Incentive Effects of Environmental Adders in Auctions for Electric Power

James B. Bushnell and Shmuel S. Oren

January 4, 1994

Abstract

We show that adders mess up things

1 Introduction

Public Utility Commissions in several states have adopted the philosophy of 'least cost planning' for the meeting of electricity needs in their states. The philosophy is to examine all possible aspects of planning - supply and demand side - in a combined and comprehensive manner in order to achieve globally optimal resource plans. Importantly, 'least cost' is meant to incorporate all costs, including the social costs of environmental degradation and the costs associated with the lack of a diverse fuel base. While few argue that the philosophy of least cost planning is an admirable one, there has been considerable contention over its implementation.

One aspect of least cost planning that has been a large source of controversy is the incorporation of environmental factors into the planning process for electric generation supply. Several states have included environmental 'adders' - a concept that will be explained below - in both the supply planning procedures of individual utilities and the competitive procedures used to acquire non-utility generation (NUG). Competitive procedures for acquiring generation capacity include contracts offered under the Public Utilities Regulatory Policies Act and NUG auctions. There has been some interesting recent discussion about when and if to include adders in competitive procedures for acquiring new generation. These studies examine whether adders should be used and if they are, what an adder should be.

Beyond these fundamental questions however, there has been little analysis of what to do with adders once the decision to use them is made. In this article, we make a detailed examination of the mechanisms used to incorporate environmental considerations into the generation acquisition process. As we shall discuss below, environmental adders may be implemented in several different ways which could have dramatically different impacts on both the selection and operation of generation sources. We will systematically examine these various implementation methods and outline their effects on NUG and utility incentives. Some of these resultant incentives appear to be contrary to the policies of the institutions implementing them. While the context of our discussion of environmental adders is auctions for power supply, we believe the insights gained from examining the interactions of adders with auctions can be extended to other areas of utility planning such as DSM evaluation.

There are two questions we wish to address in our analysis of adders and auctions. How can adders be implemented in a way that insures that the winners of the auction will be, at least theoretically, the socially least cost suppliers? Further, will an electric system partially supplied through competitive auctions be operated in an efficient manner with respect to economic as well as environmental considerations.

2 Environmental Adders

The environmental adder was developed to serve as a tax (or subsidy) that would theoretically internalize the external environmental costs of electric generation. When used in the planning process, an environmental cost value is added onto the monetary costs of generation, and system expansion plans are optimized using this 'social cost' value.

The use of adders has been a controversial subject. One of the primary objections to adders has been that the actual marginal damages of emissions are not well understood or easily quantified. Even given the assumption that the marginal damages of emissions can be estimated, there has been a debate over whether the marginal damages should be used as the value for the adder. Much of the controversy arises over the effects of potentially overlapping or even contradictory regulations. Joskow [7] expresses great skepticism over the use of adders. He argues that an adder approach will cover some pollutants that are already controlled through other regulation, such as command and control and, in the case of SO_2, a system of tradable permits. Joskow also objects to the piecemeal coverage that will result from proposed adder systems - covering some but not all pollutants and of course covering only some of the polluters, the electric utilities.

Freeman, et. al. [4] agree that the marginal damage of a pollutant is not necessarily the correct adder value, but maintain that a correct number can be derived when all the relevant regulations are taken into consideration. Hobbs [6] comes to a similar conclusion when considering the interaction of adders with a system of tradable emissions permits, although he argues that the high level of rational coordination that would be required of state regulators is unlikely to occur. A key to calculating adder values in both of the previous two articles is the fact that marginal damages of pollutants will differ with the location of the emission, while the costs imposed by other regulations (such as permits) will not. Adders provide a tool for correcting this gap between costs and damages.

It is important to remember that the adder, by definition, is a per unit ($/kwh) cost. this is in recognition that the damages done by a generation facility will depend upon the level of operation of that facility. However, as we discuss below, this property causes other incentive problems when implemented in a PURPA auction setting.

