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Short communication

A mechanism for the efficient provision of Potential Pareto public goods ☆

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ABSTRACT

Providing a public good that causes a local harm to its host poses two problems previously unexplored together: where to locate it and how large it should be. We propose a mechanism combining some market-like properties with a modified second-price auction. The mechanism selects a host, a facility size, a compensation for hosting the project, and determines how the compensation is split among the non-hosts. If each community bids truthfully for becoming the host–a strategy from which no community has incentives to deviate–the selected allocation is globally optimal, even if communities' preferences are private information. In contrast with the literature, the host *pays* the second-highest bid while receiving the market benefits to prevent distortions in the optimal size.

1. Introduction

A Potential Pareto Public Good (PPPG) creates an aggregate net benefit to society while harming some of the involved participants in the process (Dekel et al., 2017). Examples include waste treatment facilities (e.g., incinerators or disposals), prisons, and wind turbines (Meyerhoff et al., 2010; Zerrahn, 2017). The collective provision of a PPPG is convoluted and has two dimensions: where to build the project, what we call the *siting* problem; and how large the PPPG would be, what we call the *sizing* problem. Since larger projects may be more efficient but cause greater harm, making the compensation attractive to the host who can provide the most extensive public good is fundamental to reaching its Pareto potential.

The literature has separately tackled the siting and sizing problems. One strand has proposed mechanisms that select the host of the PPPG and grant a compensation that ensures voluntary participation (Minehart and Neeman, 2002; Sakai, 2012). They address a "not in my backyard"–NIMBY–or "locally unwanted land use"–LULU–situation, acronyms revealing the emphasis on the *siting* problem (Popper, 1983; Schively, 2007). The other strand, addressing the *sizing* problem, has focused on incentive-compatible mechanisms that guarantee the efficient provision of public goods, often with personalized taxes reflecting the intensity in the valuation of the public project (Chen, 2002; Van Essen and Walker, 2017).

We aim to solve together the siting and sizing problems by proposing a mechanism that simultaneously selects a "suitable" host for the PPPG and the optimal size embedded in a Lindahl allocation, defined as an efficient allocation with a set of prices reflecting a burden-sharing agreement (Buchholz and Peters, 2007). Embedding the two problems within our mechanism has three advantages derived from the relationship between project size and the required host's compensation. First, marginal costs and benefits become central in the normative analysis of PPPG provision. Thus, marginal changes in the size-dependent compensation are more informative about welfare considerations compared to analysis based on binary provision decisions. Second, the collective decision on project size alleviates the NIMBY's popular resistance because the mechanism embeds elements to curb project size. Third, an endogenous project size allows conceiving this problem in terms of optimally installed capacities, improving future planning and reducing the required facilities.

Solving the two problems together is non-trivial. If the host selection criteria combine suitability and public good size, mechanisms tackling the *siting* problem may lose their truthful revelation properties because potential hosts may distort their messages to avoid the local harm. Solutions in this direction select the host first and, in a further stage, the other communities determine the size-dependent

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compensation (Laurent-Lucchetti and Leroux, 2011). Nonetheless, such informational requirements are equivalent to knowing *ex ante* who the most suitable host is. On the other hand, mechanisms tackling the *sizing* problem may not induce voluntary participation if prices follow a Clarke tax rule (e.g., the Vickrey–Clarke–Groves mechanism). Prices based on the caused externality discourage potential hosts because removing their negative utility from the welfare computations would have yielded larger facilities.

In our mechanism, each community submits a four-dimensional message. Three components interplay in a market-like fashion: a desired size (or quantity) of the facility, a requested price per unit for being the host, and a paid price per unit for being a non-host community. The fourth component, a bid, allows communities to compete to become the host in a modified second-price auction. The market-like components generate Lindahl allocations in equilibrium: the efficient quantity is attained by charging each community a price proportional to its marginal benefit from this provision (called a Lindahl tax), granting that the total payments are enough to finance the public good. The host's Lindahl tax is negative and reflects the compensation, or earnings, from hosting the facility. If the sum of prices per unit of non-host communities is sufficient to cover the price requested by the host and the building cost per unit, the facility is implemented, and its size is defined by the geometric average of all the desired quantities. An equilibrium with project implementation implies that: (i) each community submits its Lindahl tax, and the total payment matches the total cost and compensation; (ii) the outcome quantity is *locally* optimal for each community.

The market-like part of the mechanism does not guarantee a globally optimal allocation because we can have as many Lindahl allocations as communities involved. Communities may be better off as the host, relative to being a non-host, due to the financial compensation in the former role. Moreover, host selection based on prices will create strategic incentives to overstate the willingness to host the facility. Communities interested in taking this role would compete à la Bertrand, and the winner would select a size above its optimal adjusted by a lower compensation per unit of the facility.

The auction-like component in our mechanism addresses the "role strategic uncertainty" (i.e., whether a community that benefits from being the host should behave like one) and induces the selection of the globally optimal Lindahl allocation. Each community announces a bid they are willing to pay to become the host. The highest bidder is selected and pays the second-highest bid. This payment acts as a selection device: a community that bears the lower cost of hosting the facility has, after receiving the Lindahl tax, the higher net benefit of being the host and, therefore, the highest willingness to pay for this role. As in standard second-price auctions, truthful bidding (given the other communities' strategies) leads to an efficient allocation even if each community's preferences remain private information: no community can profit by misreporting the gains from becoming the host.

The dual approach of our mechanism reveals that efficient sizing is a *local* property and efficient siting is a *global* property. Besides, our mechanism differs from the existing ones in two features. First, whereas former mechanisms conceive the transfer as a compensation (Kunreuther et al., 1987; O'Sullivan, 1993; Kleindorfer and Sertel, 1994; Minehart and Neeman, 2002), our auction-like component induces competition among communities to become the "seller" in the market-like component of our mechanism. Second, most previous mechanisms sacrifice efficient host selection to maintain budget balance. We took the opposite direction because the payment made by the host is only positive when there is some contestability for the hosting role. Hence, our auction-like component preserves budget balancedness as long as there is a single community willing to host.

