DIW BERLIN

1983

Discussion Papers

Deutsches Institut für Wirtschaftsforschung 2021

Optimal Discounts in Green Public Procurement

Olga Chiappinelli and Gyula Seres

IMPRESSUM

DIW Berlin
German Institute for Economic Research
Mohrenstr. 58
10117 Berlin

Tel. +49 (30) 897 89-0
Fax +49 (30) 897 89-200
https://www.diw.de

ISSN electronic edition 1619-4535

Papers can be downloaded free of charge from the DIW Berlin website:
https://www.diw.de/discussionpapers

Discussion Papers of DIW Berlin are indexed in RePEc and SSRN:
https://ideas.repec.org/s/diw/diwwpp.html
https://www.ssrn.com/link/DIW-Berlin-German-Inst-Econ-Res.html

Optimal Discounts in Green Public Procurement*

Olga Chiappinelli[†], Gyula Seres[‡]

November 16, 2021

Abstract

We consider a Green Public Procurement setting where the procurer provides a bid discount to environment-friendly technologies to foster their use. We assume that, before the auction, firms may switch to green technology via a publicly observable costly investment. We show that investment acts as a signaling device. This mitigates the effect of incomplete information on firms' costs, thereby triggering more competitive bidding, which results in lower prices for the procurer. Therefore, even a procurer with no preference toward green technology can find it optimal to use a discount. Our results challenge the common perception that Green Public Procurement always implies a trade-off between environmental performance and purchasing price.

JEL Codes: D44, H57, Q58, Q55

Keywords: Public Procurement; Environmental Policy; Auctions

1 Introduction

In this paper, we challenge the common perception that a preferential procurement program for green firms implies a trade-off between environmental performance and purchasing price. Unlike other existing preferential programs, e.g., for domestic firms or small and medium-sized enterprises (SMEs), in green procurement, the eligibility to the preferential treatment is endogenous, in the sense that all bidders can obtain it by investing in green technology. Using a theoretical model where investment in green technology is observable, we find that preferential treatment of environment-friendly firms in green public procurement may decrease rather than increase procurement costs. The underlying mechanism is that investment by the most cost-efficient types acts as a signaling device that reduces informational asymmetry between firms and triggers more competitive bidding.

*We are grateful to Jochen Schlapp, Christoph Wolf, Christine Zulehner, Jacques Crémer, Vera Zipperer, Karsten Neuhoff, Alessandro De Chiara, Patrick Rey, Frikk Nesje, Pio Baake, Nicola Dimitri, Riccardo Camboni, Sebastian Schwenen, as well as seminar participants at DIW Berlin, University of Gothenburg, Universitat de Barcelona, Tilburg Law and Economics Center, and the University of Bremen. We also thank conference participants at the World Congress of the Econometric Society 2020 (WCES Milan 2020), Annual Conference of the European Association of Environmental and Resource Economists 2021 (EAERE Berlin 2021), Annual Conference of the European Economic Association 2021 (EEA-ESEM Copenhagen 2021), Annual Conference of the European Association for Research in Industrial Economics (EARIE Bergen 2021), 3rd ZEW Workshop on the Economics of Public Procurement, and members of Berlin School of Economics for their useful comments. Olga Chiappinelli acknowledges funding from the Mistra Carbon Exit project. All errors are our own.

[†]DIW Berlin. Corresponding author. Email: ochiappinelli@diw.de

[‡]Humboldt University Berlin, Faculty of Economics and Business Administration and Tilburg Law & Economics Center. Email: gyula.seres@hu-berlin.edu.

Public procurement accounts for 12% of GDP in developed economies (OECD, 2019).[1] Being the largest buyers in several markets, governments, and other public authorities have the opportunity to exploit their procurement decisions to pursue objectives beyond the best value for money. Among these objectives, environmental protection and climate change mitigation enjoy particular attention. By using procurement practices that value the environmental quality of bids in the award of public contracts, so-called Green Public Procurement (GPP), public entities can reduce the environmental impact of their economic activity. Using their sheer size, they can also leverage public purchasing power to create demand and markets for environmentally-friendly products and services, thereby incentivizing the production and consumption of green options. Existing environmental policies struggle to generate these incentives in the short term.[2] Such a potential market pull role of GPP is especially relevant for sectors that both have a large environmental impact and where public authorities command substantial shares of the market.[3]

Despite its potential as an environmental policy, GPP is overall moderately implemented so far (UN, 2017; Chiappinelli and Zipperer, 2017). GPP is largely a voluntary instrument. In the European Union, for example, a soft broad legal framework explicitly permits the use of GPP without mandating it or setting binding targets, except for a few sectors.[4] Therefore, the single Member States, sub-national governments, and individual authorities are free to determine the extent and mode of implementation. Beyond a few virtuous experiences in countries with high levels of environmental commitment (e.g. Sweden, Netherlands, the UK), the adoption rates of GPP are generally low.[5]

Several survey studies highlight that a major barrier to broader implementation is the presumption that the higher cost of green technologies inflates prices for the procurer (Geng and Doberstein, 2008; Varnäs et al., 2009; Brammer and Walker, 2011).[6] The standard reasoning for the price-rising effect of GPP is as follows. Green technology increases marginal costs of production. Suppliers reflect this extra cost in their bids. To the extent that the GPP mechanism rewards environmental quality relative to price, the procurer may consequently face higher purchasing prices. This argument relies on a static assessment of procurement policies that considers market structure as fixed and where bidders are assumed to make a simultaneous choice of available technology and price. However, the argument disregards that, by triggering investment in green technology, GPP can change the relevant pool of suppliers, which might affect competition in procurement auctions and, in turn, purchasing prices in a not-straightforward way.

Motivated by these considerations, this paper aims at providing a theoretical framework to assess the total effect of GPP on purchasing price and answer the following questions: Can GPP ever reduce rather than increase the purchasing price? To what extent should a procurer implement

[1] This figure excludes procurement by state-owned enterprises.

[2] For example, the incentives provided through carbon pricing in emission trading systems have so far been insufficient to trigger investment in clean production processes of materials or for material efficiency in construction or manufacturing (Neuhoff et al., 2019).

[3] Defense, health, construction, and transportation are examples of sectors both responsible for large shares of greenhouse gas (GHG) emissions and dominated by public buyers (see e.g., Wiedmann and Barrett (2011) and Chiappinelli et al. (2019)).

[4] At the EU level procurement is regulated by Directives 2014/24/EU and 2014/25/EU. There are sector-specific legal measures that require certain energy efficiency standards for office IT equipment (EU Regulation No 106/2008) or road transport vehicles (EU Directive 2009/33/EC).

[5] See e.g. Kadefors et al. (2021) for a cross-country overview of best-practices in GPP of infrastructure works.

[6] Especially at the local level, where contracting authorities typically face tighter budget constraints, this can be sufficient to deter implementation. See also Testa et al. (2012), Testa et al. (2016) and Rosell (2021) for other empirical investigations of the determinants of and barriers to GPP adoption.

GPP? To answer these questions, we consider a dynamic game with the following characteristics. Firms are *ex-ante* brown and have private information on their cost. The procurer announces a GPP auction where green firms enjoy a bid discount. Before bidding, firms can undertake a publicly observable costly investment to switch to green technology. Therefore, in our setting, higher costs appear as a sunk-cost investment rather than higher marginal costs.[7] Firms then participate in a first-price sealed-bid reverse auction where green firms receive the bid discount.[8]

We find that investment triggered by the discount-based GPP mechanism acts as a signaling device. In equilibrium, the most cost-efficient firms invest.[9] Signaling efficiency through investment reduces incomplete information on costs and increases competition between *ex-post* green firms, which lowers the expected purchasing price. Therefore, GPP does not necessarily imply a trade-off between purchasing price and environmental performance. Consequently, we find that even a procurer with weak, or even no, environmental preferences can be better off by choosing a positive discount level to foster competition.

