_a^{3_i}$, which corresponds to Case (i) in Figure 2. Case (ii) has a similar structure and so we skip its discussion. For high assessment costs (i.e., $A > A^{B^*}(c_a)$), the buyer does not offer AA, resulting in no EE investment since it is also not attractive for the supplier to self-perform the assessment. In this case, the buyer prefers a short-term contract to retain the switching flexibility. When the assessment cost is sufficiently low (i.e., $A \le A^{B^*}(c_a)$), the buyer offers AA and evaluates the tradeoff between the switching flexibility provided by a short-term contract and the potentially higher EE cost savings offered by a long-term

[8] The transformations follow from the definitions of A^S in (9) and A^{S_p} in (16)

contract. When the alternate supplier is sufficiently expensive (i.e., $c_a \geq c_a^B(A)$), the buyer offers PC which complements her AA to help the supplier eliminate the EE gap. When the alternate supplier is cheap (i.e., $c_a < c_a^B(A)$), the buyer offers AA but not PC, leading to the EE gap being reduced, but not eliminated.

4. Impact of Third-party Assessment Assistance

In this section, we address our second research question by investigating how the addition of free third-party assistance affects the dynamics between the buyer and the supplier, and whether this further reduces the EE gap. In the presence of third-party assistance, the supplier can *always* request for a *free* assessment and retain α as his private knowledge in period 1. This implies that the supplier's reservation profits without and with PC are respectively given by $\psi^*_{0_{b3}} = A^S(c_a)$ and $\psi^*_{0_{pb3}} = A^{S_p}(c_a)$, which are strictly higher than their corresponding counterparts given in (9) and (16) when third-party support is not available. Applying these changes to the previous analyses allows us to characterize the buyer's optimal decision to offer AA without and with PC as follows.

Proposition 6. *In the presence of third-party assistance, the buyer offers her own AA without PC (with PC) iff* $A \leq A^{B_a}_{3p}(c_a)$ $\left(A \leq A^{B_p}_{3p}(c_a)\right)$. *The thresholds* $A^{B_a}_{3p}(c_a)$ *and* $A^{B_p}_{3p}(c_a)$ *are given by*

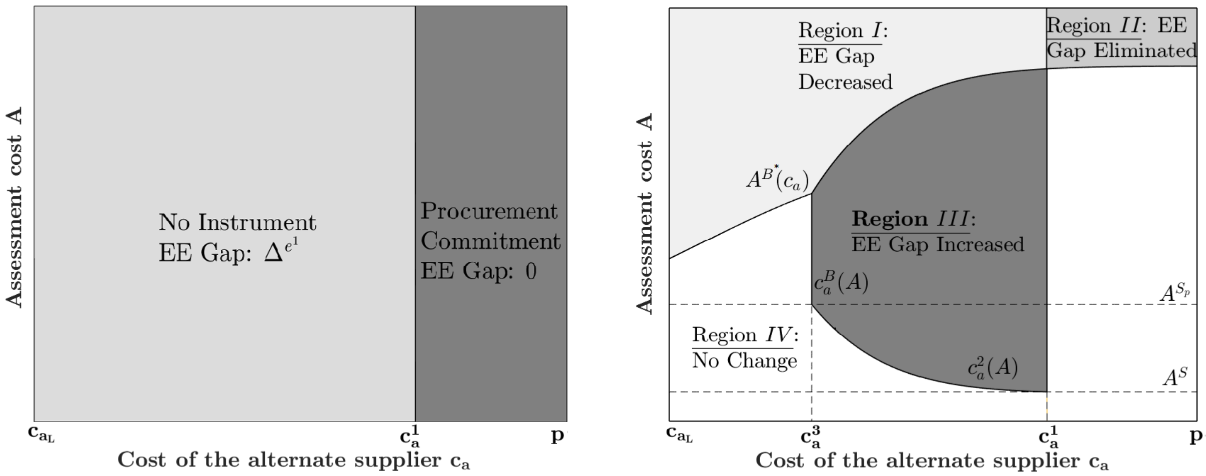
$$A^{B_a}_{3p}(c_a) = \int_{\alpha_L}^{\alpha_s^*} \left[2c_a - \mu - \mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde{c}_2|c_1]\left(1 - \frac{\mu\tilde{\alpha}^2}{4\beta}\right), c_a\right) + \frac{(\mu\tilde{\alpha})^2}{8\beta}\right] f(\tilde{\alpha})d\tilde{\alpha},$$