Our model abstains from two aspects. First, unlike Waehrer (2003) and Ambec and Kervinio (2016), we do not consider spatial effects and implicitly assume that the facility's costs are encapsulated in the hosting community. Abandoning this assumption will increase the complexity of our mechanism because having more than two types (due to buyers' proximity) would increase the message's submitted prices. Second, we abstain from discussing the aggregation of preferences within a community. That is, we do not consider the individual incentives behind the delegation process of the community's decision.

2. A comparative analysis with existing mechanisms

The existing mechanisms cannot provide feasible solutions to the siting and sizing problems since they either hurt participation, have stringent informational requirements, or assume that the problem is purely reallocative.

Under voluntary participation, the VCG mechanism drives away the most desirable hosts because the selected host would *necessarily* pay a positive Clarke tax in equilibrium. That is, a price equal to the externality the host causes by limiting the size of the facility. Each community's externality is the welfare difference between the other communities under the most efficient allocation, with and without the excluded community's utility. Excluding the host's disutility would increase the desired facility size, a negative externality that raises her tax. Even if one could oblige participation, the tax revenue from the VCG could lead to a budget unbalancedness that may offset the facility's welfare generation. By contrast, our mechanism ensures Pareto optimality, does not harm participation, and yields a limited (potentially null) surplus on payments such that the disturbances to budget balancedness are minor.

In contrast with Perez-Castrillo and Wettstein (2002) and Laurent-Lucchetti and Leroux (2011), our framework allows preferences to be private knowledge. Pérez-Castrillo and Wettstein's mechanism is locally efficient, budget-balanced, and allows introducing spatial effects into the NIMBY problem. Still, it comes at the cost of assuming individual preferences to be common knowledge. In the mechanism proposed by Laurent-Lucchetti and Leroux, all the communities are *ex ante* aware of who the most efficient host is. This is a weaker informational requirement than in Pérez-Castrillo and Wettstein's, but determining the most efficient host is one of the most challenging problems our paper addresses.

Previous works imposing informational requirements similar to ours consider the private costs caused by the facilities as concave (Sakai, 2012; O'Sullivan, 1993; Minehart and Neeman, 2002). Under this cost structure, the socially optimal allocation is equivalent to a corner solution in a siting problem: building the largest possible facility in the least costly community. We instead focus on public goods causing *convex* private costs for hosts and *concave* benefits for non-hosts.

3. Framework

Let $N = \{1, 2, \ldots, n\}$ be a set of $n \geq 3$ communities, all involved in a one-time collective decision of providing a PPPG Z of variable size and a marginal financial cost c, assumed to be common knowledge. Communities are interested in the benefits of using a common facility that, given its noxious nature, yields benefits that are globally enjoyed by all the non-host communities and costs (aside from the building toll) locally borne by the host.

We introduce v_i to represent the facility size valuation for non-hosts and the host community. Let Q be the total size of the facility Z. We define $v_i(Q)$ as i's willingness to pay to enjoy, as a non-host, the benefits of Z. In addition, i's willingness to accept hosting this facility is $-v_i(-Q)$ (i.e., $v_i(-Q)$ is negative). For $i \in N$, we let $v_i : \mathbb{R} \rightarrow \mathbb{R}$ be a function respecting $v_i(0) = 0$, $v_i' > 0$, $v_i'' < 0$, $\lim_{x\to\infty} v_i(x) = \infty$, $\lim_{x\to-\infty} v_i'(x) = \infty$, and $\lim_{x\to\infty} v_i'(x) = 0$. The assumption $v_i' > 0$ for non-hosts captures the technological benefit engendered by Z. For example, if Z acts as a sink of waste if this device is an incinerator. A lower supply of waste means that the market price to dispose of waste is lower, so the economic disutility of the waste produced by each community (even the ones not using the facility) is now lower.

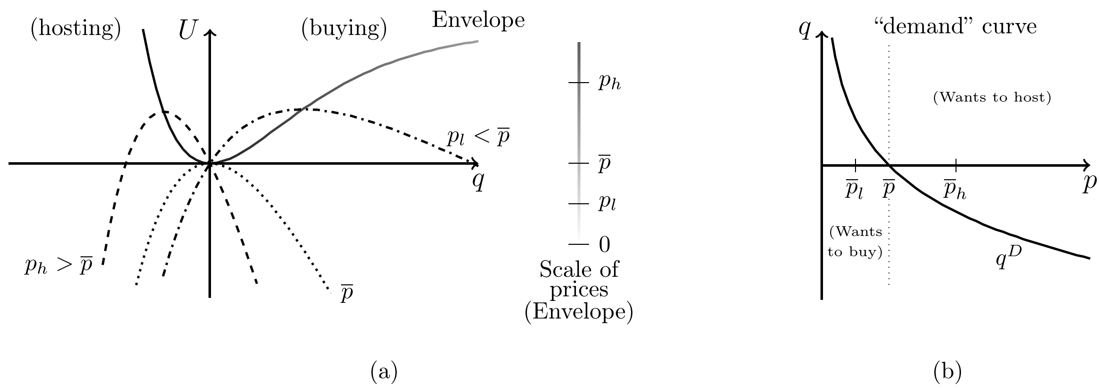

Fig. 1. The no-trade price is $\overline{p}$, and we have $p_l < \overline{p} < p_h$. (a) Utility level as a function of the size of Z for the three prices p_h, $\overline{p}$, and p_l. Each point of the Envelope curve represents the optimal quantity and the corresponding utility value for a given price. (b) The "demand" curve for Z, q^D. Notice that, after $\overline{p}$, there is a demand for negative quantities that translates into an acceptance to host.

This reasoning applies to every PPPG that is either a sink of bads or a source of goods (e.g., the electrical power generated by a nuclear power plant).

If the provision of Z for community i is q (which is negative if i is the host) and i receives a transfer T, then its utility, defined as $u_i(q,T)$, is given by $v_i(q)+T$. Note that building the facility in a community with low values of v_i' implies a low social cost. The v's from the communities are private information. We assume that there is an $i_s \in N$, who we call *suitable host*, such that for all x, $v_{i_s}'''(x) > 0$, $v_{i_s}'(x) = \min_i\{v_i'(x)\}$ and $v_{i_s}''(x) = \max_i\{v_i''(x)\}$. Intuitively, it is the least sensitive community to the externality generated by increasing the size of Z. Without loss of generality, we set $i_s = 1$, but no one (not even the suitable host itself) knows who community 1 is. The objective of our mechanism is to generate an equilibrium that selects the suitable host and indicates how large should be the facility built on this land.