Insofar we model GPP as a procurement auction with preferential treatment (bid discount) for green firms, we mostly contribute to the literature on preferential programs in procurement. This literature extensively discusses the competition and price effects of these programs. McAfee and McMillan (1989) study the competition effects of a preferential procurement program where domestic firms are favored over foreign ones. They find that the optimal discount policy grants an advantage to the more expensive bidder type: non-favored bidders bid more aggressively and compensate for the positive effect on purchasing price due to favoritism, with the net effect depending on cost asymmetries and the magnitude of the discount. Corns and Schotter (1999) provide experimental evidence supporting this. Krasnokutskaya and Seim (2011) consider a model of firms' participation and bidding decisions in the presence of a bid discount in favor of SMEs. They argue that preferential programs also affect entry: non-favored firms might be deterred, which puts additional upward pressure on the price. Hubbard and Paarsch (2009) also study a similar setting with endogenous participation and find that, for some cost distributions, the price-increasing preference and participation effects can be dominated by the price-decreasing competitive effect. Hence, preferential policies can lead to cost savings for the government.[10]

Our contribution to this literature is that in our setting the eligibility for the advantage is endogenous rather than exogenous, as brown firms can become green through investment. Our central argument is that investment has a signaling effect as GPP triggers green investment by the most cost-efficient bidders. This changes the relevant pool of suppliers, which affects competition in procurement auctions and, in turn, purchasing price. GPP can, on the one hand, put upward pressure on price, as green firms are given a competitive advantage and can inflate bids in the auction, but, on the other hand, can also reduce the price, as most cost-efficient firms that invest

[7]For example, a logistic service provider may replace its fleet equipped with internal combustion engines with electric vehicles.

[8]The Dutch Infrastructure Authority (Rijkswaterstaat) adopted this approach for the procurement of low-carbon infrastructure. The mechanism provides a bid discount proportional to GHG emission reduction relative to a baseline (Kadefors et al., 2021).

[9]While we find a separating equilibrium, this is not necessarily the case for dynamic investment games. For example, Aoki and Reitman (1992) consider an R&D game in which firms can invest in cost-reducing technology before engaging in Cournot competition and find a partial pooling equilibrium.

[10]Similarly, mixed evidence emerges from the analysis of preference programs in the form of set-asides rather than bid discounts. On the one hand, set-asides can reduce competition by excluding incumbents (Athey et al. (2013)). On the other hand, they can increase competition by inducing higher entry of targeted firms (Nakabayashi (2013)). Jehiel and Lamy (2015) also consider the role of endogenous entry on optimal discrimination in auctions with incumbents and entrants.

will bid more aggressively. We also show that this result is robust to an alternative implementation of GPP in the form of a scoring auction rather than a bid-discount program.

Our paper, therefore, puts forward a positive argument favoring GPP. In this, we counteract the relatively negative assessment provided by the so-far very scarce theoretical economic literature on GPP. Marron (1997) considers a quantity-based procurement policy (i.e., set-asides) in a full information setting where the government buys through markets rather than competitive bidding and shows that GPP is ineffective as an environmental policy due to a substitution effect between public and private relative consumption of green and conventional goods. Lundberg et al. (2013) aims at assessing GPP's potential of achieving environmental objectives at the lowest cost to society. They consider a setting with complete information where GPP is implemented in the form of binding technical environmental requirements and where suppliers must adopt new technology to fulfill them. They conclude that GPP is not cost-effective, as potential suppliers have different marginal costs of adjusting their technology to the standard. These papers, therefore, suggest that GPP does not live up to the expectations as an environmental policy and might perform worse than other measures.[11] Our contribution to this literature is to investigate the price effect of a discount-based GPP mechanism in an auction theory setting with incomplete information.

The rest of the paper is structured as follows. Section 2 presents the model. Section 3 provides the equilibrium analysis and characterizes the solution for the procurer's problem. Section 4 illustrates the main results with numerical examples. Section 5 performs some robustness checks and discusses the comparison with alternative GPP mechanisms. Last, Section 6 concludes the paper. Proofs are relegated to the Appendix.

2 Model

We consider a setting where a procurer seeks to allocate an indivisible project to a supplier. The contract can be awarded to one of n firms that enter a competitive auction, the rules of which we describe below. Although we do not model the procured service or good explicitly, we focus on markets in which bidders have sufficient time to undertake an investment after the announcement of the auction but before submitting their bids.[12]

Firms have private information on their cost of implementing the contract. The cost type c_i is identically and independently drawn from a strictly positive compact support $[\underline{c}, \bar{c}]$, $\underline{c} > 0$, with twice continuously differentiable log-concave cumulative density function $F(c_i)$, with derivative $f(c_i)$, which we assume positive everywhere. Log-concavity implies that $F(c_i)$ meets the regularity condition that $\frac{1-F(c_i)}{f(c_i)}$ is monotonically decreasing (An, 1998). This is a weak standard assumption implying that the winning bidder's expected bid is increasing in their own cost (McAfee and McMillan, 1989).[13]

[11] Empirical papers reach more mixed conclusions. Simcoe and Toffel (2014) find that municipal policies in California on the GPP of buildings triggered the adoption of a green building standard from the private sector. Analyzing cleaning service data, Lundberg et al. (2015) find that green requirements only have a weak effect on the participation decision and the aggregate number of bidders. Lindström et al. (2020) find that a Swedish organic food procurement policy is associated with a significant positive impact on organic agricultural land.

[12] Therefore, we describe situations where undertaking the investment is not prolonged or does not involve a large degree of uncertainty. In particular, we exclude innovation procurement.

[13] Log-concavity is satisfied by several distribution types that are frequently used in applied research, including the (multivariate) normal, exponential, uniform, logistic, extreme value, Laplace, and Weibull distributions (Bagnoli and Bergstrom, 2005).

Environmental technology is described by a firm-specific binary variable $E_i \in \{G, B\}$, which assumes G if the technology is *green* or environment-friendly and B if it is *brown* or polluting at the time of the auction. We assume that the technology type is initially brown for all firms and the decision whether they invest or not in green technology is publicly observable.[14] The players participate in a dynamic game with the following stages.

$t = 0$ Firms learn their cost-types c_i (private).

$t = 1$ The procurer announces to the firms the GPP auction and the extent of bid discount $\alpha \geq 0$.

$t = 2$ Firms may switch to green technology for a fixed cost $T > 0$ or remain brown for no additional cost. The decisions are publicly observable.

$t = 3$ Firms participate in a first-price sealed-bid auction with preference given to green technology. Each firm i submits a bid denoted by b_i. Green firms receive a discount according to parameter α. The winner of the auction is the one with the lowest score, where the score or "corrected bid" s_i is such that

$$s_i = \begin{cases} \frac{b_i}{(1+\alpha)}, & \text{if } E_i = G \\ b_i, & \text{if } E_i = B. \end{cases} \tag{1}$$

In this framework, $\alpha = 0$ denotes a standard first-price auction with no discount, whereas $\alpha > 0$ stands for preferential treatment of green firms. The winner is awarded her bid b_i and pays the cost of implementing the contract. Therefore, the winner's payoff equals $b_i - c_i$ whereas others receive their outside option 0. That is, α influences the allocation of the good, but not the conditional payoffs.

Players' payoffs are as follows. Firm i's profit equals

$$\pi_i = \begin{cases} b_i - c_i, & \text{if } i \text{ does not invest and wins,} \\ b_i - c_i - T, & \text{if } i \text{ invests and wins,} \\ 0, & \text{if } i \text{ does not invest and loses,} \\ -T, & \text{if } i \text{ invests and loses.} \end{cases} \tag{2}$$

As for the preferences of the procurer, we extend the standard setting of a cost-minimizing procurer and allow him to also value environmental quality. We assume that the procurer has a generic two-dimensional utility function over expected environmental quality e and expected price p, $U(e, p)$, where the expected environmental quality is the *ex-ante* probability of a green winning bidder. We assume that the utility function $U(e, p)$ is continuously differentiable with respect to p and that the procurer has a strong preference for lower price: $\frac{\partial U(e,p)}{\partial p} < 0$, while he has a weak preference for a green winner: $U(G, p) \geq U(B, p)$ for all $p \geq 0$. This modelling choice avoids restrictions of the objective function while including the baseline cost-minimizing preferences.

Bidders as well as the procurer are risk-neutral and expected payoff-maximizing. As a tie-breaking rule, firms indifferent between the two options in stage 2 invest. In the following, we focus on

[14] Although it is not legally mandated for not publicly traded companies to publicly disclose their investments, firms have strong incentives to do so if this improves their environmental performance, as this has a value for stakeholders.

pure-strategy weak perfect Bayesian equilibria.

3 Equilibrium Analysis

We proceed with the analysis in two steps. The first subsection characterizes the equilibrium of the auction for a given discount parameter α. The second subsection addresses the procurer's problem of setting the discount level.