$$A^{B_p}_{3p}(c_a) = \int_{\alpha_L}^{\alpha_p^*} \left[2(c_a - \mu) + \frac{(\mu\tilde{\alpha})^2}{2\beta}\right] f(\tilde{\alpha})d\tilde{\alpha},$$

where α_s^* *and* α_p^* *are respectively characterized in Lemmas 1 and 3.*

Proposition 6 suggests that even in the presence of third-party assistance, it can be advantageous for the buyer to offer her own AA when the assessment cost A is sufficiently low. This is because AA still allows the buyer to earn the EE cost savings under *all* realization of α, unlike under third-party assistance when EE cost savings are enabled only with sufficiently high α. Also, since the supplier requires higher reservation profits in this case, $A^{B_a}_{3p}(c_a)$ and $A^{B_p}_{3p}(c_a)$ are strictly lower than their corresponding counterparts $A^{B_a}(c_a)$ and A^{B_p} when third-party assistance is not available.

We again characterize the buyer's optimal choice of instrument(s) under Assumption 1 since closed-form solutions for α_s^* and α_p^* are not available. Recall that under Assumption 1, $\alpha_s^* = \alpha_p^* = \alpha_L$ and it follows that $A^{B_a}_{3p}(c_a) = A^{B_p}_{3p}(c_a) = 0$, $\forall c_a \in [c_{a_L}, p]$, implying that the buyer never offers her own AA. Proposition 7 summarizes this intuition and characterizes the buyer's instrument selection in the presence of third-party assistance.



(a) **The buyer's optimal choice of EE instruments** (b) **Comparison of the EE gap**

Figure 4 Impact of third-party assistance on the buyer's optimal choice of EE instruments and the EE gap

PROPOSITION 7. *Under Assumption 1 and in the presence of third-party assistance, the buyer never offers AA and offers PC iff* $c_a \geq c_a^T = c_a^1$.

Figures 4a and 4b, respectively, illustrate the buyer's EE instrument selection and the change in the EE gap when third-party assistance becomes available. For $A > A^{B^*}(c_a)$, an assessment is conducted only when third-party support is available and so the buyer can enjoy the higher EE benefit resulting from PC without having to support the assessment herself. It follows that the buyer may offer only PC in this range of A when the alternate supplier is sufficiently expensive (i.e., $c_a \geq c_a^T = c_a^1$), which was not the case without third-party support. Consequently, the addition of third-party assistance, not surprisingly, helps reduce the EE gap in region I of Figure 4b and even eliminate it when c_a is sufficiently high in region II. For $A \leq A^{B^*}(c_a)$, the buyer originally offered AA without third-party support but no longer does so when this option becomes available. Without the complementary effect of her own AA, the buyer is less inclined to offer PC in this range of A, i.e., $c_a^T = c_a^1 \geq c_a^B$. As such, in region III of Figure 4b where the cost of the alternate supplier is moderate (i.e., $c_a^B(A) \leq c_a < c_a^T$), the addition of third-party assistance interestingly results in a *higher* EE gap. In Region IV, adding third-party AA does not affect the EE gap since it does not change the buyer's PC decision. Proposition 8 formalizes these insights on the impact of third-party assessment assistance.

PROPOSITION 8. *Under Assumption 1, the availability of third-party assessment assistance will*
– *decrease the EE gap when* $A > A^{B^*}(c_a)$,
– *increase the EE gap when* $A \leq A^{B^*}(c_a)$ *and* $c_a^B(A) \leq c_a < c_a^T$,
– *does not change the EE gap, otherwise.*

5. Impact of Energy Market Characteristics

We now address our third research question by examining how energy market conditions (characterized by the expected energy cost μ, volatility σ and cross-period correlation ρ) influence the buyer's optimal strategy and the subsequent EE gap. To that end, we focus on how an increase in each of the parameters ρ, σ and μ affects the buyer's assessment and procurement thresholds, i.e., $A^{B^*}(c_a)$ and $c_a^B(A)$ as defined in Proposition 5 (under Assumption 1), starting with σ and ρ.