3.1. Lindahl outcomes

Definition of Lindahl outcomes

We mirror the standard Lindahl efficiency properties from the provision of public goods in the context of PPPGs. Suppose that Z is offered to community i at a price p. In this case, i is interested in the provision of q units of Z, where q respects $v_i'(q) = p$. Whether community i prefers to be the host or a buyer depends on the relationship of the offered price p with respect to $\overline{p}_i := v_i'(0)$, which we call the *no-trade price* of community i. We have a null demand ($q = 0$) if $p = \overline{p}_i$; a demand for buying, with $q > 0$, if $p < \overline{p}_i$; and a demand for hosting, with $q < 0$, if $p > \overline{p}_i$. Note that, since community 1 is the suitable host, we have $\overline{p}_1 < \overline{p}_i$ for $i \in N \setminus \{1\}$. Fig. 1 illustrates these three cases. Notice from panel (a) that the utility is negative whenever the community is a buyer (resp. the host) under a price greater (resp. smaller) than $\overline{p}$. Panel (b) depicts the "demand" curve for Z, remarking a switch in the desired role of a community in $\overline{p}$.

For some $\boldsymbol{p} = (p_1, p_2, \dots, p_n)$, $Q > 0$, and $j \in N$, the triplet $(j, Q, \boldsymbol{p})$ is a *Lindahl outcome* if it respects three conditions:

(i) *(buyers' optimality)* for each $i \in N \setminus \{j\}$, i pays p_i per unit of Z, and Q is the optimal quantity for i under p_i;
(ii) *(host's optimality)* j receives p_j per unit of Z as a host and Q is the optimal hosted quantity for j under p_j;
(iii) *(price clearance)* the buyers' total payment matches the payment asked by the host plus the cost of implementation of Z. That is, $\sum_{i\neq j} p_i = p_j + c$.

Conditions for existence and multiplicity of Lindahl outcomes

We describe the conditions under which a Lindahl outcome $(j, Q, \boldsymbol{p})$ exists. Since Q is the optimal quantity for each community under $\boldsymbol{p}$, we have $v_i'(Q) = p_i$ for each $i \neq j$, and $v_j'(-Q) = p_j$. Applying these first-order conditions to the price clearance condition gives us

$$c = \sum_{i\neq j} v_i'(Q) - v_j'(-Q). \quad (1)$$

From standard analysis arguments, we can show that (1) has a unique solution in Q. When this solution is positive, it is straightforward to see that the three conditions of a Lindahl outcome are respected. This implies that community j is a potential host in a Lindahl outcome if, and only if, it belongs to the set

$$L_I := \Big\{k \in N \,|\, c < \sum_{i\neq k} v_i'(0) - v_k'(0)\Big\}, \quad (2)$$

where L_I stands for "Lindahl-implementable". We denote a positive solution for (1) as Q^{L_j} and we define $p_j^{L_j} := v_j(-Q^{L_j})$ and $p_i^{L_j} := v_i(Q^{L_j})$ for $i \neq j$, and we call Lindahl-j the Lindahl *outcome* $(j, Q^{L_j}, \boldsymbol{p}^{L_j})$. Besides, we call the pair (j, Q^{L_j}) a Lindahl-j *allocation.*

From the definition of L_I, there might exist up to n Lindahl outcomes, depending on the parameter c and the v's. Roughly, Lindahl-j exists if each community in $N \setminus \{j\}$ can pay an aggregate price that covers the building cost of Z and the disutility of j for hosting the facility. In particular, a low building cost (e.g., $c \leq (n-2)\overline{p}_1$) is a sufficient condition for the existence of Lindahl-1.

Efficiency properties of Lindahl outcomes

Consider the social planner problem under the monetized welfare metric, constrained to implement Z in community j and to a balanced budget. The social planner maximizes

$$\sum_{i\neq j} v_i(x) + v_j(-x) - cx$$

in $(x, j) \in \mathbb{R}_+ \times N$. Note that, for any $j \in L_I$, the first-order condition of this problem coincides with (1). That is, provided that $L_I \neq \emptyset$, the planner's solution is necessarily a Lindahl allocation. Not surprisingly, the welfare is maximized under a Lindahl-1 allocation since the suitable host (community 1) imposes the lowest social cost for any given facility size. This idea is formalized in Proposition 1. The proof of this and the following propositions, as well as the accompanying lemmata, are presented in the Supplementary Online Material.

Proposition 1. *If L_I is non-empty, Lindahl-1 is welfare-maximizing, and the Lindahl-1 allocation is the only one yielding an optimal facility size. If L_I is empty, a null provision is welfare-maximizing.*