From the game structure, the subgame that follows the setting of the discount parameter α has two stages, the investment stage and the bidding stage. Like Krasnokutskaya and Seim (2011), we restrict attention to equilibrium bidding functions that are strictly increasing and differentiable in cost, and in which a bidder that expects zero profit submits a bid equal to her cost.[15]

3.1 Equilibrium of the Auction Game

If α is set to zero, the setting is a symmetric first-price sealed-bid auction identical to the one described by Myerson (1981). With n bidders, the unique bidding equilibrium is

$$b^*(c_i, n) = c_i + \frac{\int_{c_i}^{\bar{c}} [1 - F(s)]^{n-1} ds}{[1 - F(c_i)]^{n-1}}. \tag{3}$$

Next, for $\alpha > 0$, we characterize the following type of subgame: There is a cutoff value c^* such that bidders invest if and only if $c_i \leq c^*$ and all players in the bidding stage share this belief. After characterizing the bidding stage, we show that this is the only subgame played in equilibrium if there is any investing type.

If a cutoff-value exists and investment is observable, players update their beliefs about the conditional cost distribution of their opponents based on the outcome of the investment stage. That is, the cumulative distribution function of their cost-types becomes $\check{F}(c_i) = \frac{F(c_i) - F(\underline{c})}{F(c^*) - F(\underline{c})}$ if they invest and become green, as $c_i \leq c^*$ and $\hat{F}(c_i) = \frac{F(c_i) - F(c^*)}{F(\bar{c}) - F(c^*)}$ if they do not invest and stay brown, as $c_i > c^*$.

After the investment stage, we can distinguish the following subgames according to the number of investing firms, which we denote by k: no firm invests ($k = 0$) i.e. all firms remain brown, only one firm invests ($k = 1$) i.e. there is exactly one green firm *ex-post*, at least two firms invest ($k \geq 2$) i.e. there are at least two green firms *ex-post*.

We briefly characterize the solution for these bidding games. The bidding equilibria will be denoted with $b^*(c_i, k, n)$.

Case 1: No firm invests ($k = 0$). If $c_i > c^*$ for all i, the resulting auction stage is a symmetric auction with a smaller type space according to distribution $\hat{F}(c_i)$ as all players have the same *interim* type distribution conditionally on reaching that subgame. In this case the unique bidding equilibrium is

[15] The latter assumption is needed to exclude multiplicity of bidding equilibria.

$$b^*(c_i, 0, n) = c_i + \frac{\int_{c_i}^{\bar{c}} [1 - \hat{F}(s)]^{n-1} ds}{[1 - \hat{F}(c_i)]^{n-1}}. \tag{4}$$

Case 2: Only one firm invests ($k = 1$). In this case, the auction is asymmetric and we prove that the unique equilibrium of this bidding subgame is as follows:

$$b^*(c_i, 1, n) = \begin{cases} c_i, & \text{if } E_i = B \\ c^* \cdot (1 + \alpha), & \text{if } E_i = G. \end{cases} \tag{5}$$

The non-investing types have zero probability of winning and, therefore, bid their cost, while the investing type bids to ensure that it wins with certainty while taking into account that it enjoys the discount. To prove that the one stated is the equilibrium, we note that $\hat{F}(c_i)$ and $\check{F}(c_i)$ are truncated distributions of $F(c_i)$, hence, log-concave as well (An, 1998). Therefore, the *interim* distribution of the single investing bidder conditionally first-order stochastically dominates that of the opposing non-investing bidders and their virtual cost is increasing in their cost c_i (Maskin and Riley, 2000).[16]

Case 3: At least two firms invest ($k \geq 2$). Similar to Case 2, brown firms have zero chance of winning and bid their cost. The green firms enter the auction with symmetric type distribution $\check{F}(c_i)$, hence, they bid according to a symmetric bidding equilibrium. The unique bidding equilibrium in this case is as follows:

$$b^*(c_i, k, n) = \begin{cases} c_i, & \text{if } E_i = B \\ c_i + \frac{\int_{c_i}^{c^*} [1 - \check{F}(s)]^{k-1} ds}{[1 - \check{F}(c_i)]^{k-1}}, & \text{if } E_i = G. \end{cases} \tag{6}$$

where $k \geq 2$.

It is relevant to notice that disclosure of information through the investment decision can have a very different impact on bidding behavior depending on whether it results in an *ex-post* symmetric or asymmetric setting, which in turn depends on the number of investing firms. If only one firm invests, an asymmetric subgame arises where a low-cost green firm strongly dominates over the high-cost brown firms, so competition is soft. On the other hand, it is sufficient that two firms invest to have a much more favorable outcome for competition: in this case, *ex-post* green firms compete in a symmetric setting with a smaller type space, which reduces the room for cost-shading.

Next, we show that the more efficient types invest, i.e., there exists a unique cutoff value such that a firm invests to become green if and only if its cost does not exceed that value. That is, the subgames characterized above are reached in equilibrium.

Let us assume that there is a unique Bayesian equilibrium in the bidding stage in all subgames. Consider a bidder i and denote all bidders other than i with $-i$. As the investment decision is observable, it changes the distribution of opposing bids in the bidding stage as well as whether i enjoys a discount. There are two different *interim* distributions of opposing equilibrium bids. Let us define $H_{E_i}(s_{-i})$ as the distribution of the strongest opposing equilibrium score s_i after the

[16] This ensures that the "strong" green player's gain from bidding is large enough to be sure to outbid the "weak" brown player.

investment stage. Here, we consider discounted values so that $H_{E_i}(s_{-i})$ determines the chance of winning. That is, for $E_i = G$,

$$s_j = \begin{cases} (1+\alpha)b_j, & \text{if } j = B \\ b_j, & \text{if } j = G \end{cases} \tag{7}$$

while for $E_i = B$,

$$s_j = \begin{cases} b_j, & \text{if } j = B \\ \frac{b_j}{1+\alpha}, & \text{if } j = G \end{cases} \tag{8}$$

Bidder i compares the two expected payoffs from the two options of investing and not investing.

Let us define the conditional expected payoffs from the bidding stage in the two subgames with investment and without investment as optima of the objective function of the following problem

$$\pi(c_i, H_{E_i}) = \max_{b_i}(1 - H_{E_i}(b_i))(b_i - c_i) \tag{9}$$

in which the right-hand side of the equation is the respective optimization problem. Therefore, player i invests if and only if

$$\pi(c_i, H_G) - T \geq \pi(c_i, H_B). \tag{10}$$

For a type such that $c_i \leq c^*$ condition (10) can be explicitly written as,

$$\begin{aligned} \sum_{k=2}^{n} \binom{n-1}{k-1} F(c^*)^{k-1} \cdot (1 - F(c^*))^{n-k} \cdot (b^*(c_i, k, n) - c_i) \cdot (1 - \check{F}(c_i))^{k-1} + \\ \binom{n-1}{0} F(c^*)^0 \cdot (1 - F(c^*))^{n-1} \cdot (b^*(c_i, 1, n) - c_i) - T \geq \\ (1 - F(c^*))^{n-1} \cdot (c^* - c_i) + \binom{n-1}{1} F(c^*)^1 \cdot (1 - F(c^*))^{n-1} \cdot (c^* - c_i) + \\ \sum_{k=2}^{n} \binom{n-1}{k} F(c^*)^{k-1} \cdot (1 - F(c^*))^{n-k-1} (b^0(c_i, k, n) - c_i) \cdot [1 - B(b)]^k \end{aligned} \tag{11}$$

where $b^0(c_i, k, n) = \arg\max_b [1 - B(b)]^k (b - c_i)$ and $B(\cdot)$ is the cumulative distribution function of bids of investing firms following (6). Notice that $[1 - B(b)]^k > 0$ if and only if $c_i < c^*/(1 + \alpha)$.

On the other hand, for a type $c_i > c^*$:

$$\begin{aligned} (1 - F(\frac{\tilde{b}(c_i, 1, n)}{1+\alpha}))^{n-1} \cdot (\tilde{b}(c_i, 1, n) - c_i) - T \leq \\ (1 - F(c_i))^{n-1} \cdot (b^*(c_i, 0, n) - c_i) \end{aligned} \tag{12}$$

where $\tilde{b}(c_i, 1, n) = \arg\max_b [1 - F(b/(1 + \alpha))]^{n-1} (b - c_i)$

Proposition 1. *For sufficiently low T ($T \leq T^*(\alpha, n)$) or sufficiently large α ($\alpha \geq \hat{\alpha}(n, T)$), there exists a type $c_i \geq \underline{c}$ that undertakes the investment in stage 1. In that case, there exists an unique* *critical value $c^*(\alpha, n, T)$ such that a brown firm of type c_i finds it optimal to invest in period 2 if and only $c_i \leq c^*(\alpha, n, T)$.*

Hence, this game has an equilibrium in which efficient firms with low costs invest in green technology. This decision is fully described by a cutoff value $c^*(\alpha, n, T)$. For the sake of understanding the role of the discount parameter, we must analyze how α affects the critical value, hence, investment level.