3 NUG Auctions with Environmental Considerations

In this section, we present a model of an auction for NUG generation in order to analyze the incentive effects of environmental adders. The model is based upon that of Bushnell and Oren [2]. In this auction model, bidders are characterized by three attributes, fixed cost, energy cost, and emissions. The fixed and variable costs of a resource are the private information of the bidder and are influenced by such factors as fuel type, design, and the efficiency of construction and maintenance. All types of emissions are condensed into a single emission attribute. The emissions level (lbs./kwh) of a potential resource is assumed to be observable and public knowledge. A bidder is therefore unable to 'lie' about the amount of emissions his proposed resource might produce.

3.1 Bidder Attributes

We assume bidders are endowed with their three defining attributes, and that these attributes are drawn from a subspace of $\Re^3$. These three attributes are

$k_i \in \Gamma$	Fixed cost of bidder i
$c_i \in \Lambda$	energy cost of bidder i
$e_i \in \Sigma$	Emissions level (lbs/kwh) of bidder i

From their private knowledge of their attributes, bidders formulate a fixed a variable price bid, using a vector valued bidding function B, taken from strategy space β. B maps from (k, c, e) into a two dimensional bid, (b_k, b_c). The range of allowable bids is assumed bounded in the intervals $[0, K]$ and $[0, C]$ respectively.

$$B : \Gamma \times \Lambda \times \Sigma \Rightarrow [0, K] \times [0, C]$$

and

$$(b_k, b_c) \quad = \quad B(k, c, e)$$

3.2 Auction Characteristics

The purchasing utility evaluates the bids on the basis of the fixed and variable prices and, depending on local policies, the bid's environmental characteristics as well. Using a scoring function $S(b_k, b_c, e)$, purchasing utilities map each vector valued bid into a scalar ranking. We assume that S is at least once differentiable in all of its parameters.

$$S : [0, K] \times [0, C] \times E \Rightarrow \Re_+$$

If environmental attributes are not to be considered in the selection process, $S(.,.)$ is a function of b_k and b_c only. Without loss of generality, we assume that the lowest scores are the most desirable to the purchasing utility. Utilities would therefore select projects in increasing order of score until their capacity need is filled.

We assume that the bidding NUGs are required to be dispatchable. In other words, the utility operates the NUGs on the basis of those NUGs' energy prices. The purchasing utility estimates the hours of operation of a NUG having energy price b_c with the function $\rho(b_c)$, which will be derived from the cost projections of the utilities own system. The use of a marginal cost duration curve (figure 1), which plots the number of hours in a year in which a utility's system marginal cost will be at or above a given cost level, is common a method for estimating $\rho(b_c)$. We assume that $\rho(b_c)$ is once differentiable and monotonically decreasing in b_c. $\rho(b_c)$ is published by the utility before the auction and is therefore considered public knowledge. We further assume that the utility system is large enough that $\rho(b_c)$ will be unaffected by the costs of the winning bidders.

INSERT FIGURE 1 HERE

Bidders are assumed to formulate subjective probabilities which we represent in the most general form with the probability function $P(.,.,.)$. $P(S(b_k, b_c, e))$ is a bidder's subjective probability of being a winner in the auction with a bid of $\{b_k, b_c\}$ and with environmental value e. For economy of notation, we assume that bidder attributes are independent between bidders, allowing subjective probability to be a function of *score alone*. These results extend to cases where bidder characteristics are probabilistically linked (see Bushnell and Oren, 1994) so the independence assumption is made only to simplify notation.

One of our objectives for this analysis is to determine the efficiency of an electric system that is assembled in part through auctions such as these. A concern for efficiency is whether the dispatch order implemented by the utility is the same as the one that would have resulted if the utility had built all the generation itself. When the purchasing utility is paying the NUGs their bid prices, the utility, unless commanded not to, will operate those NUGs as if they were units in the utility's system possessing energy costs equal to their bid prices. It is therefore necessary for the efficient operation of the NUGs that those NUGs bid an energy price equal to their true energy costs. Truthful revelation of energy costs has been the focus of regulatory and academic examination [9] [1] [2]. Here, we examine whether environmental adders in auctions can be compatible with truthful revelation of energy costs, and therefore with efficient system operations.

4 Environmental Adders in NUG Auctions

Using the framework we have outlined above, we now examine the options for implementing environmental considerations into the auction process. Environmental considerations can influence an auction in three ways.

1. Through 'shadow' values to be used in the scoring of bids.
2. Through actual monetary payments/penalties given to winning bidders.
3. Through the operation of the NUGs with respect to the purchasing utility's system.