PROPOSITION 9. *Under Assumption 1, an increase in either energy price volatility (σ) or cross-period correlation (ρ) will decrease the buyer's assessment threshold $A^{B^*}(c_a)$ and increase the PC threshold $c_a^B(A)$.*

From the buyer's perspective, a higher σ or ρ decreases the expected cost savings from EE in period 2 and thus increases the relative value of the alternate supplier. This reduces her incentive to offer both instruments, i.e., $A^{B^*}(c_a)$ decreases and $c_a^B(A)$ increases. These results imply that when an increase in ρ or σ does not lead to a change in the buyer's strategy (i.e., when A and c_a are sufficiently far away from their respective thresholds), the EE gap is unaffected. This occurs because the supplier approaches the EE investment decision as if the buyer always switches to the alternate supplier in period 2 (without PC) or always stays (with PC). However, at the boundary where the buyer changes her optimal strategy in response to an increase in ρ or σ, the EE gap will increase. We next characterize the impact of the expected energy cost μ in the following proposition.

PROPOSITION 10. *Under Assumption 1, an increase in expected energy cost μ will decrease $A^{B^*}(c_a)$ for $c_a < \min(c_a^3, \hat{c}_a^{B_a})$ and for $c_a^B \leq c_a < \max(c_a^3, \hat{c}_a^{B_p})$ but increase it, otherwise, where $\hat{c}_a^{B_a}$ and $\hat{c}_a^{B_p}$ are either from the set $\{c_{a_L}, p\}$ or the respective unique solution to $\frac{\partial A^{B_a}(\hat{c}_a^{B_a})}{\partial \mu} = 0$ and $\frac{\partial \left[A^{B_p} + \mu - \mathbb{E}_1 \min\left(\mathbb{E}_2[\tilde{c}_2|c_1], \hat{c}_a^{B_p} \right) \right]}{\partial \mu} = 0$.*

On one hand, a higher μ increases the cost of the focal supplier and decreases the buyer's incentive to offer AA. On the other hand, increasing μ enhances the cost saving benefits of the supplier's EE investment, making AA more attractive. When the alternate supplier is relatively cheap (i.e., $c_a \leq \hat{c}_a^{B_a}$ without PC or $c_a \leq \hat{c}_a^{B_p}$ with PC), the detrimental impact of increasing μ dominates, and the buyer's assessment threshold $A^{B^*}(c_a)$ decreases. As $A^{B^*}(c_a)$ decreases in μ, the buyer may flip from offering to not offering AA for a given A. Such a flip leads to a decrease in the supplier's EE investment. On the other hand, when $A^{B^*}(c_a)$ increases due to an increase in μ (i.e., when $\min(c_a^3, \hat{c}_a^{B_a}) \leq c_a < c_a^B$ or $c_a \geq \max(c_a^3, \hat{c}_a^{B_p})$), the supplier's EE investment may increase at the boundary region where the buyer changes her decision from not offering to offering AA. The impact of increasing μ on the buyer's PC threshold c_a^B is, however, analytically difficult to derive, and so we resort to numerical study in the next section to develop insights.

6. Computational Insights

Our goals in this section are to (i) investigate how our results would be affected when Assumption 1 is not satisfied, (ii) develop insights into the impact of μ on the PC thresholds c_a where analytical results are not possible, and (iii) understand the joint impact of buyer-offered and third-party instruments in realistic settings. To this end, we conducted a numerical study using data from the U.S. Department of Energy (DoE) and the Industrial Assessment Centers (IAC) Database.