Intuitively, firms have stronger incentives to invest if they expect a larger discount in the auction stage. Based on Proposition 1, if there is any investment, efficient firms invest. Based on the incentive compatibility constraint (10), the driving force behind this is that the discount increases the chance of winning as investing firms can submit higher bids with the same chance of winning.

Next, we show that a higher discount α indeed increases incentives to invest i.e. attracts less efficient brown firms to invest. Given $T \leq T^*(\alpha, n)$ (or $\alpha \geq \hat{\alpha}(n, T)$), the focus is on interesting settings in which a separating equilibrium emerges, hence, at least some types invest.

Proposition 2. *The share of investing brown firms is increasing in the discount parameter and decreasing in the costs of investment: $\frac{\partial c^*(\alpha,n,T)}{\partial \alpha} > 0$ and $\frac{\partial c^*(\alpha,n,T)}{\partial T} < 0$.*

Here, the critical type $c^*(\alpha, n, T)$ is implicitly defined by the indifference condition between undertaking and abstaining from investment:

$$\left(\alpha \cdot c^*(\alpha, n, T) - \int_{c^*(\alpha,n,T)}^{\bar{c}} (1 - \hat{F}(s))^{n-1} ds\right) \cdot (1 - F(c^*(\alpha, n, T)))^{n-1} - T = 0 \qquad (13)$$

A straightforward interpretation of Proposition 2 is that a higher discount parameter always attracts more green investment, while a higher investment cost will reduce it. A procurer that (weakly) prefers a green winner is better off with more green investment but it is unclear if that results in higher purchasing prices. As we argue in the introduction, common wisdom suggests a trade-off between fostering investment and prices. We scrutinize this notion in the following section.

3.2 Optimal Discount Choice

The procurer's problem is to choose a value of the discount parameter $\alpha \geq 0$ to maximize the objective function

$$\max_{\alpha} \mathbb{E}[U(e(\alpha, n, T), p(\alpha, n, T)]. \qquad (14)$$

Lemma 1. *The total effect of the discount parameter on expected price $p(\alpha, n, T)$ can be decomposed as follows*

$$\frac{dp(\alpha, n, T)}{d\alpha} = \frac{\partial p(\alpha, n, T)}{\partial c^*(\alpha, n, T)} \cdot \frac{dc^*(\alpha, n, T)}{d\alpha} + \frac{\partial p(\alpha, n, T)}{\partial \alpha}. \qquad (15)$$

1. *a* market power effect $\frac{\partial p(\alpha,n,T)}{\partial \alpha}$
2. *a* signaling effect $\frac{\partial p(\alpha,n,T)}{\partial c^*(\alpha,n,T)}$
3. *and an* incentive effect $\frac{dc^*(\alpha,n,T)}{d\alpha}$

if $c^*(\alpha, n, T)$ exists, i.e. α is sufficiently high ($\alpha \geq \hat{\alpha}(n, T)$).

Lemma 1 shows that α has both a direct effect and an indirect effect on price. The direct effect is the effect the discount has in the auction by giving an advantage to investing over non-investing firms. The indirect effect is the effect of α via investment and is made of two components: the incentive effect, i.e., the effect of the discount on the investment threshold, and the signaling effect, i.e., the effect that in turn investment has on bidders strategies via information disclosure.

From Proposition 2, we know that the incentive effect is positive as higher α increases investment. In the following, we show that the market power effect is non-negative whereas the signaling effect's sign is ambiguous.

Lemma 2. *The market power effect is non-negative, $\frac{\partial p(\alpha,n,T)}{\partial \alpha} \geq 0$ and zero if and only if $\alpha \leq \hat{\alpha}(n, T)$.*

Not surprisingly, a larger discount increases the extent to which the investing firm can inflate the bid, which increases the price for the procurer. Given Lemma 2, and as the sign of the incentive effect is positive by Proposition 2, we can also state:

Corollary 1. *If $c^*(\alpha, n, T) = \underline{c}$, the sign of the total effect of the discount parameter α on the expected price $p(\alpha, n, T)$ is identical to the sign of the signaling effect.*

Next, we assess the sign of the signaling effect at $c^*(\alpha, n, T) = \underline{c}$, that is when $\alpha = \hat{\alpha}(n, T)$.

Lemma 3. *The signaling effect $\frac{\partial p(\alpha,n,T)}{\partial c^*(\alpha,n,T)}$ is negative at $c^*(\alpha, n, T) = \underline{c}$ for n sufficiently low and positive for n sufficiently high.*

Lemma 3 points out two things. Either for sufficiently high number of firms n or investment cost T, the signaling effect, and, therefore, the total effect, is positive at $c^*(\alpha, n, T) = \underline{c}$. Nevertheless, for sufficiently low values, the effects can be negative.

Next, we demonstrate what happens if α is large.

Lemma 4. *A very high discount results in a higher price than no discount:*

$$\lim_{\alpha \to \infty} p(c^*(\alpha, n, T), n, T) = n \cdot T + n(n-1) \int_{s=\underline{c}}^{\bar{c}} sf(s)F(s)(1-F(s))^{n-2} ds \tag{16}$$

It is interesting to note that in the limit the procurer pays a price premium equal to the total cost of investment relative to the case $\alpha = 0$, where the expected price equals $n(n-1) \int_{s=\underline{c}}^{\bar{c}} sf(s)F(s)(1 - F(s))^{n-2}ds$. This reflects the event - which happens at the limit with a very small probability - that an investing bidder acts as a monopolist and charges a very high price, i.e., delegates the total cost of investment to the procurer. The reason behind this is that high α eliminates the signaling effect on price. As α increases, $c^*(\alpha, n, T)$ converges to $\bar{c}$ and there is very little to learn about the competitors after the investment stage. On the other hand, the positive effect of the discount on price persists. Therefore, it is worth noticing that while a very large discount would result in the same allocation and investment level as imposing mandatory investment (e.g. via technical requirements) the discount-based mechanism would result in a higher price. Notice, however, that this result is conditional on assuming fixed entry.

In the following proposition, we state what the results of this section imply for the optimal choice of the procurer.

Proposition 3. *Provided the cost of investment T and the number of firms n are sufficiently low, choosing $\alpha = 0$ is never optimal as*

$$U(e(\hat{\alpha}(n,T)+\varepsilon,n,T),p(\hat{\alpha}(n,T)+\varepsilon,n,T)) > U(e(\alpha,n,T),p(\alpha,n,T))$$

if $0 \leq \alpha \leq \hat{\alpha}(n,T)$ and ε is an arbitrary small value.

Note that $e(\cdot)$ is increasing in α, which simply follows from Proposition 2, as the chance of investment for any firm is $F(c^*(\alpha,n,T))$.