From a policy standpoint, any or all of these influences may be employed through the policies and auction formats adopted by purchasing utilities and their respective Utility Commissions. There are two primary issues at stake when environmental considerations are introduced into the auction process, the implications on the efficient operation of the resulting electric system and the socially efficient selection of new generation. Coinciding with the goals of the rest of this document, we will focus on the operational efficiency issues. It is impossible to completely ignore some of the selection issues, however, as they overlap with operational issues. We therefore will be using arguments that examine the making of rational choices for new generation with regards to the environment.

4.1 Environmental Adders Used in Scoring

As mentioned above, there are two ways in which environmental 'shadow' adders can be brought into an auction system, for use in the selection of the winners of the auction (i.e. the scoring of bids), and for use in the operation of resources that are successful in winning contracts. At first glance use of adders for both selection and operational purposes seems to be optimal. However, as Joskow [7] points out, the adders are only being applied to new sources of generation. A relatively clean new resource with a modest adder could potentially leapfrog in the dispatch order a very clean existing resource with no adder. When the current configuration of electric systems are considered, it therefore seems desirable not to include environmental factors in the operational decisions of NUGs.

One option that remains is to employ an adder, that is an incremental environmental bonus/penalty whose value depends on the rate of pollution, only in the scoring of the potential projects. This was the approach adopted by Consolidated Edison of New York [3]. We now examine the implications of such an approach on bidder's strategies for selecting a fixed and variable price bid.

Under this approach, environmental factors do not directly influence the payments made to winning bidders. The expected profits of bidder i in a first-price auction of this form would therefore be

$$E(\pi_i(b_k, b_c)) = [b_k - k_i + \rho(b_c)(b_c - c_i)]\, P(S(b_k, b_c, e)) \tag{1}$$

Where $P(S(.,.))$ is bidder i's subjective probability of being a winner given his bid produces score S. To analyze bidder incentives in this auction, we derive a necessary condition for the existence of an equilibrium bid strategy that includes truthful revelation of energy costs. The necessary condition is that the marginal rates of substitution between fixed and variable prices in the scoring function equal the marginal rates of substitution between those prices in the profits made by winning bidders when the energy price bid is set equal to true energy cost.

Proposition 1 *Consider a first price auction as defined above where environmental factors are used in the scoring of bids. A necessary condition for the existence of a Bayes-Nash equilibrium consisting of bidder strategies that include bidding true energy costs is*

$$\frac{\partial S(b_k, b_c, e)/\partial b_c}{\partial S(b_k, b_c, e)/\partial b_k} = \rho(b_c) \quad \textit{at } b_c = c_i \quad \textit{for all } c_i. \tag{2}$$

A proof of Proposition (1) is provided in the appendix. This result limits considerably the form that the scoring of environmental factors can take in the function $S(.,.,.)$. Since e_i

does not appear on the right hand side of (2), e_i can only appear in $\frac{\partial S}{\partial b_c}$ and $\frac{\partial S}{\partial b_k}$ in an identical multiplicitave fashion, or not at all, if truth telling of variable costs is to be a feasible bidder strategy. From this observation, we can further conclude that any environmental scoring that uses energy price in it's calculation must also use the fixed price.

Corollary 1 *If the contribution to total score of emissions is invariant to fixed price, i.e.* $\frac{\partial S^2}{\partial e \partial b_k}=0$*, then the contribution to total score of emissions must also be invariant to energy price,* $\frac{\partial S^2}{\partial e \partial b_c} = 0$*, if truthful bidding of energy costs is to be a feasible strategy. In an auction in which NUGs are curtailable, this means that the emission component of total score must also be unaffected by operating hours (kwh).*

Proof: From (2) we have $\frac{\partial S}{\partial b_c} = \frac{\partial S}{\partial b_k}\rho(b_c)$. Differentiating both sides of this equality with respect to e yields the result.□

This result implies that environmental factors must either be evaluated independently of both bid prices or in conjunction with both prices. We argue, however, that from a common sense standpoint fixed price should have no effect on the environmental contribution to score. Two bids with the same level of total emissions but different fixed prices should not produce different environmental scores. If they did, a scenario involving a dirtier NUG with a low fixed price displacing a cleaner NUG with a higher fixed price solely on the basis of the *fixed prices* contribution to the environmental score could arise. Since the fixed price is simply a transfer payment with no implications for operation or emissions, such a result would clearly violate rational standards of selection. Unfortunately the alternative, evaluating the environment independent of hours of operation is also clearly not rational since such an approach would implicitly ignore the total amount of pollution produced by the competing projects.