6.1. Data and Model Calibration

The IAC is a program funded by the U.S. Department of Energy that provides free industrial assessments at manufacturers' request to identify opportunities to improve productivity, reduce waste, and save energy. We used data from the IAC database for years $1981-2015$ to calibrate our model parameters. To focus on SMMs, we excluded firms with more than 500 employees or sales revenues exceeding US$50 millions, as well as firms in non-manufacturing industries. Following previous empirical research using the IAC database (Anderson and Newell 2004, Muthulingam et al. 2013), we considered energy management projects with payback periods between 0.025 and 9 years. For each manufacturer, we scaled the payback periods and implementation costs to compute the total estimated investments across two periods for all eligible recommended projects. Since we are interested in capital intensive EE investments that are technology and equipment based (which typically have costs in the tens of thousands), we excluded firms with less than $\$50,000$ and more than $\$500,000$ in total cost of investment opportunities. The average annual energy cost of the sample is $\$653,226$, and so we set the benchmark value at $\hat{\mu}=\$6.5\times10^5$ and consider $\mu\in[\$4\times10^5,\$9\times10^5]$, covering roughly 50% of the sample. The average possible energy savings is roughly 13%, corresponding to the average α value of 0.00045 with the benchmark $\hat{\mu}=\$6.5\times10^5$. Consequently, we set $\alpha_H=0.0006$ and $\alpha_L=0.0003$. The industrial energy audit cost may be up to \$0.55 per square foot.[9] Since the average plant area of manufacturers in the sample is $132,411$ square feet, this translates into an assessment cost as high as $\$66,000$ for an average-sized supplier.

We used average annual industrial prices (normalized to 2014 dollars) for natural gas (from 1997 to 2014) and electricity (from 1991 to 2014) across states from the DoE to estimate σ and ρ. For each price distribution, we calculated the coefficient of variation ($cv=\frac{\sigma}{\mu}$), resulting in a range from 5% to 35%. Since we assume a Normal distribution for energy price, we excluded values of cv higher than 30% to ensure no negative realizations and chose the average $cv=20\%$ as our benchmark. This, combined with our benchmark $\hat{\mu}=\$6.5\times10^5$, translated into a benchmark value $\hat{\sigma}=\$1.625\times10^5$. The Ljung-Box Q-test for 1-period lag autocorrelation yielded significant correlation coefficients ranging

[9] http://www.edge-gogreen.com/audits-ratings/commercial-energy-audits/%20commercial-energy-audit-pricing/ (accessed August 21, 2017)

from 0.59 to 0.95 with a mean of 0.75, which is used for our benchmark (i.e., $\hat{\rho} = 0.75$). We considered c_a in the range $[\$6.5 \times 10^5, \$10.125 \times 10^5]$ (i.e., from 100% of the benchmark $\hat{\mu} = \$6.5 \times 10^5$ to 112.5% of the highest μ value $\$9 \times 10^5$), consistent with the comparison of global production costs.[10] We then set the benchmark $\hat{c}_a = \$7.3125 \times 10^5$ (112.5% of the benchmark $\hat{\mu} = \$6.5 \times 10^5$). Finally, we fixed $\beta = 1/2$ and $p = \$20 \times 10^5$. Table 2 summarizes our numerical calibration.

Parameter	Definition	Benchmark	Range	Increment
μ	Supplier's expected energy cost per period	$\hat{\mu} = \$6.5 \times 10^5$	$[\$4, \$9] \times 10^5$	$\$50,000$
σ	Energy cost volatility	$\hat{\sigma} = 20\%$ of $\hat{\mu}$	$[5\%, 30\%]$ of μ	2.5% of μ
ρ	Cross-period energy price correlation	$\hat{\rho} = 0.75$	$[0.59, 0.95]$	0.045
c_a	Cost of the alternate supplier	$\hat{c}_a = \$7.3125 \times 10^5$	$[\$6.5, \$10.125] \times 10^5$	$\$16,250$
p	Buyer's selling price	$\$20 \times 10^5$	N/A	N/A
A	Assessment cost	N/A	up to $\$6.6 \times 10^4$	N/A
(α_L, α_H)	Supports for distribution of EE assessment result	$(2, 5) \times 10^{-4}$	N/A	N/A

Table 2 Parameter Settings.

6.2. Results and Insights

For each μ value considered in Table 2, we investigated our results when Assumption 1 is *not* satisfied, i.e., when $\mu \le c_a \le c_{a_L}$. We observed in all the investigated instances that $\alpha_s^* = \alpha_p^* = \alpha_L$, implying that the analytical results developed in Propositions 5, 7, 9 and 10 continue to apply even when Assumption 1 is not met. This observation suggests that in realistic settings, EE cost savings are substantially high and so the buyer optimally offers a sufficiently high price to ensure the supplier's acceptance under all α realization.