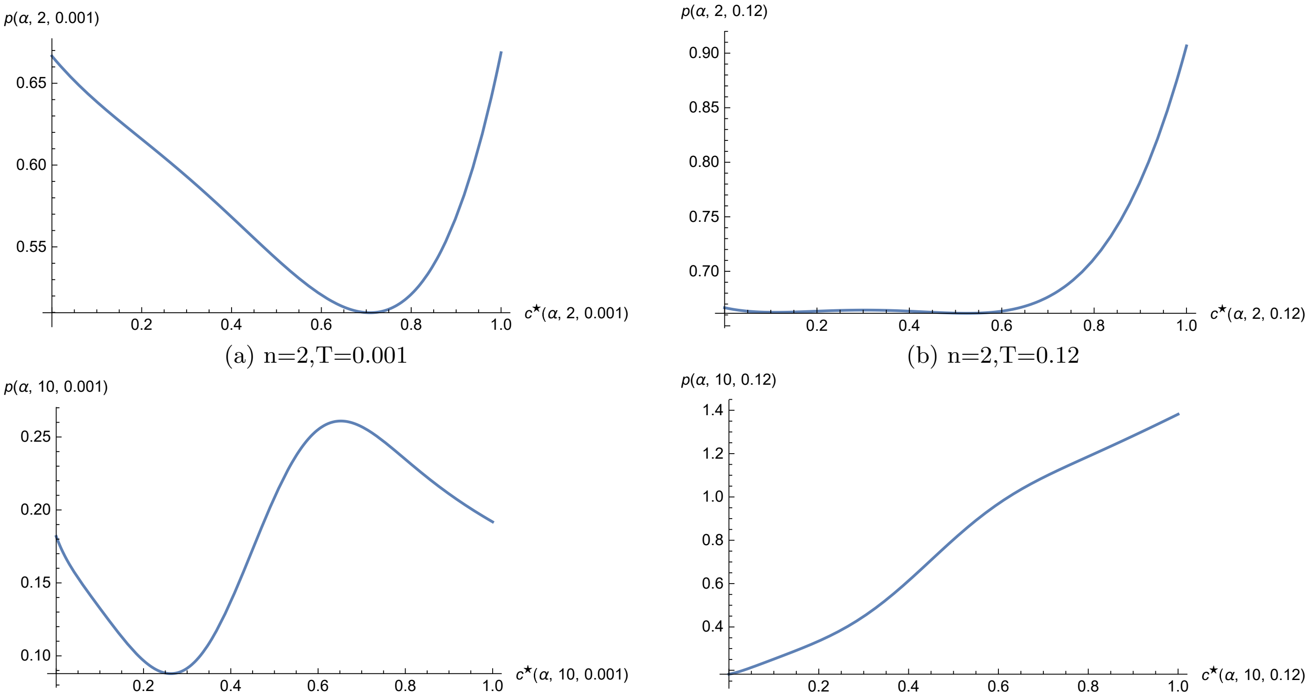
What is evident from the above results is that the discount parameter has different effects on price. First, *given the market structure*, in the bidding game it increases the dominance of green over brown firms. This is the common-wisdom "market power" effect: by increasing the market power of green firms, GPP increases the price paid by the procurer. However, the discount has an additional indirect effect insofar *it also changes the market structure*. A larger discount increases the investment threshold by facilitating investment (the "incentive effect"). This, in turn, can reduce the price for the procurer. This is so because the threshold segments the market and allows competition between more similar types, thus reducing room for bid-shading (the "signaling effect"). The price-decreasing signaling effect can compensate for the price-increasing market effect if the discount is not too large. As a result, even a procurer with no or weak preference for environmental performance can find it optimal to set positive values of the discount.

4 Examples

The previous section shows some ambiguity regarding the total effect of the discount parameter α on the expected price. In this section we confirm with examples our main results. Consider bidders whose cost type is drawn independently from a uniform distribution with closed support $[0,1]$. They face investment cost T if they choose a green technology. Figure 1 depicts the expected equilibrium price $p(\alpha,n,T)$ as a function of $c^*(\alpha,n,T)$. Since the latter is a monotonic function of the discount α, the figure can be interpreted as a proxy of the behavior of the price as a function of the discount. There are four graphs with the following parameter configurations: 1.(a) has $n=2, T=0.001$, (b) has $n=2, T=0.12$, (c) has $n=10, T=0.001$, and (d) has $n=10, T=0.12$.[17]

The examples highlight the main results of the previous section. First, a low discount parameter α is not optimal for sufficiently low n and T. For all examples except for the case in Figure 1.(d), there is always a range of values of $c^*(\alpha,n,T)$ and, therefore, of α where the slope of the expected price is negative; i.e., the total effect is negative, so that the procurer is better off increasing the level of the discount. In particular, the slope of the expected price is negative at $c^*(\alpha,n,T) = \underline{c}$ that is at $\alpha = \hat{\alpha}(n,T)$. Thus, it is confirmed that $\alpha = 0$ is not optimal. Second, for a very high discount, the procurer pays a high price premium, so that high discounts are not optimal.

[17]The graphs were created in Wolfram Mathematica. The codes are available on request.



(a) n=2,T=0.001 (b) n=2,T=0.12

(c) n=10,T=0.001 (d) n=10,T=0.12

Figure 1. Expected price as a function of $c^*(\alpha, n, T)$. In all examples, cost types are drawn from a uniform distribution with support $[0, 1]$.

5 Discussion

In this section, we implement some robustness checks on our analysis as well as discuss the comparison of our discount-based mechanism with other GPP mechanisms adopted in practice.

5.1 Robustness

Our results do not serve as a general argument in favor of GPP. The overall incentive effect of a discount depends on several factors that are relevant in an actual dynamic procurement market. In the following, we discuss a number of these.

First, while we assumed that the investment cost T is independent from the cost of implementing the contract c_i, these are, in practice, likely correlated. For example, the investment to switch from a combustion-engine transport fleet to an electric one will also change the cost of providing the transportation service, as the cost of operating the two types of fleet differ. However, the sign of this correlation is not straightforward (e.g., conventional engines might be cheaper but electric ones have longer life cycle). Adding such complexity to the model is beyond the scope of the analysis.

In addition, while we assumed that the investment cost T is fixed, in a competitive market, there may be heterogeneity in the adaptation costs. There are few studies on this and it is generally thought that firm size has a non-linear effect on adaptation costs (Camacho, 1991), making modeling difficult.

Note that we focus on a market with no *ex-ante* presence of green technology. This assumption approximates well the current status of the relevant pool of suppliers bidding for public contracts, a predominantly non-green market. However, it might be less so in a dynamic perspective where the share of green suppliers increases. The benefit of the discount in terms of creating incentives for investment might be lower in a setting where there are already green bidders.

Furthermore, we consider the environmental type of the firm to be binary. It remains an open question how, in a more realistic scenario with a continuous environmental type, a discount parameter changes incentives and which types of firms will be more inclined to improve their environmental performance.[18]

5.2 Comparison with other GPP mechanisms

While our setting considers a first-price auction with bid discount, alternative mechanisms are employed in practice for GPP implementation. These primarily include technical requirements, where all bidders must comply with minimum environmental standards, and scoring auctions (Asker and Cantillon, 2008, 2010), where an explicit weight is given to environmental quality relative to price. Finding an optimal mechanism requires a range of assumptions, but the model allows for a comparison of the discount-based GPP with these alternative methods.

5.2.1 Bid discount vs environmental standards

Our analysis reveals that a very large discount would result in the same allocation and investment level of making investment mandatory (i.e. requiring an environmental standard) but at a higher cost. This is as for high discounts, the price-decreasing signaling effect is strongly dominated by the price-increasing market power effect, such that total investment costs are delegated to the procurer. However, notice that we abstract from entry effects. In presence of costly technical requirements that increase the compliance cost for bidders, entry in the procurement auction might be discouraged, which might soften competition and increase price more than in a discount-based mechanism.

5.2.2 Bid discount vs scoring

As the procurer's objective function is two-dimensional and providing quality is costly, it is a natural question to ask whether a scoring auction provides a higher payoff to the procurer. Asker and Cantillon (2010) approach the problem by assuming that quality is chosen from $q_i \in [0, +\infty)$. They derive the optimal auction mechanism in which price p_i and quality q_i are chosen simultaneously by the bidders. Here, the winning bidder's profit is $p_i - c_i - d_i \cdot q_i$ where d_i is the privately known marginal cost of quality. In our model, the payoff function is a special case of this as we have $d_i = T$ and $q_i \in \{0, 1\}$. There are two key differences, both related to the fact that in our model quality is not a product characteristic, but an investment. First, the cost of providing quality is also borne by the losing bidders. Second, the game is dynamic so that the quality is observable in the bidding stage. In this respect, the two mechanisms are not comparable.

Nevertheless, it is natural to ask how a discount-based GPP compares to the widely used scoring

[18]For example, different green technologies have different potentials to reduce emissions relative to a given conventional technology benchmark (Bataille et al., 2018; Chiappinelli et al., 2021).

mechanism. Consider that the observability of investment is a technical feature of the market that is determined mainly by the size of investment and the time necessary to implement it.