4.2 Environmental Adders to Payments

Another means by which the adder concept can be incorporated into electric power auctions is to actually pay an adder value to successful bidders for each hour in which those bidders operate. We denote the adder value as $a(e_i)$. The CPUC's policy is to reward NUGs who have cleaner emissions rates than the unit the utility would have built had there not been an auction. Therefore $a(e_i)$ can be positive or negative, depending on how the NUG's emissions compare with this standard. $a(e_i)$ is always decreasing in e_i.

One problem with this approach is that it makes the cleaner units (those who would receive the largest adders) look the least attractive to the central dispatcher. With this incentive problem in mind, California regulators have required that the hours of operation of an independent generator must depend only on the energy price bid and on no other factors [5]. In other words, dispatchers are required to ignore the adder portion of the utility's payment when making operational decisions about independent generators. While there can be no direct consideration of adders during the dispatch process, we will argue that there may be indirect effects of the adders on dispatch due to the strategic bidding behavior of the NUGs. This indirect effect is the opposite of the one that the CPUC was concerned with, but still should be recognized as a potential difficulty.

Proposition 2 *Consider an electric power auction in which environmental adder payments, $a(e_i)$, are made to successful bidders on a \$/kwh basis. Adders do not directly affect the operation or selection of successful projects. Under such a policy, a bid strategy involving the truthful bidding of energy costs cannot be a Bayes-Nash equilibrium one.*

Proof: The expected profits of bidder i in a first price auction of the form described above would be

$$E(\pi(b_k, b_c, k_i, c_i, e_i)) = (b_k - k_i + \rho(b_c)(b_c + a(e_i) - c_i))\, P(S(b_k, b_c)) \tag{3}$$

for a strategy $\{b_k, b_c\}$ with $b_c = c_i$ to be an equilibrium one, first order conditions for a maximum of (3) must be met. Those first order conditions are

$$\begin{aligned} \frac{\partial E(\pi_i)}{\partial b_k} &= P(S(b_k, b_c)) - (b_k - k_i + \rho(b_c)(b_c + a(e_i) - c_i))\, \frac{\partial P}{\partial S}\frac{\partial S}{\partial b_k} = 0 && (4) \\ &\text{and} \\ \frac{\partial E(\pi_i)}{\partial b_c} &= (\rho(b_c) + \rho'(b_c)(b_c + a(e_i) - c_i))\, P(S(b_k, b_c)) && (5) \\ &\quad - (b_k - k_i + \rho(b_c)(b_c + a(e_i) - c_i))\, \frac{\partial P}{\partial S}\frac{\partial S}{\partial b_c} = 0 \end{aligned}$$

at $b_c = c_i$. Rearranging (4) and (5) and setting $b_c = c_i$ yields

$$\frac{\partial S/\partial b_c}{\partial S/\partial b_k} = \rho(b_c) + \rho(b_c)a(e_i) \quad \text{at } b_c = c_i \quad \text{for all } c_i. \tag{6}$$

(6) implies that environmental factors must be used in the scoring function S if a strategy involving bidding $b_c = c$ is to be feasible. However, the policy being examined does not allow any consideration of the environment in the scoring of bids. Therefore strategies involving the truthful bidding of energy costs cannot be equilibrium ones under this policy.□

Proposition 2 shows that, even though it may be determined that adders should not affect scoring or operation, they in fact will in at least an indirect way. To further examine how adder payments will indirectly influence scoring and operations, we now look at a second-price auction framework such as was adopted in California.

The policy for the California second-price auction is to pay bidders their actual variable bid price and a fixed price that, when combined with the winning bid's variable price, yields a score equal to that of the lowest losing bid. Let K_{sp} denote the fixed price payment made to a winning bidder, then

$$K_{sp} = S^{-1}(s; b_c) = \{k | S(k, b_c) = s\}$$

where s is the total score of the lowest losing bidder.