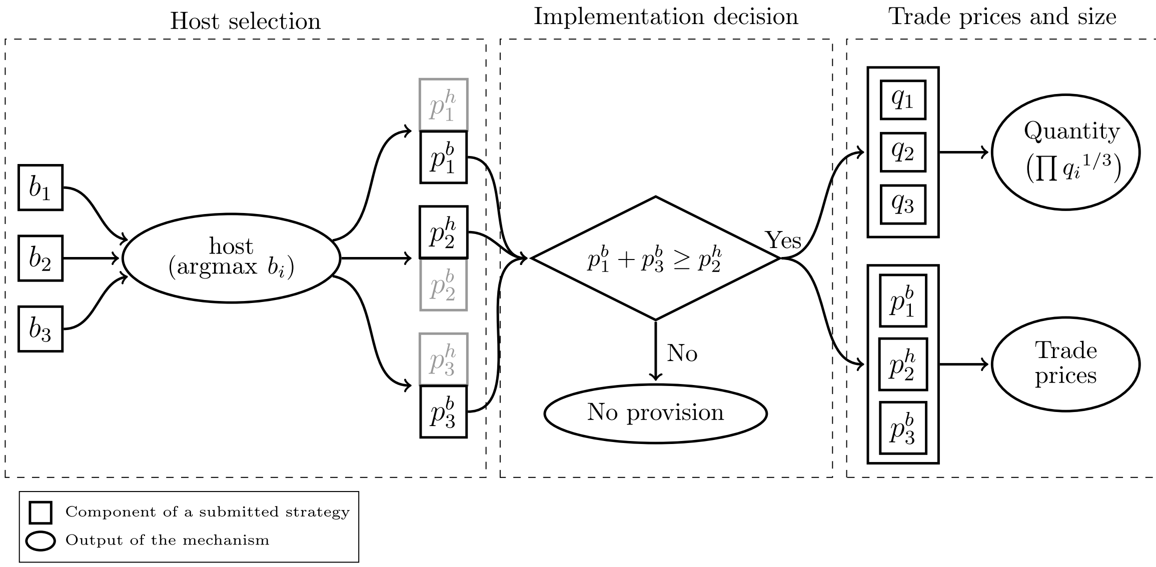

Fig. 2. An illustration of the mechanism with communities 1, 2, and 3, with no building cost, when 2 sets the highest bid. The sequential outputs of the mechanism are observed in the three dashed boxes when read from left to right. On the leftmost box, bids define the host and the operating prices p_1^b, p_2^h, and p_3^b. The central box verifies whether the sum of 1's and 3's prices as buyer meets the price as host of 2 to grant implementation. The rightmost box displays the provided quantity and trade prices.

Proposition 1 ensures that, when it exists, Lindahl-1 is Pareto optimal. However, it does not tell us anything about Pareto dominance between Lindahl outcomes. Indeed, if $j \in L_I \setminus \{1\}$, each community in $N \setminus \{1, j\}$ benefits more from Lindahl-1 than from Lindahl-j.[1] Since community 1 prefers Lindahl-1 to Lindahl-j, if v_j is close enough to v_1, then they virtually share the same preferences, and community j must be better off as the host in Lindahl-j compared to being a buyer in Lindahl-1.

Therefore, any mechanism that generates a socially optimal allocation must uncover who the suitable host is, considering that other communities might have incentives to take over the role of host.

4. The mechanism

In the proposed mechanism, each community i submits a four-element message: the price as host p_i^h (the marginal willingness to accept the project), the price as buyer p_i^b (the marginal willingness to pay for the project), a desired quantity q_i, and a bid b_i.

Although the multi-dimensional strategies are simultaneously submitted, we provide a first glimpse of how the mechanism operates by following the sequential outputs it yields, illustrated in Fig. 2. First, the community with the highest bid is selected as the host and its submitted price as host becomes its operating price for the rest of the mechanism. Similarly, for each other community, its operating price corresponds to the submitted price as buyer. The project is implemented only if the aggregate marginal willingness to pay–the sum of all buyers' operating prices–meets the host's marginal willingness to accept (plus the marginal cost of the facility's construction).

Formally, let $\Omega := \mathbb{R}_{++} \times \mathbb{R}_+^3$ be the space of strategies. For any strategy profile $\boldsymbol{s} \in \Omega^n$, we define the mechanism $\mathcal{M} : \Omega^n \to N \times \mathbb{R}_+ \times (\mathbb{R})^n$, $\boldsymbol{s} \mapsto (\hat{\imath}(\boldsymbol{s}), \hat{Q}(\boldsymbol{s}), (\hat{T}_i(\boldsymbol{s}))_{i \in N})$. We identify $\hat{\imath}(\boldsymbol{s})$ as the host, $\hat{Q}(\boldsymbol{s})$ as the provision level of Z, and $\hat{T}_i(\boldsymbol{s})$ as the (positive or negative) financial transfer made by community i. In this section, we let $\boldsymbol{s} = (s_1, s_2, \ldots, s_n)$, where $s_i = (q_i, p_i^b, p_i^h, b_i)$ is the strategy of community $i \in N$. We also set two auxiliary functions that help us properly define the mechanism's outcomes: $\hat{\jmath} : \Omega^n \to N$ and $\hat{\pi} : \Omega^n \to \mathbb{R}$. In the continuation of this section, by an abuse of notation, we omit the argument $\boldsymbol{s}$ from the outcomes (e.g., we write $\hat{Q}$ to denote $\hat{Q}(\boldsymbol{s})$).

Host selection. The community with the highest bid is selected as the host. If there is a tie, the first tie-breaking criterion is the lowest price as host. A draw is used as a second tie-break criterion.[2] We denote the host as $\hat{\imath}$. We define the community with the second-highest bid (following the same tie-break rules if necessary) as $\hat{\jmath}$. With the definition of the host $\hat{\imath}$, the prices p_i^h for $i \neq \hat{\imath}$ and $p_{\hat{\imath}}^b$ are discarded because they do not enter into the mechanism's computations. We call them the *residual* prices. By contrast, we call $p_{\hat{\imath}}^h$ and p_i^b for $i \neq \hat{\imath}$ the *operating* prices.

Provision. We start by defining the *excess contribution* $\hat{\pi}$ as the difference between the aggregate marginal willingness $\sum_{i \neq \hat{\imath}} p_i^b$ and the marginal costs—the host's compensation $p_{\hat{\imath}}^h$ plus the building cost c. That is, $\hat{\pi} := \sum_{i \neq \hat{\imath}} p_i^b - c - p_{\hat{\imath}}^h$. The facility is implemented when the excess contribution is non-negative. We call this condition the *implementation rule*. When it is respected, the facility size $\hat{Q}$ is given by the geometric mean of the submitted quantities. That is, $\hat{Q} = \prod_{i \in N} (q_i)^{1/n} \mathbb{1}_{\{\hat{\pi} \geq 0\}}$.

Transfers. First, we define the prices communities will pay (or receive, in the host's case) per unit implemented of the project, which we call the *trade prices*. These prices are given by the operating prices, compensated by a share of the excess contribution such that the condition of price clearance is met. The share of each buyer is $1/(2(n-1))$. Thus, if community i is a buyer (i.e., if $i \in N \setminus \{\hat{\imath}\}$), its trade price is given by $\hat{p}_i^b := p_i^b - \hat{\pi}/(2(n-1))$ and i receives the (non-positive) transfer $\hat{T}_i := -\hat{Q}\hat{p}_i^b$.

