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Natalia Fabra and Juan Pablo Montero

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Centre for Economic Policy Research
33 Great Sutton Street, London EC1V 0DX, UK
Tel: +44 (0)20 7183 8801
www.cepr.org

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Abstract

An imperfectly-informed regulator needs to procure multiple units of a good that can be produced with heterogeneous technologies at various costs. Should she run technology-specific or technology-neutral auctions? Should she allow for partial separation across technologies (technology banding)? Should she instead post separate prices for each technology? What are the trade-offs involved? We find that one size does not fit all: the preferred instrument depends on the nature of the available technologies, the extent of information asymmetry regarding their costs, the costs of public funds, and the degree of market power. Using Spanish data on recently deployed renewables across the country, we illustrate how our theory can shed light on how to more effectively procure these technologies. Beyond this motivation/application, the question of how to procure public goods in the presence of multiple technologies is relevant for a wide variety of goods, including central banks liquidity, pollution reduction, or land conservation, among others.

JEL Classification: N/A

Keywords: Procurement, auctions, quantity regulation, Price regulation, third degree price discrimination, market power

Natalia Fabra - natalia.fabra@uc3m.es
Universidad Carlos III de Madrid and CEPR

Juan Pablo Montero - jmontero@uc.cl
PUC-Chile

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Technology-Neutral *vs.* Technology-Specific Procurement*

Natalia Fabra
Universidad Carlos III and CEPR

Juan-Pablo Montero
PUC-Chile and ISCI

December 10, 2020

Abstract

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1 Introduction

A regulator needs to procure multiple units of an homogenous good or service that can be produced with heterogenous technologies. Should she procure these units by running a single auction or several auctions, one for each technology? Should she rather run a single auction in which some technologies get a handicap (technology banding)? Or should she post prices

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instead? In answering these questions, what are the trade-offs involved and how do they depend on the nature of the available technologies, the extent of information asymmetry regarding their costs, and the degree of market power?

These questions are motivated by a fundamental challenge faced by many governments around the world in their efforts to reduce carbon emissions: how to accelerate the deployment of multiple low-carbon technologies, including renewable energies (e.g., solar, wind, or biomass) or storage facilities (e.g. pumped storage or batteries), at the lowest possible fiscal cost (Council of European Energy Regulators, 2018). In practice, several instruments have been used (and continue to be used) for such purposes, e.g., quantity-based instruments such as auctions or tradeable quota obligations, or price-based instruments like Feed-in-Tariffs or Feed-in-Premia. Some of these instruments have treated technologies separately, whether by type, location and/or scale. Other instruments have been technologically neutral.[1] And yet other instruments have relied on hybrid approaches (so called technology banding) that allow for some degree of competition across technologies while favouring some over others (e.g., by deflating the bids associated to some technologies, or by granting more green certificates to some technologies).

Beyond this motivation, the question of how to procure goods in the presence of multiple technologies is relevant in a wide variety of public-procurement settings. Another notable example arises in the context of the liquidity auctions ran by central banks, in which borrowers (i.e., the banks) offer either good or bad collateral in exchange for liquidity (Klemperer, 2010). The three options are for the central bank to fix the interest rate for each type of collateral (technology-specific price approach), run a joint auction for both types of collateral (technology-neutral quantity approach), or a separate auction for each type of collateral (technology-specific quantity approach).[2] While central banks currently favour joint auctions, they have used simpler approaches in the past, such as running separate auctions (Frost et al., 2015). The debate regarding the design of liquidity auctions is still ongoing. Other settings in which the choice across these approaches is relevant include procurement of pollution reduction (Laffont and Tirole, 1996), or land conservation (Mason and Plantinga, 2013), among others.