Proposition 3 *Consider a second-price auction such as the one defined above where environmental adder payments will be made to successful bidders on a per kwh basis, but not directly considered in the selection or operation of successful bidders. Then*

i. The bid strategy that consists of stating true costs cannot be an equilibrium one

and

ii. If the scoring of the bids on the basis of price alone, $S(b_k, b_c)$ is evaluated according to the net surplus scoring function

$$S(b_k, b_c) = b_k + \int_0^{b_c} \rho(c)dc \tag{7}$$

then the strategy of bidding $b_k = k$ and $b_c = c - a(e)$ is a dominant strategy.

A proof of Proposition 3 appears in the appendix. The net surplus scoring function (7) takes the area under the marginal cost duration curve and the energy price and adds that area to the fixed price to yield a net cost calculation. It has been shown [2] that the family of scoring functions that are monotonic transformations of (7) are unique for meeting the necessary conditions for truth telling of energy costs to be a feasible bid strategy in the absence of adders.

Proposition 3 therefore implies that if a scoring system is designed to elicit truth revealing bids when costs alone are considered, the payment of environmental adders to successful bidders will destroy the possibility of bidders following a truth revealing strategy. In fact, there exists an equilibrium where bidders state a variable price equal to their true energy cost *minus their adder*. Thus cleaner resources would appear to the utility to have lower energy costs than they really have. Those clean resources would therefore run relatively more than dirtier ones. This appears to be a positive outcome for the environment until one considers that this de-facto environmental dispatch would only be applied to units added as a result of auctions and not to the utilities' own units.

4.3 Remaining Options for Incorporating Environmental Considerations

The results of the previous two sections show that, besides the more fundamental arguments against adders, they have yet to be incorporated into NUG auctions in a way that satisfactorily agrees with the underlying theory of auctions and environmental economics. We therefore examine some remaining options for improved implementation of environmental adders into the NUG auction process.

Incorporating Adders into Dispatch Decisions

A potential solution to the incentive problems presented by environmental adders is to allow utilities to act in their own self interest and dispatch NUGs on the basis of the total (energy + adder) costs seen by the utility. If utilities' dispatch according to energy price plus the adder and NUGs bid their energy cost minus the adder, then operating hours would be based on energy cost alone. This option has the added attraction of eliminating the sticky problem of enforcing the policy of not using adder payments in the dispatch process. It is very possible that an enterprising utility could develop ways of 'cheating' in its dispatch process (in favor of non-adder generation) without being detected.

Our objection to this policy stems from its reliance on bidders' not telling the truth about their energy costs. While this has been shown to be an equilibrium strategy in our auction model, real world intrusions make reliance on this result precarious. The introduction of uncertainty in both the prediction of operating hours and in fuel prices makes the 'liars equilibrium' quite uncertain. We believe the policy goal of auction designers should be to create efficient, risk free equilibria, rather to rely upon potentially complicated strategic behavior of bidders. Further, this policy seems to defeat the original purpose of favoring cleaner generators in some way. For these reasons, we feel this option is not practical.

Incorporating Adders into Score and Payments:

Another option is to combine the policies of sections 4.2 and 4.3. One way to describe the problems with those two policies is to argue that the marginal rates of substitution between fixed and variable prices have been changed in one component of the auction (scoring or payments) without being altered in the other. The obvious solution when one views the problem in this light is to alter both the scoring and the payments made to the winning bidders.

Corollary 2 *Consider a second-price auction such as described in section 4.3 with the addition that the environment will be considered in the scoring of bids. Winning bidders will receive a fixed payment* $K_{sp} = S^{-1}(s; b_c, e) = \{k|S(k, b_c, e) = s\}$. *Environmental adder payments are made to winning bidders for each hour of operation. Then the strategy of bidding* $\{b_k = k - \rho(b_c)a(e), b_c = c\}$ *is a dominant strategy if and only if the scoring function* $S(b_k, b_c, e)$ *meets the condition*

$$\frac{\partial S/\partial b_c}{\partial S/\partial b_k} = \rho(b_c) + \rho(b_c)'a(e) \tag{8}$$

A proof of Corollary 2, which follows from that of Proposition 3, is also provided in the appendix. This policy solves some problems while creating other somewhat strange results. The strategic adjustments due to the environmental adders is pushed into the fixed portion of the bid strategy, but not eliminated. Operations, with regards to energy price and environmental adders, can therefore proceed as when adders were not present in any form. The selection of winners, however, also occurs just as in the case when no adders are used since the $\rho(b_c)a(e)$ added to the total score is offset by the strategy to understate fixed costs by exactly the same amount.