In the same way, the host's trade price is $\hat{p} := p_{\hat{\imath}}^h + \hat{\pi}/2$ so that $\hat{\imath}$ receives from the other communities $\hat{Q}\hat{p}$. Note that, whereas the share of each buyer is $1/(2(n-1))$, the host's share is half of the excess contribution, so the total amount paid by the buyers is received by the host. Fig. 3 illustrates the relation between submitted, residual, operating, and trade prices. The host also bears the potential cost of paying the second-highest bid, $b_{\hat{\jmath}}$, in case of implementation. Therefore, the net transfer received by the host $\hat{\imath}$ is given by $\hat{T}_{\hat{\imath}} = \hat{Q}\hat{p} - b_{\hat{\jmath}} \mathbb{1}_{\{\hat{\pi} \geq 0\}}$. Budget balancedness is thus attained only when $b_{\hat{\jmath}} = 0$. Fig. 3 depicts the interplay between the operating prices and the excess contribution, yielding the trade prices for each community. The payoff community i

[1] We use the negative concavity of v and the monotonicity of Q^{L_j} to show that a community in $N \setminus \{1, j\}$ is better off in Lindahl-1. Lemma 4 shows the same for community 1.

[2] The first tie-break criterion aids the efficient selection of the host. The second criterion's purpose is to define a unique host for any given strategy profile.

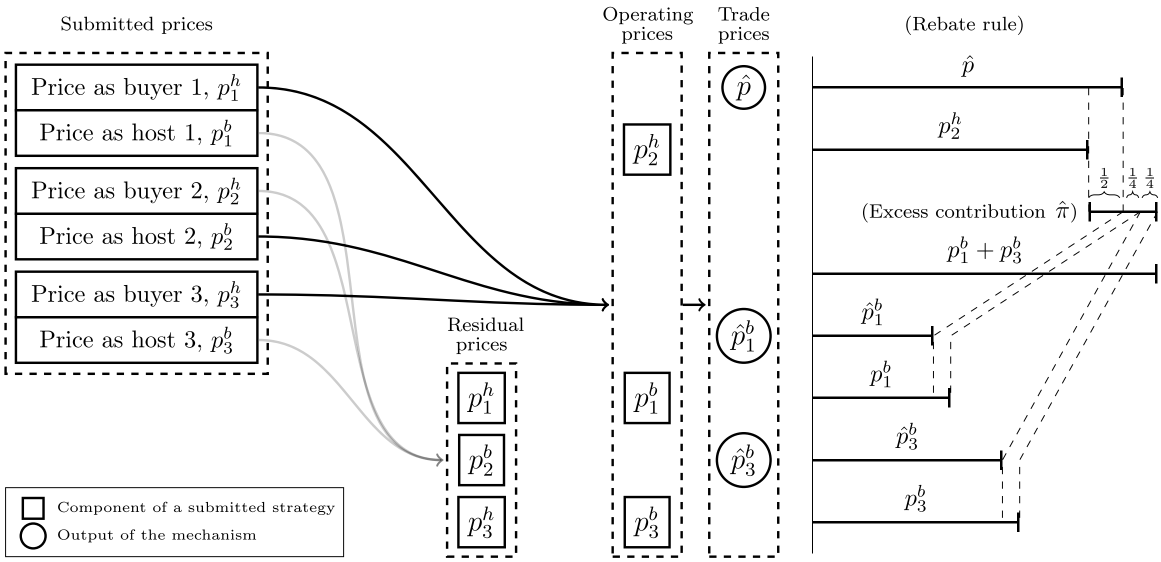

Fig. 3. An illustration of how submitted prices are divided into residual and operating prices, and how the latter define trade prices using a simple rebate rule. We continue with the example from Fig. 2: communities 1, 2, and 3, no building cost, and 2 setting the highest bid.

receives under this mechanism is

$$\left(v_i(\hat{Q}) - \left(p_i^b - \tfrac{\hat{\pi}}{2(n-1)}\right)\hat{Q}\right)\mathbb{1}_{\{i\neq\hat{i}\}} + \left(v_i(-\hat{Q}) + (p_{\hat{i}}^h + \tfrac{\hat{\pi}}{2})\hat{Q} - b_{\hat{j}}\right)\mathbb{1}_{\{i=\hat{i}\}}.$$

5. Equilibrium analysis

We use the notion of *ex post* equilibria to study the mechanism $\mathcal{M}$. As in any Nash equilibrium under private information lacking a dominant strategy, the equilibria in our mechanism imply that each community's strategy depends on its preferences and the strategies of the other communities, but not on other communities' preferences. However, the *ex post* equilibria (EPE) allow each community to *adapt* its strategy to the strategies of the other communities. This is a stronger informational requirement compared to the Bayesian Nash equilibria (BNE), but it has a convenient "dynamic" interpretation: learning about other communities' responses eliminates role strategic uncertainty and the associated welfare losses from buyers behaving as the suitable host, and *vice versa*.[3] In the Supplementary Online Material we show that, given the role asymmetry in the NIMBY problem, there is no mechanism to be implemented as BNE that simultaneously achieves an optimal allocation, Pareto dominates the status quo, and does not need external financing. Moreover, since the functions v_i are not parameterized, the designer's knowledge of the type space required in BNE may be too demanding (Bergemann and Morris, 2008).

For each $i \in N$ and a strategy profile $\boldsymbol{s} = (s_1, \ldots, s_n) \in \Omega^n$, we define the strategy-based utility of community i as

$$U_i(\boldsymbol{s}) = v_i(-\hat{Q}(\boldsymbol{s}))\mathbb{1}_{\{i=\hat{i}(\boldsymbol{s})\}} + v_i(\hat{Q}(\boldsymbol{s}))\mathbb{1}_{\{i\neq\hat{i}(\boldsymbol{s})\}} + \hat{T}_i(\boldsymbol{s}).$$

In addition, we define $\boldsymbol{s}_{-i} := (s_1, \ldots, s_{i-1}, s_{i+1}, \ldots, s_n)$ and denote $\boldsymbol{s} = (s_i; \boldsymbol{s}_{-i})$. We say that $\boldsymbol{s}$ is an equilibrium if, for each i, there is no $\tilde{s}_i$ such that $U_i(\tilde{s}_i; \boldsymbol{s}_{-i}) > U_i(s_i; \boldsymbol{s}_{-i})$.