Consider a scoring auction in which the bidder with the lowest score wins. The score is $b_i - \beta$ for investing and b_i for non-investing firms. The timing of the game is identical to our model; hence, at the time of submitting their bid, players know all investment decisions. Note that both the cost and the quality score are binary. It is easy to see that the equilibrium will have a similar form to that of a discount-based mechanism: For any n, β, T, there exists a critical value $c^*(n, \beta, T)$ such that investment occurs in equilibrium if and only if $c_i \leq c^*(n, \beta, T)$. The proof is analogous to that of Proposition 1. Analogously to (13), the critical type is indifferent between investing and not investing:

$$(\beta - \int_{c^*(\beta,n,T)}^{\bar{c}} (1 - \hat{F}(s))^{n-1} ds)(1 - F(c^*(n, \beta, T)))^{n-1} - T = 0. \tag{17}$$

The interesting finding from this is that under the assumption that the investment stage is observable, the scoring mechanism and discount-based mechanism are isomorphic. To see this, consider $\beta = \alpha \cdot c^*(n, \alpha, T)$. In that case, $c^*(n, \beta, T) = c^*(n, \alpha, T)$ satisfies the equation, which means there is a one-to-one correspondence between α and β. Moreover, this results in the same expected payoff to the procurer as the discount-based mechanism. Revisiting the three different kinds of subgames we discuss in Subsection 3.1 it is possible to note the following: If there are no or at least two investing firms, the setting is symmetric and the discount plays no role. If there is exactly one investing firm, this will submit a bid equal to $c^*(n, \beta, T) + \beta = (1 + \alpha) \cdot c^*(n, \alpha, T)$, which is identical to the bid submitted in the same subgame of discount-based GPP (Case 2).

What follows from this is that our main results are preserved by modeling GPP as a standard scoring auction, indicating that our findings are mostly driven by the dynamic nature of the game and consequent information disclosure rather than the specific mechanism adopted at the bidding stage.

6 Conclusion

In this paper, we challenge the perception that procurers face a trade-off between price and the environmental performance of the purchased good or service. In doing so, we consider a theoretical framework of Green Public Procurement (GPP) in which the procurer gives a bid discount to environment-friendly (green) bidders.

In our setting, bidders participate in a standard first-price sealed-bid auction with identically and independently drawn cost types. Our model assumes that bidders are *ex-ante* not environment-friendly (brown) but can undertake a costly and publicly observable investment and become green before the auction. We find that firms with lower costs invest, which acts as a signaling device. Information disclosure allows competition between similar types, inducing them to bid more aggressively, which puts downward pressure on price (the signaling effect). This can outweigh the price-increasing effect of giving an advantage to green firms in the auction, which allows investing types to inflate the bid (the market power effect). We conclude that even a procurer with no preference toward green technology will introduce a strictly positive discount at the optimum.

Therefore, GPP does not always imply a trade-off between purchasing price and environmental performance. Hence, even public buyers with a weak preference for environmental protection should consider its implementation. This consideration might be especially relevant for implementation at the local level, where contracting authorities typically face tighter budget constraints and implement a large share of public procurement.

While GPP needs to be complemented by other environmental policies to create a sufficient scale of incentives for suppliers to invest in environment-friendly options, it can play a crucial role in the short-term as broader policies need consensus to be adopted and time to become effective (Neuhoff et al. (2019)). It provides a flexible and tangible instrument for governments to reduce their environmental impact and create lead markets for green options, which can also signal their commitment to broader policies. Therefore, supporting the implementation of GPP is crucial and a robust economic assessment of barriers and drivers for implementation is necessary. This paper takes a step in this direction and suggests that financial constraints might be less relevant as a barrier than what is commonly believed.

A final consideration is that the model is not specific to the subject of green technology in the sense the same model could be applied to any quality dimension included in procurement that requires a costly publicly observable investment from firms. Nevertheless, existing public procurement regulations and practices only have a limited number of clearly defined objectives. Environmental performance stands out in its role both as a priority quality dimension and as an investment-induced factor. Therefore, green procurement seems to be well justified as the main application of the paper. Another frequently adopted objective that could be fitting this description is innovation procurement.

References

An, M. Y. (1998). Logconcavity versus logconvexity: a complete characterization. *Journal of Economic theory*, 80(2):350–369.

Aoki, R. and Reitman, D. (1992). Simultaneous signaling through investment in an r d game with private information. *Games and Economic Behavior*, 4(3):327 – 346.

Asker, J. and Cantillon, E. (2008). Properties of scoring auctions. *The RAND Journal of Economics*, 39(1):69–85.

Asker, J. and Cantillon, E. (2010). Procurement when price and quality matter. *The Rand Journal of Economics*, 41(1):1–34.

Athey, S., Coey, D., and Levin, J. (2013). Set-asides and subsidies in auctions. *American Economic Journal: Microeconomics*, 5(1):1–27.

Bagnoli, M. and Bergstrom, T. (2005). Log-concave probability and its applications. *Economic Theory*, 26(2):445–469.

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., and Rahbar, S. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the paris agreement. *Journal of Cleaner Production*, 187:960–973.

Brammer, S. and Walker, H. (2011). Sustainable procurement in the public sector: an international comparative study. *International Journal of Operations & Production Management*, 31(4):452–476.

Camacho, A. (1991). Adaptation costs, coordination costs and optimal firm size. *Journal of Economic Behavior & Organization*, 15(1):137–149.

Chiappinelli, O., Gerres, T., Neuhoff, K., Lettow, F., de Coninck, H., Felsmann, B., Joltreau, E., Khandekar, G., Linares, P., Richstein, J., Śniegocki, A., Stede, J., Wyns, T., Zandt, C., and Zetterberg, L. (2021). A green covid-19 recovery of the eu basic materials sector: identifying potentials, barriers and policy solutions. *Climate Policy*, 0(0):1–19.

Chiappinelli, O., Gruner, F., and Weber, G. (2019). Green public procurement: Climate provisions in public tenders can help reduce german carbon emissions. *DIW Weekly Report*, (51-52):433–441.

Chiappinelli, O. and Zipperer, V. (2017). Using public procurement as a decarbonisation policy: A look at germany. *DIW Economic Bulletin*, 7(49):523–532.

Corns, A. and Schotter, A. (1999). Can affirmative action be cost effective? An experimental examination of price-preference auctions. *American Economic Review*, 89(1):291–305.

Geng, Y. and Doberstein, B. (2008). Greening government procurement in developing countries: Building capacity in China. *Journal of Environmental Management*, 88(4):932–938.

Hubbard, T. P. and Paarsch, H. J. (2009). Investigating bid preferences at low-price, sealed-bid auctions with endogenous participation. *International Journal of Industrial Organization*, 27(1):1–14.

Jehiel, P. and Lamy, L. (2015). On discrimination in auctions with endogenous entry. *American Economic Review*, 105(8):2595–2643.

Kadefors, A., Lingegård, S., Uppenberg, S., Alkan-Olsson, J., and Balian, D. (2021). Designing and implementing procurement requirements for carbon reduction in infrastructure construction – international overview and experiences. *Journal of Environmental Planning and Management*, 64(4):611–634.

Krasnokutskaya, E. and Seim, K. (2011). Bid preference programs and participation in highway procurement auctions. *American Economic Review*, 101(6):2653–86.

Lindström, H., Lundberg, S., and Marklund, P.-O. (2020). How green public procurement can drive conversion of farmland: An empirical analysis of an organic food policy. *Ecological Economics*, 172:106622.

Lundberg, S., Marklund, P.-O., et al. (2013). Green public procurement as an environmental policy instrument: cost effectiveness. *Environmental Economics*, 4(4):75–83.

Lundberg, S., Marklund, P.-O., Strömbäck, E., and Sundström, D. (2015). Using public procurement to implement environmental policy: an empirical analysis. *Environmental Economics and Policy Studies*, 17(4):487–520.

Marron, D. B. (1997). Buying green: government procurement as an instrument of environmental policy. *Public Finance Review*, 25(3):285–305.

Maskin, E. and Riley, J. (2000). Asymmetric auctions. *The Review of Economic Studies*, 67(3):413–438.

McAfee, R. P. and McMillan, J. (1989). Government procurement and international trade. *Journal of international economics*, 26(3-4):291–308.

Milgrom, P. and Shannon, C. (1994). Monotone comparative statics. *Econometrica*, pages 157–180.

Myerson, R. B. (1981). Optimal auction design. *Mathematics of operations research*, 6(1):58–73.

Nakabayashi, J. (2013). Small business set-asides in procurement auctions: An empirical analysis. *Journal of Public Economics*, 100:28–44.

Neuhoff, K., Chiappinelli, O., Gerres, T., Haussner, M., Ismer, R., May, N., Pirlot, A., and Richstein, J. (2019). Building blocks for a climate-neutral european industrial sector. Technical report, Climate Strategies.

OECD (2019). Public procurement spending. In *Government at a Glance 2019*. OECD Publishing.

Rosell, J. (2021). Getting the green light on green public procurement: Macro and meso determinants. *Journal of Cleaner Production*, 279:123710.