The main problem with this approach is that it would be politically untenable. The NUGs with the largest adders are receiving the highest scores. Since adders are decreasing in e, this means that the cleanest generators are being punished the most in this scoring system. Theoretically this scoring bias against clean NUGs is canceled out by the fact that those NUGs will also understate their fixed cost by an amount exactly equal to the environmental penalty they receive. This policy therefore achieves the stated goal of California regulators that environmental adder payments not affect the scoring or operation of NUGs. That this end can only be achieved by penalizing clean generators in the scoring system exposes it as a questionable goal.

Environmental Dispatch:

In section 4.2, we concluded that, if the CPUC adopts the scoring system shown to be unique for inducing the truthful revelation of costs from bidders, it's policy of adder payments to winning bidders will indirectly result in the equivalent to environmental dispatch of NUGs. A primary problem with such a result is that it would apply only to NUGs added in auctions. One way around this problem is to operate existing units according to their combined energy and environmental costs, resulting in environmental dispatch for all units.

Although it has been shown to be very efficient for meeting some environmental goals [8], environmental, or 'social cost' dispatch has yet to be embraced by utilities or regulatory commissions. It seems that some form of operation with regards to the environment will eventually be adopted, but that development could be many years away.

Nevertheless, the results of this article demonstrate that it is impossible to rationally implement adders into the planning process alone. If adders are to be adopted as a key policy tool for the environmental regulation of electric systems, the fact that they implicitly affect operational decisions should be made explicit. This could best be achieved by committing to environmentally dispatching all units in the electric system, NUGs as well as existing generation. Incorporating adders into scoring and payments would no longer be necessary, since the environmental impact of new projects would be implicitly reflected in their hours of operation.

Further, by using a 'social marginal cost' duration curve, compiled by evaluating generation costs plus the respective adders, to evaluate projects, the benefits from displacing existing dirty generation can be incorporated into a bid's score. Let $\hat{\rho}$ be the functional expression of the social marginal cost duration curve (see figure 2), then the score of a bid would be its net social surplus

$$S^*(b_k, b_c, e) = b_k + \int_0^{b_c+e} \hat{\rho}(c)dc. \tag{9}$$

It can be verified that, if winning bidders are dispatched according to their social costs, $b_c + e$, bidding true costs will be a dominant strategy. The problem remains of how to induce utilities to dispatch according to social and not economic costs. This is an issue that must be resolved before environmental dispatch of any kind can be effectively implemented.

5 Conclusions

In this article, we have looked at some of the ways in which utilities are incorporating environmental considerations into electric power auctions. As we have shown, none of these methods sustain the possibility of an equilibrium in which bidders state their true energy costs in our model. By including any environmental considerations in both the scoring and the payments made to winners an equilibrium in which energy costs are truthfully revealed is possible, but the environmental bonus (or penalty) must be of the opposite sign in the score as it is in the payments made to winners. Thus in order to implement adders in such a way that they do not affect the scoring or operation of NUGs, environmental bonuses must be given in one component and then taken away in the other.

It therefore can be concluded that adders cannot be implemented in a rational way to affect only the planning process. They will either directly or indirectly, through the strategic behavior of NUGs, also affect the operations of the resulting electric system. If adders are to be used, regulators and utilities must therefore be comfortable enough with the adder approach to adopt it into their dispatch process as well as the planning or competitive acquisition process. Otherwise the economic rational for the use of adders breaks down.