Our first equilibrium result is that our mechanism induces Lindahl outcomes before the bid payment.

[3] Imagine a trade-off where BNE favors lower informational requirements, but surplus maximization is *conditional on* the available information; whereas EPE requires the actual parameters (instead of its distribution) but yields the exact surplus maximization. The stark role asymmetry makes welfare evaluation highly "host-dependent", yielding EPE more suitable for the efficiency analysis in the light of our distinction between the global optimum (Lindahl-1) and local optima (Lindahl-j).

Proposition 2 (*Necessity*). *Suppose that* $\boldsymbol{s}$ *is an equilibrium with project implementation. Then, the prices and quantities obtained from* $\tilde{\mathcal{M}}(\boldsymbol{s})$ *correspond to a Lindahl outcome, and* $\mathcal{M}(\boldsymbol{s})$ *Pareto dominates the status quo.*

There are three main statements in this proposition. First, $\mathcal{M}(\boldsymbol{s})$ improves the outcome for each community with respect to the *status quo*. Since the mechanism aggregates quantities geometrically, if $U_i(\boldsymbol{s}) < 0$, community i could arbitrarily decrease the provision level of Z to reduce its disutility, contradicting the fact that $\boldsymbol{s}$ is an equilibrium. Second, any equilibrium with implementation is a Lindahl outcome. The implementation rule implies that $p_{\hat{i}}^h \leq \sum_{i\neq\hat{i}} p_i^b - c$, but if the inequality were strict $\hat{i}$ would have incentives to increase its price as host. Satisfying $p_{\hat{i}}^h = \sum_{i\neq\hat{i}} p_i^b - c$ means that communities act as price-takers to not jeopardize provision. Given the geometric aggregation of quantities under our mechanism, $\hat{Q}$ must be simultaneously optimal for each community for such given prices. Hence, the selected prices reflect an optimal quantity for each community, implying that all conditions of a Lindahl outcome are met. Third, when $L_I = \emptyset$, any equilibrium implies no implementation.

The next proposition shows that the set of equilibria with implementation is non-empty when L_I is non-empty. To lighten the notation, we define, for any $\boldsymbol{s} \in \Omega^n$ and each $i \in N$, $\bar{b}_i(\boldsymbol{s}_{-i}) := \max\{b_j : j \in N \setminus \{i\}\}$,

$$g_i^b(\boldsymbol{s}_{-i}) := \sup\{U_i(s, \boldsymbol{s}_{-i}) : s \in \Omega \text{ and } i \text{ is a buyer}\},$$
$$g_i^h(\boldsymbol{s}_{-i}) := \sup\{U_i(s, \boldsymbol{s}_{-i}) + \bar{b}_i(\boldsymbol{s}_{-i}) : s \in \Omega \text{ and } i \text{ is the host}\},$$

and $\Delta_i(\boldsymbol{s}_{-i}) := g_i^h(\boldsymbol{s}_{-i}) - g_i^b(\boldsymbol{s}_{-i})$. For a given $\boldsymbol{s}_{-i}$, we have that $g_i^h(\boldsymbol{s}_{-i})$ and $g_i^b(\boldsymbol{s}_{-i})$ are the best outcomes that community i can get as the host and as a buyer, respectively, before the bid payment. The quantity $\Delta_i(\boldsymbol{s}_{-i})$ reflects the willingness to pay of community i to change from being a buyer to becoming the host, for a given opponent's profile. We call $\Delta_i(\boldsymbol{s}_{-i})\mathbb{1}_{\{\Delta_i(\boldsymbol{s}_{-i})\geq 0\}}$ the *switching valuation* since this is the bid that i is willing to offer to switch from buyer to host. Note that the switching valuation is a function of $\boldsymbol{s}_{-i}$. We say that community i bids truthfully conditional to $\boldsymbol{s}_{-i}$ if $b_i = \Delta_i(\boldsymbol{s}_{-i})\mathbb{1}_{\{\Delta_i(\boldsymbol{s}_{-i})>0\}}$. Hereafter, we refer to it as the *truthful bid* given its resemblance with a second-price auction.

Proposition 3. *Let* $s^\star$ *be the strategy profile:*

(i) the submitted quantities are all Q^{L_1}*;*
(ii) the submitted prices satisfy $p_1^h = p_1^{L_1}$, $p_1^b = v_1'(Q^{L_1})$, *and, for every* $i \geq 2$, $p_i^b = p_i^{L_1}$ *and* $p_i^h = \max\{p_1^{L_1} - p_i^{L_1} + p_1^b, v_i'(0)\}$*;*

(iii) the submitted bids satisfy $b_i = \Delta_i(s^\star_{-i})\mathbb{1}_{\{\Delta_i(s^\star_{-i})\geq 0\}}$ *for each* $i \in N$.

Then, $s^\star$ *is an equilibrium and* $\tilde{\mathcal{M}}(s^\star)$ *is Lindahl-1. Moreover, this equilibrium is robust to any coalition of communities in the set* $N \setminus \{1\}$.

Under the strategy $s^\star$, communities bid truthfully and the operating prices and submitted quantities yield a Lindahl-1 allocation. The intuition behind Proposition 2 revealed that communities act as price-takers to respect the implementation rule, so no community has an incentive to deviate from the trade prices. To sketch the proof for the other decision variables and give some intuition (see the Appendix for a technical version), let us consider three groups of communities: those with $\Delta_i(s^\star_{-i}) \leq 0$, those with $\Delta_i(s^\star_{-i}) > 0$ that are not the suitable host, and community 1. The former group and Community 1 do not have any strategic role uncertainty, meaning a lack of incentives to deviate from their truthful bid: 0 and $\Delta_1(s^\star_{-1})$, respectively. With certainty in their roles as buyer and host, their preferred quantity is Q^{L_1} (and Community 1 would have also preferred Q^{L_1} if it had been a buyer). Since communities with $\Delta_i(s^\star_{-i}) \leq 0$ would always be buyers, their residual price (as host) would not alter their utility, so there are no incentives to deviate. For community 1, setting the residual price is more strategic, but this was already captured in $s^\star_1$: as 1 would also prefer Q^{L_1} as a buyer, p^b_1 was set low enough to reflect that it is willing to pay very little if someone else hosts the facility. More importantly, this low price secures the host's role because $\Delta_j(s^\star_{-j}) < \Delta_1(s^\star_{-1})$ for $j \geq 2$, regardless of how close some v_j might be from v_1.