Simchi-Levi, D., Chen, X., Bramel, J., et al. (2005). The logic of logistics. *Theory, algorithms, and applications for logistics and supply chain management.*

Simcoe, T. and Toffel, M. W. (2014). Government green procurement spillovers: Evidence from municipal building policies in california. *Journal of Environmental Economics and Management*, 68(3):411–434.

Testa, F., Annunziata, E., Iraldo, F., and Frey, M. (2016). Drawbacks and opportunities of green public procurement: an effective tool for sustainable production. *Journal of Cleaner Production*, 112:1893–1900.

Testa, F., Iraldo, F., Frey, M., and Daddi, T. (2012). What factors influence the uptake of GPP (green public procurement) practices? New evidence from an Italian survey. *Ecological Economics*, 82:88–96.

UN (2017). Global review of sustainable public procurement. Technical report, United Nations.

Varnäs, A., Balfors, B., and Faith-Ell, C. (2009). Environmental consideration in procurement of construction contracts: current practice, problems and opportunities in green procurement in the Swedish construction industry. *Journal of Cleaner Production*, 17(13):1214–1222.

Wiedmann, T. and Barrett, J. (2011). A greenhouse gas footprint analysis of UK Central Government, 1990–2008. *Environmental Science Policy*, 14(8):1041–1051.

Appendix

Proof of Proposition 1. We prove that there exists a unique cutoff value by showing that the decision problem in (10) satisfies the single-crossing property (Milgrom and Shannon, 1994): Lower (more efficient) types have more to gain from investment compared to the no-investment case. In other words, the benefit of investment $\pi(c_i, H_G) - \pi(c_i, H_B)$ is decreasing in c_i.

Let us consider two types c_i and c_i' such that $c_i \leq c_i'$.

$$\pi(c_i, H_G) - \pi(c_i, H_B) \geq \pi(c_i', H_G) - \pi(c_i', H_B) \tag{18}$$

where the investment cost T cancels out on both sides. Inequality (18) is satisfied if $\pi(\cdot)$ is convex (Simchi-Levi et al., 2005). The second-stage objective functions in (9) are concave in b_i; hence, their upper contour set is convex. That is, $\pi(c_i, H_G)$ and $\pi(c_i, H_B)$ are convex.[19]

If a critical value $c^*(\alpha, n, T)$ exists, the game proceeds as follows in equilibrium. In period 2, a firm invest if and only if $c_i \leq c^*(\alpha, n, T)$. In period 3, players face one of different subgames depending on how many firms have invested. As period 2 decisions are observable, bidders update their beliefs to a truncated type distribution of the cost type of an opposing bidder depending on the investment decision.

In the bidding stage, there can be two kinds of bidders, non-investing firms with $c_i > c^*(\alpha, n, T)$ and investing firms that turn green with $c_i \leq c^*(\alpha, n, T)$.

We show that a critical value $c^*(\alpha, n, T)$ can exist only if T is sufficiently low or α is sufficiently high, otherwise, no investment is undertaken by any type. That is, for any game parameters n, α, there is a pooling equilibrium without investment if T is large. Analogously, for any n, T, there is a pooling equilibrium without investment if α is low. In this case, investment is off the equilibrium path. We narrow our focus on the system of beliefs in which other bidders believe that an investing firm's type is $\underline{c}$ with certainty. Given the single crossing property, it is sufficient to inspect the most efficient type, i.e., $c_i = \underline{c}$. There is no investing firm if and only if this type is worse off from investing. The proof is as follows. Firm i wins with certainty irrespective of the investment decision. The critical T^* satisfies that type i is indifferent between investing or not as follows

$$(1 + \alpha)b^*(\underline{c}, 1, n) - \underline{c} - T = b^*(\underline{c}, 0, n) - \underline{c} \tag{19}$$

that is

$$T^*(\alpha, n) = \alpha \cdot b^*(\underline{c}, 1, n) - b^*(\underline{c}, 0, n). \tag{20}$$

An equivalent threshold on α, $\hat{\alpha}(n, T)$ can be derived. Therefore $c^*(\hat{\alpha}(\cdot), n, T) = c^*(\alpha, n, T^*(\cdot)) = \underline{c}$. □

[19] Intuitively, the case where a less efficient type invests while a more efficient one does not cannot occur in equilibrium, as given monotonicity the more efficient type has a larger probability of winning conditional on investment and, therefore, can profitably deviate.

Proof of Proposition 2. We implicitly determine the threshold cost type $c^*(\alpha, n, T)$ that is indifferent between investing and not investing. In order to do so, we solve the maximization problem of that type in both subgames. Second, we use these solutions to characterize the indifference condition and apply the implicit function theorem to determine the comparative statics of the threshold relative to the discount and the investment cost, i.e. the signs of $\frac{\partial c^*(\alpha,n,T)}{\partial \alpha}$ and $\frac{\partial c^*(\alpha,n,T)}{\partial T}$.

Consider the expected payoff for type $c^*(\alpha, n, T)$ after undertaking and abstaining from investment. An investing firm with $c^*(\alpha, n, T)$ wins with certainty if and only if it is the only investing firm. In that case, from (5) we have that its equilibrium bid is $b^*(c^*(\alpha, n, T), 1, n) = c^*(\alpha, n, T) \cdot (1 + \alpha)$ and the payoff $\alpha \cdot c^*(\alpha, n, T)$.

That i has the lowest cost $c^*(\alpha, n, T)$ happens with probability $(1 - F(c^*(\alpha, n, T)))^{n-1}$. Again, if the firm does not invest, it only wins if the other firms also do not invest, so the chance of winning is identical. Conditionally on not investing, there is a symmetric first-price auction in which the critical type bids according to (4):

$$b(c^*(\alpha, n, T), 0, n) = c^*(\alpha, n, T) + \frac{\int_{c^*(\alpha,n,T)}^{\bar{c}} (1 - \hat{F}(s))^{n-1} ds}{(1 - \hat{F}(c^*(\alpha, n, T)))^{n-1}}$$

$$= c^*(\alpha, n, T) + \int_{c^*(\alpha,n,T)}^{\bar{c}} (1 - \hat{F}(s))^{n-1} ds. \tag{21}$$

From this, as the critical type is indifferent between undertaking and abstaining from investment:

$$\left(\alpha \cdot c^*(\alpha, n, T) - \int_{c^*(\alpha,n,T)}^{\bar{c}} (1 - \hat{F}(s))^{n-1} ds\right) \cdot (1 - F(c^*(\alpha, n, T)))^{n-1} - T = 0 \tag{22}$$

which implicitly defines the critical value $c^*(\alpha, n, T)$. From (22), using the implicit function theorem, we get

$$\frac{\partial c^*(\alpha, n, T)}{\partial \alpha} = -\frac{\frac{\partial LHS}{\partial \alpha}}{\frac{\partial LHS}{\partial c^*(\alpha,n,T)}} = -\frac{c^*(\alpha, n, T)}{\frac{\partial LHS}{\partial c^*(\alpha,n,T)}} > 0. \tag{23}$$

where LHS is the left hand side of (22) which is positive as the denominator is negative due to the single crossing property. It is straightforward to check that

$$\frac{\partial c^*(\alpha, n, T)}{\partial T} = -\frac{\frac{\partial LHS}{\partial T}}{\frac{\partial LHS}{\partial c^*(\alpha,n,T)}} = -\frac{-1}{\frac{\partial LHS}{\partial c^*(\alpha,n,T)}} < 0. \tag{24}$$

□

Proof of Lemma 2. The expected winning bid $p(\alpha, n, T)$ can be rewritten as the weighted sum of expected winning bids in the different subgames determined by the number of investing brown firms. As we learn above, there are three distinct subcases. If there are at least two investing firms ($k \geq 2$), competition is between *ex-post* green firms with symmetric *interim* beliefs on type distribution. If there is only one investing firm ($k = 1$), that firm wins with certainty. If none of them invests ($k = 0$), brown firms compete again with symmetric *interim* beliefs on type distribution. That is (dropping the arguments of c^* to lighten the notation),

$$p(\alpha,n,T)=\sum_{k=2}^{n}\binom{n}{k}F(c^*)^k\cdot(1-F(c^*))^{n-k}\cdot\int_{s=\underline{c}}^{c^*}sk(k-1)f(s)F(s)(1-F(s))^{k-2}ds+$$
$$\binom{n}{1}F(c^*)\cdot(1-F(c^*))^{n-1}c^*(1+\alpha)+\binom{n}{0}F(c^*)^0\cdot(1-F(c^*))^n\cdot\int_{s=c^*}^{\bar{c}}sn(n-1)f(s)F(s)(1-F(s))^{n-2}ds \tag{25}$$

which can be rewritten as

$$p(\alpha,n,T)=\sum_{k=2}^{n}\binom{n}{k}F(c^*)^k\cdot(1-F(c^*))^{n-k}\cdot k(k-1)\int_{s=\underline{c}}^{c^*}sf(s)F(s)(1-F(s))^{k-2}ds+$$
$$nF(c^*)\cdot(1-F(c^*))^{n-1}c^*(1+\alpha)+(1-F(c^*))^n\cdot n(n-1)\int_{s=c^*}^{\bar{c}}sf(s)F(s)(1-F(s))^{n-2}ds \tag{26}$$