6 Appendix

Proof of Proposition 1

The expected profits of a bidder i in a first price auction of the form described in Proposition 1 are

$$E(\pi(b_k, b_c, k_i, c_i, e_i)) = (b_k - k_i + \rho(b_c)(b_c - c_i))\, P(S(b_k, b_c, e_i)) \tag{10}$$

for a strategy $\{b_k, b_c\}$ with $b_c = c_i$ to be an equilibrium one, first order conditions for a maximum of (10) must be met. Those first order conditions are

$$\frac{\partial E(\pi_i)}{\partial b_k} = P(S(b_k, b_c)) - (b_k - k_i + \rho(b_c)(b_c - c_i))\,\frac{\partial P}{\partial S}\frac{\partial S}{\partial b_k} = 0 \tag{11}$$

and

$$\begin{aligned}\frac{\partial E(\pi_i)}{\partial b_c} &= (\rho(b_c) + \rho'(b_c)(b_c - c_i))\, P(S(b_k, b_c)) \\ &\quad - (b_k - k_i + \rho(b_c)(b_c - c_i))\,\frac{\partial P}{\partial S}\frac{\partial S}{\partial b_c} = 0\end{aligned} \tag{12}$$

at $b_c = c_i$. Rearranging (11) and (12) and setting $b_c = c_i$ yields

$$\frac{\partial S/\partial b_c}{\partial S/\partial b_k} = \rho(b_c) \quad \text{at } b_c = c_i \quad \text{for all } c_i. \tag{13}$$

□

In proving propositions 3 and 2, we make use of the following property of $S^{-1}(s; b_c)$ and $S^{-1}(s; b_c, e)$.

Lemma 1

$$\frac{\partial S^{-1}(s; b_c)}{\partial b_c} = - \left. \frac{\partial S(k, b_c)/\partial b_c}{\partial S(k, b_c)/\partial b_k} \right|_{k=S^{-1}(s;b_c)} \qquad \forall s, b_c \tag{14}$$

Proof: By definition $S(S^{-1}(s; b_c), b_c) = s$. Differentiating both sides of this equality with respect to b_c yields the result. The result and the proof of Lemma 1 are also exactly the same for $S^{-1}(s; b_c, e)$.□

Proof of Proposition 3:

For part i, we need to show that an arbitrary bidder i would never find it optimal to bid $b_c = c_i$ if there are no adders in the scoring function. For part ii, we need to show that bidding $\{b_k = k_i, b_c = c_i - a(e_i)\}$ will be a dominant strategy for bidder i if the scoring function is $S(b_k, b_c) = b_k + \int_0^{b_c} \rho(c)dc$. In other words, for any possible opponent strategy, the above strategy will maximize the expected profit of bidder i. Let the distribution $G(s)$ represent the probability that, given some arbitrary strategies adopted by i's opponents, the highest score amongst those opponents will be less than s. then, given this arbitrary combination of strategies by opponents, bidder i's expected profits are:

$$E(\pi_i(b_k, b_c)) \;=\; \int_{S(b_k,b_c)}^{\bar{S}} \left[S^{-1}(s; b_c) - k_i + \rho(b_c)(b_c + a(e_i) - c_i)\right] dG(s) \tag{15}$$

Clearly the bidder's payoff is unchanged by making the substitution $b_k = S - \int_0^{b_c} \rho(c)dc$ and transforming the bid space to $\{S, b_c\}$. This substitution transforms bidder i's payoffs to be

$$E(\pi_i(S_i, b_c)) = \int_{S_i}^{\bar{S}} \left[S^{-1}(s; b_c) - k_i + \rho(b_c)(b_c + a(e_i) - c_i)\right] dG(s) \tag{16}$$

Equation 16 can be optimized for b_c pointwise for all s. In other words, the optimal bid *b_c is independent of the net score, S_i, that is bid.* The first order condition for the pointwise optimization of (16) with respect to b_c is

$$\frac{\partial S^{-1}}{\partial b_c} + \rho(b_c) + \rho(b_c)'(b_c + a(e_i) - c_i) = 0 \tag{17}$$

Using Lemma 1, it is clear that this first order condition can be met at $b_c = c_i$ if and only if

$$\frac{\partial S/\partial b_c}{\partial S/\partial b_k} = \rho(b_c) + \rho'(b_c)a(e_i)$$

Since the auction format does not allow e_i in the scoring function, a strategy that includes bidding $b_c = c_i$ cannot be an equilibrium one.