The challenge to $s^\star$ may come from community i with $\Delta_i(s^\star_{-i}) > 0$. Given $s^\star_{-i}$, it may prefer to host than be a buyer and adjust its strategy to outbid community 1. The mechanism's auction-like component dissipates this strategic role uncertainty given that $\Delta_j(s^\star_{-j}) < \Delta_1(s^\star_{-1})$ for $j \geq 2$. In other words, given $s^\star_{-i}$, community i cannot successfully set a price as host and a quantity that would allow it to deviate from a truthful bid and yield a higher utility than the one granted in its role as buyer under Lindahl-1 (see Lemma 5 in the Appendix). The reason is that, compared to community 1, community i would have a higher disutility from hosting for any Q (which also explains why buyers' coalitions would not work either). Since any effort to take over the hosting role would yield a utility loss with respect to its role as buyer, i has no incentives to deviate its bid, quantity, or prices, from $s^\star_i$. In Section 7, we illustrate this point with a numerical example.

We thus guarantee the existence of an equilibrium that is also globally efficient. The next proposition states that if each community bids its switching valuation, then Lindahl-j cannot be an equilibrium.

Proposition 4. *If communities bid truthfully, then there is no* $s \in \Omega^n$ *such that* $\tilde{\mathcal{M}}(s)$ *is Lindahl-j for* $j \geq 2$.

If $j \geq 2$ wants to host the project, its Lindahl-j allocation determines its best price as host and quantity. Since truthful bidding pins down the bid, the only variable j can manipulate to sustain a Lindahl-j allocation is its price as buyer, which can be lowered to reduce others' switching valuations (and, therefore, their bids). Proposition 4 says that j's attempt to take over community 1's role would make it set a price as buyer that is so low, that it would become attractive for j to be a buyer. Therefore, no equilibrium with j being the host can be sustained, no matter how close v_j is to v_1.

6. Efficiency analysis

The main result of this section, a corollary of Propositions 1 to 4, states that our mechanism induces the implementation of a PPPG that is efficient in both size and site. Propositions 1 and 3 tell us that Lindahl-1 is welfare-maximizing and that our mechanism can generate the Lindahl-1 allocation in equilibrium, respectively. Proposition 2 rules out as equilibrium any allocation that is not a Lindahl-1, and Proposition 4 eliminates Lindahl-j allocations for $j \geq 2$ as equilibrium, as long as communities bid their switching valuations. This is enough to prove the following theorem.

Theorem 5. *If communities bid truthfully, then the unique equilibrium allocation is the efficient one.*

Unlike most existing mechanisms for locating PPPGs, we opted for an efficient quantity in equilibrium at the cost of having a non-deficitary budget unbalancedness for two reasons. First, surplus on transfers is a weaker form of inefficiency than a deadweight loss because the excess payment can become a non-distortionary transfer. Second, moving from a Lindahl-j to a Lindahl-1 allocation simultaneously improves siting and sizing. Since the average unit of Z becomes less costly for society, better locations also grant welfare improvements from larger projects.

Since the efficiency loss is the bid paid by the host, we can comment on the best- and worst-case scenarios from the host's perspective. In the best-case scenario, communities in $N \setminus \{1\}$ would bid 0, so the second-highest bid would be null and the mechanism would generate a budget balanced outcome. In the worst-case scenario, community j has *identical* preferences to community 1, meaning that the host will pay its switching valuation as bid and would be indifferent between being the host or a buyer. As in a regular second-price auction, the competition between 1 and j dissipates the gains of the highest bidder.

Summing up the efficiency properties, our mechanism guarantees a Lindahl-j allocation in equilibrium for some $j \in N$. It is Pareto dominant because all communities acting as buyers are better off and the host is not worse off than in the *status quo* (and it yields the *status quo* when no provision is the efficient outcome). When we limit our attention to truthful bids, allocative efficiency is granted by selecting the Lindahl-1 equilibrium, with budged balancedness being achieved when v'_1 small relative to v'_j.

7. An example of the mechanism's implementation

Consider three communities with preferences given by $v_1(q) = d_1(1 - e^{-q})$, $v_2(q) = d_2(1 - e^{-q})$, and $v_3(q) = d_3(1 - e^{-q})$ for $q \in \mathbb{R}$. Assume also that the marginal cost to build the facility is $c = 0$. Under the assumption that $d_1 < d_2 < d_3$, community 1 has the lowest d and therefore it is the suitable host.

Our departing point is Proposition 2: any equilibrium will be a Lindahl outcome, so we can use its properties to determine the submitted prices and quantities. The condition for existence of a Lindahl-j, depicted in (2), simplifies to $d_j < \sum_{i \in N_j} d_i$. Since d_1 and d_2 are smaller than d_3, Lindahl-1 and Lindahl-2 exist. Lindahl-3 exists only if $d_3 < d_1 + d_2$. From (1), Q^{L_j} for any j must respect

$$0 = \sum_{i \in N_j} d_i e^{-Q^{L_j}} - d_j e^{Q^{L_j}} \Leftrightarrow Q^{L_j} = \ln\left(\sqrt{\frac{\sum_{i \in N_j} d_i}{d_j}}\right).$$

After validating the existence of a Lindahl outcome, we employ two of its conditions, (i) the optimality as buyer and (ii) the optimality as host, to define a set of equations in which the submitted prices depend on the parameters d and the optimal quantity, Q^{L_j}. We thus have

$$p^{L_j}_j = d_j e^{Q^{L_j}} \text{ and } p^{L_j}_i = d_i e^{-Q^{L_j}} \text{ for } i \in N_j.$$