By taking the relevant derivative of (26) it is straightforward that

$$\frac{\partial p(\alpha,n,T)}{\partial\alpha}=nF(c^*)\cdot(1-F(c^*))^{n-1}c^*\geq 0 \tag{27}$$

with $\frac{\partial p(\alpha,n,T)}{\partial\alpha}=0$ when $c^*=\underline{c}$. □

Proof of Lemma 3. Using (13), we can express α as a function of c^*, which allows to rewrite (26) as follows

$$p(c^*,n,T)=\sum_{k=2}^{n}\binom{n}{k}F(c^*)^k\cdot(1-F(c^*))^{n-k}\cdot k(k-1)\int_{s=\underline{c}}^{c^*}sf(s)F(s)(1-F(s))^{k-2}ds+$$
$$nF(c^*)\cdot(1-F(c^*))^{n-1}c^*(1+\frac{\frac{T}{(1-F(c^*))^{n-1}}+\int_{c^*}^{\bar{c}}(1-\hat{F}(s))^{n-1}ds}{c^*})+$$
$$(1-F(c^*))^n\cdot n(n-1)\int_{s=c^*}^{\bar{c}}sf(s)F(s)(1-F(s))^{n-2}ds \tag{28}$$

Taking the relevant derivative of (28),

$$\frac{\partial p(c^*,n,T)}{\partial c^*}=\sum_{k=2}^{n}\binom{n}{k}k(k-1)F(c^*)^{k-1}f(c^*)(1-F(c^*))^{n-k-1}\cdot$$
$$[(k-F(c^*)n)\int_{s=\underline{c}}^{c^*}sf(s)F(s)(1-F(s))^{k-2}ds+F(c^*)^2(1-F(c^*))^{k-1}c^*]+$$
$$n\cdot f(c^*)\cdot(1-F(c^*))^{n-2}[1-F(c^*)n]\cdot[c^*+\frac{T}{(1-F(c^*))^{n-1}}+\int_{c^*}^{\bar{c}}(1-\hat{F}(s))^{n-1}ds]+$$
$$nF(c^*)\cdot(1-F(c^*))^{n-1}[1+\frac{T\cdot(n-1)(1-F(c^*))^{n-2}f(c^*)}{(1-F(c^*))^{n-1}}-(1-\hat{F}(c^*))^{n-1}]+$$
$$n(n-1)f(c^*)(1-F(c^*))^{n-1}\cdot$$
$$[-n\int_{s=c^*}^{\bar{c}}sf(s)F(s)(1-F(s))^{n-2}ds-c^*F(c^*)(1-F(c^*))^{n-1}] \tag{29}$$

Evaluating (29) at $c^* = \underline{c}$, we get

$$n \cdot f(\underline{c}) \cdot [\underline{c} + T + \int_{\underline{c}}^{\bar{c}} (1 - F(s))^{n-1} ds - n(n-1) \int_{\underline{c}}^{\bar{c}} sf(s)F(s)(1 - F(s))^{n-2} ds] \tag{30}$$

Using that

$$T^*(\alpha, n) = \alpha \cdot b^*(\underline{c}, k, n) = \alpha \cdot [\underline{c} + \int_{\underline{c}}^{\bar{c}} [1 - F(s)]^{n-1} ds],$$

we know the maximum value that (30) can take is

$$n \cdot f(\underline{c}) \cdot [(1 + \alpha)(\underline{c} + \int_{\underline{c}}^{\bar{c}} (1 - F(s))^{n-1} ds) - n(n-1) \int_{\underline{c}}^{\bar{c}} sf(s)F(s)(1 - F(s))^{n-2} ds]. \tag{31}$$

We show that

$$n \cdot f(\underline{c}) \cdot [\underline{c} + \int_{\underline{c}}^{\bar{c}} (1 - F(s))^{n-1} ds - n(n-1) \int_{\underline{c}}^{\bar{c}} sf(s)F(s)(1 - F(s))^{n-2} ds] < 0 \iff$$
$$\underline{c} + \int_{\underline{c}}^{\bar{c}} (1 - F(s))^{n-1} ds - n(n-1) \int_{\underline{c}}^{\bar{c}} sf(s)F(s)(1 - F(s))^{n-2} ds < 0 \tag{32}$$

Evaluating (32) at $n = 2$:

$$\underline{c} + \int_{\underline{c}}^{\bar{c}} (1 - F(s)) ds - 2 \int_{\underline{c}}^{\bar{c}} sf(s)F(s) ds < 0 \iff$$
$$\bar{c} < \int_{\underline{c}}^{\bar{c}} F(s) + 2sf(s)F(s) ds = \int_{\underline{c}}^{\bar{c}} F(s)[1 + 2sf(s)] ds \tag{33}$$

Using integration by part, this is equivalent to

$$\bar{c} + \int_{\underline{c}}^{\bar{c}} F(s) ds + 2([\frac{1}{2} s \cdot F(s)^2]_{\underline{c}}^{\bar{c}} - \int_{\underline{c}}^{\bar{c}} \frac{1}{2} F(c)^2 ds) = \bar{c} + \int_{\underline{c}}^{\bar{c}} F(s) - F(s)^2 ds > \bar{c} \tag{34}$$

which holds. Note that

$$\lim_{n \to \infty} [\underline{c} + \int_{\underline{c}}^{\bar{c}} (1 - F(s))^{n-1} ds - n(n-1) \int_{\underline{c}}^{\bar{c}} sf(s)F(s)(1 - F(s))^{n-2} ds] =$$
$$\underline{c} + \lim_{n \to \infty} \int_{\underline{c}}^{\bar{c}} (1 - F(s))^{n-1} ds - n(n-1) \int_{\underline{c}}^{\bar{c}} sf(s)F(s)(1 - F(s))^{n-2} ds = \underline{c} > 0 \tag{35}$$

□

Proof of Lemma 4. First, we show that

$$\lim_{\alpha \to \infty} c^*(\alpha, n, T) = \bar{c} \tag{36}$$

We prove this by contradiction. As c^* is increasing in α and bounded from above, it is convergent. Assume that the RHS of this equation is instead equal to $\tilde{c} < \bar{c}$. Using (13), we have that

$$\lim_{\alpha\to\infty}\left(\alpha\cdot c^*(\alpha,n,T)-\int_{c^*(\alpha,n,T)}^{\bar{c}}(1-\hat{F}(s))^{n-1}ds\right)\cdot(1-F(c^*(\alpha,n,T)))^{n-1}-T=$$

$$\lim_{\alpha\to\infty}\alpha\cdot\tilde{c}\cdot(1-F(\tilde{c}))^{n-1}-T>0 \tag{37}$$

as both $\tilde{c}$ and $(1-F(\tilde{c}))^{n-1}$ are positive and finite, which is a contradiction.

Consider again the expression in (28) where α is expressed as a function of c^*,

$$p(c^*,n,T)=\sum_{k=2}^{n}\binom{n}{k}F(c^*)^k\cdot(1-F(c^*))^{n-k}\cdot k(k-1)\int_{s=\underline{c}}^{c^*}sf(s)F(s)(1-F(s))^{k-2}ds+$$
$$nF(c^*)\cdot(1-F(c^*))^{n-1}c^*(1+\frac{\frac{T}{(1-F(c^*))^{n-1}}+\int_{c^*}^{\bar{c}}(1-\hat{F}(s))^{n-1}ds}{c^*})+$$
$$(1-F(c^*))^n\cdot n(n-1)\int_{s=c^*}^{\bar{c}}sf(s)F(s)(1-F(s))^{n-2}ds \tag{38}$$

Taking the relevant limit gives the result in (16). □