For part ii, we examine the specific scoring function $S(b_k, b_c) = b_k + \int_0^{b_c} \rho(c)dc$. For this function, $S^{-1}(s; b_c) = s - \int_0^{b_c} \rho(c)dc$. Equation (17) then becomes

$$\rho(b_c)'(b_c + a(e_i) - c_i) = 0$$

The optimal variable price bid is therefore $b_c = c_i - a(e_i)$. Note that, since $\rho(b_c)$ is assumed monotone, this bid strategy is the only one that meets first order conditions in the feasible range [0,C], and that second order local conditions are also met at this point. It can easily be verified that the value of the function is lower at these bounds than at the point $b_c = c_i - a(e_i)$. Sufficiency conditions are therefore also met with this energy price bid.

To determine the optimal total score to be bid, we re-examine the expected profit function under the condition that $b_c = c_i - a(e_i)$.

$$\begin{aligned} E(\pi_i(S_i|b_c = c_i - a(e_i)) &= \int_{S_i}^{\bar{S}} \left[s - \int_0^{b_c} \rho(c)dc - k_i \right] dG(s) \\ &= \int_{S_i}^{S(k_i, c_i - a(e_i))} \left[s - \int_0^{b_c} \rho(c)dc - k_i \right] dG(s) \\ &+ \int_{S(k_i, c_i - a(e_i))}^{\bar{S}} \left[s - \int_0^{b_c} \rho(c)dc - k_i \right] dG(s) \end{aligned} \tag{18}$$

Since $S(k_i, c_i - a(e_i)) = k_i + \int_0^{c_i - a(e_i)} \rho(c)dc$, the first term on the right hand side of (19) is always negative and is maximized when $S_i = S(k_i, c_i - a(e_i))$. The second term is a constant value. Therefore expected profit is maximized at the score $S_i = S(k_i, c_i - a(e_i))$ and variable bid $b_c = c_i - a(e_i)$. Thus the optimal fixed price bid is k_i. This bid is optimal for all possible distributions of opposing scores and therefore for all possible opposing strategies. The bid

$\{b_k = k_i, b_c = c_i - a(e_i)\}$ is therefore a dominant strategy for bidder i.$\square$

Proof of Corollary 2

From the proof of part i of Proposition 3, we have that the bid $b_c = c_i$ is optimal against all possible opponents scores if and only if $\frac{\partial S/\partial b_c}{\partial S/\partial b_k} = \rho(b_c)+\rho'(b_c)a(e_i)$. Since Lemma 1 applies to $S^{-1}(s; b_c, e_i)$ as well, this resultis still true for this case. To determine the optimal total score to be bid, we re-examine the expected profit function under the condition that $b_c = c_i$.

$$
\begin{aligned}
E(\pi_i(S_i|b_c = c_i)) &= \int_{S_i}^{\bar{S}} \left[S^{-1}(s; c_i, e_i) + \rho(b_c)a(e_i) - k_i\right] dG(s) \\
&= \int_{S_i}^{S(k_i-\rho(b_c)a(e_i),c_i,e_i)} \left[S^{-1}(s; c_i, e_i) + \rho(b_c)a(e_i) - k_i\right] dG(s) \qquad (19) \\
&+ \int_{S(k_i-\rho(b_c)a(e_i),c_i,e_i)}^{\bar{S}} \left[S^{-1}(s; c_i, e_i) + \rho(b_c)a(e_i) - k_i\right] dG(s)
\end{aligned}
$$

By definition $S^{-1}\left(S(k_i - \rho(b_c)a(e_i), b_c, e_i); b_c, e_i\right) = k_i$ and $S^{-1}(S(\hat{k}, b_c, e_i); b_c, e_i) < k$ for all $\hat{k} < k$. The first term on the right hand side of (19) is therefore always negative and is maximized when $S_i = S(k_i, c_i, e_i)$, while the second term is a constant value. Therefore expected profit is maximized at the score $S_i = S(k_i - \rho(b_c)a(e_i), c_i, e_i)$ and variable bid $b_c = c_i$. Thus the optimal fixed price bid is $k_i - \rho(b_c)a(e_i)$. The bid $\{b_k = k_i - \rho(b_c)a(e_i), b_c = c_i\}$ is therefore a dominant strategy for bidder i.$\square$

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