Turning now to the impact of increasing μ on $c_a^B(A)$, Table 3 summarizes how c_a^1 and c_a^3 change when μ increases. For brevity, we report results for six values of μ in the range listed in Table 2 with $\$100,000$ increment. The second row of Table 3 shows that, $c_a^1 = p$ for all values of μ, implying that in the considered instances, the buyer does not offer any instrument when third-party support is available. Also, while c_a^3 increases in μ, its *relative* value with respect to μ $\left(\text{i.e., } \frac{c_a^3}{\mu}\right)$ decreases. Since $c_a^2(A)$ depends on A, we do not report its values for brevity. We did, however, observe that for any given value of A, c_a^2 behaves in a similar fashion as c_a^3 when μ increases.

Threshold	$\mu = \$4 \times 10^5$	$\mu = \$5 \times 10^5$	$\mu = \$6 \times 10^5$	$\mu = \$7 \times 10^5$	$\mu = \$8 \times 10^5$	$\mu = \$9 \times 10^5$
c_a^1	$\$20 \times 10^5 (= p)$	$\$20 \times 10^5 (= p)$	$\$20 \times 10^5 (= p)$	$\$20 \times 10^5 (= p)$	$\$20 \times 10^5 (= p)$	$\$20 \times 10^5 (= p)$
c_a^3	$\$4.7 \times 10^5$ 117.7% of μ	$\$5.4 \times 10^5$ 107.9% of μ	$\$6.2 \times 10^5$ 102.1% of μ	$\mu = \$7 \times 10^5$ 100% of μ	$\mu = \$8 \times 10^5$ 100% of μ	$\mu = \$9 \times 10^5$ 100% of μ

Table 3 Impact of increasing μ on the buyer's PC thresholds

[10] http://goo.gl/gG8QYm (accessed August 21, 2017)

We now turn to the quantification of our theoretical results, focusing on whether the addition of third-party AA decreases or increases the EE gap, i.e., which region in Figure 4b is more likely to be active. To that end, we focus on the comparison between the parameters in each instance and the boundaries of the regions in Figure 4b, defined by the threshold values $A^{B^*}(c_a)$, c_a^1 and c_a^3 (as well as $c_a^2(A)$, which depends on A and so, we only discuss its value when needed for clarity). Table 4 shows these threshold values when all parameters are at their corresponding benchmark values and when one parameter among ρ, σ and μ varies within the ranges listed in Table 2. For comparison purpose, we also report the supplier's assessment threshold in the baseline scenario (i.e., $A^S(c_a)$). When studying the effect of increasing μ, we used a different value $\check{c}_a = \$10.125 \times 10^5$ instead of the benchmark $\hat{c}_a = \$7.3125 \times 10^5$ to ensure that $\check{c}_a$ is higher than all the μ values in the considered range.

	Benchmark Parameters	$\boldsymbol{\rho : 0.59 \to 0.95}$ ($\hat{c}_a = 7.3125 \times 10^5$)	$\boldsymbol{\sigma(\% \text{ of } \mu) : 5 \to 30}$ ($\hat{c}_a = 7.3125 \times 10^5$)	$\boldsymbol{\mu : \$4 \to \$9 (\times 10^5)}$ ($\check{c}_a = 10.125 \times 10^5$)
$A^S(c_a)$	$\$22,181$	$\$22,181$	$\$22,181$	$\$8,400 \to \$42,525$
$A^{B^*}(c_a)$	$\$77,678$	$\$83,025 \to \$69,787$	$\$88,722 \to \$62,486$	$\$33,600 \to \$164,090$
c_a^1	$\$20 \times 10^5 (= p)$	$\$20 \times 10^5 (= p)$	$\$20 \times 10^5 (= p)$	$\$20 \times 10^5 (= p)$
c_a^3	$\$6.51 \times 10^5$ 100.2% of μ	$\$6.5 \to \$6.66 \times 10^5$ $100 \to 102.5$(% of μ)	$\$6.5 \to \$6.91 \times 10^5$ $100 \to 106.3$(% of μ)	$\$4.70 \to \$9 \times 10^5$ $117.7 \to 100$(% of μ)