With the submitted prices and the quantity identified, the only element left for defining a full strategy is the bid, b_i. Hence, we focus on the expressions yielding the switching valuation of communities 1 and 2 under strategy $s^\star$ (see Proposition 3). For community 3, the procedure would be similar, but in the numerical example we set d_3 large enough to make $b_3 = 0$. Recall that the utility as host is $d_1(1 - e^{Q^{L_1}}) + Q^{L_1} p^{L_1}_1$. Then, community 1's switching valuation is given by:

$$\left[d_1\left(1 - \sqrt{(d_2+d_3)/d_1}\right) + \ln\left(\sqrt{(d_2+d_3)/d_1}\right) d_1 \sqrt{(d_2+d_3)/d_1}\right]$$
$$- \left[d_1\left(1 - \sqrt{d_1/(d_2+d_3)}\right) - \ln\left(\sqrt{(d_2+d_3)/d_1}\right) d_1 \sqrt{d_1/(d_2+d_3)}\right].$$

Table 1
Inputs and outputs (in equilibrium) from our mechanism for three set of parameters.

Submitted messages	Other variables	Vector (d_1, d_2, d_3)		
		(1, 1.70, 10)	(1, 1.50, 10)	(1, 1.01, 10)
Q^{L_1}		1.23	1.22	1.20
(p_1^h, p_2^b, p_3^b)		(3.42, 0.50, 2.92)	(3.39, 0.44, 2.95)	(3.32, 0.31, 3.01)
(p_1^b, p_2^h, p_3^h)		(0.29, 3.21, 10)	(0.29, 3.24, 10)	(0.30, 3.31, 10)
(b_1, b_2, b_3)		(1.44, 0, 0)	(1.41, 0.24, 0)	(1.32, 1.29, 0)
	$(\Delta_1, \Delta_2, \Delta_3)$	(1.44, −0.06, −3.48)	(1.41, 0.24, −3.45)	(1.32, 1.29, −3.37)
	$\tilde{Q}_2$	0.64	0.77	1.18

To obtain the switching valuation of community 2 under $s^\star$, we have to calculate its best deviation, given $s^\star_{-2}$. This deviation has two key elements: community 2's highest price as buyer, given by

$$p_1^{L_1} - p_2^{L_2} + p_1^b = \sqrt{(d_2+d_3)d_1} + (d_1-d_2)\sqrt{d_1/(d_2+d_3)},$$

and the best quantity that community 2 may offer as host, given by the $\tilde{Q}_i$ (see Lemma 5). We thus have

$$\tilde{Q}_i = \ln\left(\frac{\sqrt{(d_2+d_3)d_1} + (d_1-d_2)\sqrt{d_1/(d_2+d_3)}}{d_2}\right).$$

Now we can write the switching valuation of 2 as a function of $\tilde{Q}_i$:

$$\left[d_2\left(1-e^{\tilde{Q}_i}\right) + \tilde{Q}_i\left(\sqrt{(d_2+d_3)d_1} + (d_1-d_2)\sqrt{d_1/(d_2+d_3)}\right)\right]$$
$$-\left[d_2\left(1-\sqrt{d_1/(d_2+d_3)}\right) - \ln\left(\sqrt{(d_2+d_3)/d_1}\right)d_2\sqrt{d_1/(d_2+d_3)}\right].$$

These expressions allow us to create the numerical examples reported in Table 1, where the three communities are at the Lindahl-1 equilibrium. The first row reports Q^{L_1}, which is identical to the vector of submitted quantities (q_1, q_2, q_3). The next two rows report the vectors of trade prices and residual prices, followed by the bid submitted by each community. The last two rows report two numbers that do not enter directly into the mechanism but are helpful to understand why communities bid truthfully (i.e., the vector of switching valuations) and why community 2 cannot take over the hosting role (i.e., the best quantity it can offer, or $\tilde{Q}_2$). We report the mechanism's relevant values for three scenarios differing only in the parameter value assigned to d_2.

First, the vector (d_1, d_2, d_3) is $(1, 1.7, 10)$. Although d_2 is only 0.7 units larger than d_1, its switching valuation Δ_2 is negative. That is, community 2 would not be interested in hosting the facility. In this case, community 1 will bid 1.44, while communities 2 and 3 will bid zero. As a consequence, community 1 will not pay for hosting and the mechanism will yield a budget balanced outcome. Note, from the vector of trade prices, that community 3 will pay much more for each unit of the facility given its much larger value of d.

For the second scenario, we slightly lowered d_2 to 1.5. This is sufficient to make Δ_2 positive, a configuration that will lead community 1 to pay 0.24 for keeping the role of host. Note that the increase in competition for this role slightly alters trade prices and quantities toward a lower but cheaper provision. In addition, community 2 does not have incentives to outbid 1 (by paying, say, 1.42) since the maximum gain that community 2 could obtain from taking over the role of host is 0.24.

The third scenario is qualitatively analogous to the second one, but we make d_2 only slightly larger than d_1 to show that, even when the difference between these two communities is almost negligible, the mechanism ensures that community 1 is the host.

By looking at the three scenarios within our parameterization, we see that the effect of a closer competitor for the hosting role mostly affects the host's utility through a higher payment in the second-price auction. Still, the mechanism induces its voluntary participation. On the other hand, the competition only seems to be triggered among highly resembling communities and it has little effects on the final outcome: the reduction in Q^{L_1}, the globally optimal quantity, is rather small.

8. Conclusion

We devised a mechanism that selects the only globally efficient Lindahl allocation to provide a PPPG. The functioning of our mechanism combines markets and auctions in a complementary manner. The market embedded in the mechanism ensures that some Lindahl allocation arises in equilibrium. The second-price auction embedded in the mechanism aims at selecting as a host the community that generates the greatest social benefit in this role.

Besides achieving efficiency, the mechanism displays two essential features for practical applications. First, the informational structure is realistic. Each community is required to know its own preferences, but not other communities' preferences. Second, the message submitted by each community does not become more complex as the number of participants in the mechanism or the range size of the facility increases.

Declaration of competing interest

The author declares that he has no relevant or material financial interests that relate to the research described in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jpubeco.2023.104953.

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