Table 4 Impact of Energy Market Parameters on the Buyer's Threshold Levels

Starting with the results reported in the second left column of Table 4 when all parameters are at their benchmark values, we see that in the baseline scenario with no external instruments, the supplier performs an EE assessment only when $A \leq A^S(c_a) = \$22,181$. Since the typical assessment cost A may be up to $\$66,000$, there is a wide range of A from $\$22,181$ to $\$66,000$ where the assessment would not be self-funded by the supplier, leading to an average loss of $\$88,725$ (100% of investment potential) in EE investments. Even if the supplier does perform the assessment, there is still an average investment loss of $\$66,544$ (or 75% of potential). Once the possibility of buyer-offered instruments is introduced, an assessment will be performed (with the buyer's assistance) as long as $A \leq A^{B^*}(c_a) = \$77,678$, which captures the entire range of typical assessment costs.

Note that the benchmark $\hat{c}_a = \$7.3125 \times 10^5$ is between $c_a^1 = \$20 \times 10^5 (= p)$ and $c_a^3 = \$6.51 \times 10^5$. It follows from Proposition 5 that the buyer offers PC only when this benchmark cost $\hat{c}_a$ is higher than the threshold $c_2(A)$, which decreases in A. We observed that at $A = \$32,300$, the threshold $c_2(A) = \hat{c}_a = \$7.3125 \times 10^5$. This implies that when $A \geq \$32,300$, $\hat{c}_a \geq c_2(A)$ and the buyer offers both PC and AA, helping completely close the EE gap. For $A^S = \$22,181 < A < \$32,300$, $\hat{c}_a < c_2(A)$ and the buyer offers only AA which enables EE investments that the supplier would not otherwise undertake on his own. This helps reduce but not eliminate the EE gap.

We also find that when all parameters are at their benchmark values, adding third-party AA does not help to improve the EE gap (i.e., Regions III or IV of Figure 4b are always active). In particular, for $A \geq \$32,300$, the addition of third party AA makes the buyer flip from using to not using PC (i.e., Region III of Figure 4b is active), resulting in an average loss of \$66,544 (75% of potential). For $A < \$32,300$, the addition of third party AA does not help reduce the EE gap (i.e., Region IV of Figure 4b is active). The potentially harmful effect of third-party AA is consistently observed throughout the remaining instances when one parameter among ρ, σ and μ varies within the ranges listed in Table 2 (results reported in the three rightmost columns in Table 4). In all instances, $c_a^1 = p$, suggesting that the buyer offers no instruments when third-party assistance is available (Region II of Figure 4b is never active). We find in 98.4% of instances that the $A^{B^*}(c_a)$ threshold value lies above the highest assessment cost \$66,000, implying that third party support may help reduce the EE gap (Region I of Figure 4b is active) in only 1.6% of instances. Surprisingly, the availability of third-party assistance is harmful to the supplier's EE investment (i.e., Region III is active) in more than 50% of instances, leading to an average loss of 75% of the supplier's potential investment compared to when only buyer-offered instruments are available.

7. Concluding Remarks

To the best of our knowledge, this is the first study to examine how buyer and third-party offered instruments interact to influence a supplier's EE investment decisions and potentially reduce the EE gap. We find that buyer-offered AA and PC complement each other in extending the ranges of affordable assessment costs to identify profitable EE improvements and fully capitalizing these opportunities (i.e., eliminating the EE gap). However, it is beneficial for the buyer to offer *both* instruments only when the assessment is sufficiently cheap and the alternate supplier is sufficiently expensive. When both the assessment and the alternate supplier are sufficiently cheap, the buyer offers only AA which reduces, but does not eliminate, the EE gap. These results suggest that there is not a "one-size fits all" approach for a buyer to assist its suppliers in improving EE. It is more beneficial, from both the buyer's and the EE gap reduction perspectives, to tailor strategies by supplier characteristics, including cost competitiveness, EE assessment cost and effectiveness of EE investments. This is in line with Wal-mart's new focus on *"encouraging improvement in our most strategic factories across the business,"* which began from 2016.[11]

Our results also suggest that it is the most effective for the EE gap reduction when AA and PC are both offered by the buyer. This is because of their complementary relationship that balances the give-and-take of power in the supply chain and induces the supplier to increase his EE investment level and eliminate the EE gap. Furthermore, it would be more beneficial for third-party organizations

[11] http://goo.gl/zVZPhr (accessed August 21, 2017)

to provide indirect assessment subsidies through large buyers instead of the more common practice of providing free assessments directly to suppliers. The Environmental Defense Fund's recent collaboration with Wal-mart to provide EE assessments at the retailer's suppliers is one early example of such an initiative (Plambeck and Denend 2011).

Before closing, it is important to reflect on how the assumptions used in our models influenced the results in order to assess the generalizability of our insights to different settings as well as to other types of supplier improvements with similar characteristics as EE investments (i.e., require an initial assessment and one-shot up front investment, followed by long-term periodic rewards). Our assumption that the buyer updates the supplier's *full* EE information, including the exact value of α and the committed investment level I in period 2, is applicable in scenarios where suppliers are willing to response to buyers' requests to share environmental information. For example, when suppliers are located in countries with greenhouse gas regulations or when buyers are committed to sustainability (Jira and Toffel 2013). However there may be situations where such information is not shared with the buyer. As we explain in Online Appendix B.2, it is difficult to analytically characterize or numerically evaluate the firms' optimal strategies in equilibrium in this situation. Nevertheless, we conjecture that our key insight on the potential *detrimental* impact of third-party AA would remain. This is because the information asymmetry between the buyer and supplier in period 1, the main driver of the result, still exists (and in fact may even gets worse) when the buyer does not fully update the supplier's EE information in period 2.

Our assumption that investment options I follow a continuum is consistent with the EE investment literature (e.g., Ryan 2015). This allows for a continuous cost savings function for the EE investment, facilitating our analysis. In actual applications, EE improvement opportunities often consist of a discrete (rather than continuous) set of investment levels, which could be represented by a piece-wise linear cost savings function. Incorporating such a function would remove the possibility of closed-form expressions but directional results could still be substantiated through numerical analysis. For example, the supplier's optimal investment would no longer be uniquely characterized. However, it is easy to show that EE projects could be ordered so that it is optimal for the supplier to invest up to the last project before the marginal benefit decreases. Since our results are driven by the costs of the alternate supplier and the EE assessment, we expect our directional insights (i.e., the impact of the interaction between buyer and third-party offered instruments on the supplier's EE investment decision) would continue to hold under this more complex saving function.

Our assumption that the supplier makes a single investment decision at the beginning of the time horizon is reasonable for suppliers who have to seek external loans. However, it is less applicable to suppliers who may have access to internal funding for EE investments. In that case, real option valuation techniques could be integrated into our model to investigate how the supplier makes cumulative investment decisions across time periods. Our assumption that the buyer's AA only covers the assessment cost is made from a conservative view of the buyer's assistance in the sense that buyers could also leverage their sizes and connections with third-party contractors to reduce EE equipment costs for suppliers (Wal-mart's Written Testimony 2007). The lower EE equipment costs imply that the supplier can get more savings for the same amount of investment, i.e., buyer-offered AA increases the effectiveness parameter α. This further highlights the importance of buyer-offered AA and could aggravate the potentially detrimental impact of third-party support.

Finally, while we assume that the supplier will undertake EE investments that are financially profitable, several issues may prevent such profit maximizing behavior in practice. These include required investment hurdle rates (Ross 1986, Knittel et al. 2014), competition for budgets with other investment opportunities (Ross 1986, McLean-Conner 2009), and possible behavioral biases (DeCanio 1993, Knittel et al. 2014). We also do not consider other potential costs of EE improvements, including disruptions in production processes and learning costs. Buyer-offered incentives, including those examined in this paper, as well as other possible policies, may be able to counteract some of these issues and costs to elevate EE as an investment priority. It would be interesting to further test the impact of these incentives drawing from empirical data and/or behavioral experiments.

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