The choice between technology-neutral and technology-specific instruments involves a clear trade-off between efficiency and rent extraction. On the one hand, as the European Commission (2013) has pointed out, well-designed technology-neutral approaches are more effective in find-

[1] The European Union's Energy and Environmental State Aid Guidelines (currently under revision) require that auction schemes have to treat all technologies on a non-discriminatory basis (technology-neutral), with only few exceptions allowed. This has prompted a shift from technology-specific to technology-neutral auctions in recent years, from 1 in 2015 to 18 in 2019 (Jones and Pakalkaite, 2019). Still, there exist many technology- or location-specific mechanisms in place. For instance, the 2009 European Union's Renewables Energy Directive determines renewables targets at the national level, with no trading across countries.

[2] An interesting feature of some liquidity auctions is that the central bank has flexibility to adjust its total demand, as well as the allocation across types of collateral, once the bids have been submitted. As we show in this paper, the possibility of ex-post adjustments make the technology-specific approach dominate technology-neutrality. However, there are several settings in which such ex-post adjustments are not possible, leading to a trade-off between the two approaches, as described next.

ing the cheapest technology sources, but they may also result in over-compensation. Indeed, by not discriminating among heterogenous sources, the authority may be leaving too much rents with some suppliers, unnecessarily increasing the costs of procurement. On the other hand, a well-designed technology-specific approach might fail to achieve efficiency by discriminating across technologies of unknown costs. Without ex-ante knowledge of the costs of the various technologies, setting ex-ante prices or quantities might result in inefficient but also costly allocations given that the quantities allocated to each technology do not adjust ex-post.

This trade-off between efficiency and rent extraction has been central to the regulation and public procurement literature (Laffont and Tirole, 1993). Yet, our approach takes a different angle relative to the standard principal-agent model (Laffont and Tirole, 1993; Laffont and Martimort, 2002). We consider a continuum of agents (i.e., firms) with capacity to supply one unit of some commodity (e.g., green energy) according to different costs and production technologies (e.g., wind or solar). While technologies are observable, costs are not. The principal (i.e., regulator) can therefore choose to make the regulatory contract conditional on the technology (technology-specific approach) or not (technology-neutral approach). In our context, the rent-efficiency trade-off arises as the quantity allocated to each technology (not to the various cost types) is distorted from the expected cost-minimizing allocation in order to reduce overall firms' rents (even if the rents that accrue to one technology go up).

Although this rent-efficiency trade-off has also been recognized in the realm of renewable energy procurement (EC, 2013; CEER, 2018), its impact on the preferred regulatory instrument to promote renewables has not been systematically analyzed. Furthermore, following Weitzman (1974)'s seminal work, the regulation literature has assessed the relative performance of prices versus quantities, but it has done so in the case of a single technology or under the assumption that the regulator only cares about productive efficiency, thus leaving no scope for the rent-efficiency trade-off to play a role.

Yet, it is not clear whether quantity-based approaches (e.g., auctions) should be preferred over price-based approaches (e.g., Feed-in Tariffs), and how this choice is affected in the presence of multiple technologies (e.g. solar and wind, or pumped storage and batteries). Furthermore, it is not clear when and why rent extraction concerns (i.e., the risk of over-compensating some sources) may dominate efficiency concerns (i.e., the risk of departing from cost minimization), and to what extent these concerns are best managed through technology separation or technology banding (i.e., favour some technologies over others but still have them compete in the same auction).

In the context of renewables, complementarities across technologies, which a technology-neutral approach would fail to exploit, might favour the use of a technology- or location-specific approach. There are several reasons for this. For instance, wind and solar are often seen as complementary as their availability is negatively correlated; as such, in an eletricity market with an already strong solar penetration, an additional unit of solar power may be less valuable than an additional unit of wind (Joskow, 2011; Hirth, 2013). Likewise, avoiding excessive concentration of investments in a single area is valuable as it reduces the incidence of grid bottlenecks. And because of uncertain learning spillovers, it might be optimal to diversify support across technologies rather than have investors pick the one with the lowest current costs. Similar issues arise in the context of central bank liquidity auctions, in which good and bad collateral cannot clearly be considered as substitutes. Last, some authors have advocated for the use of price instruments (e.g. Feed-in-Tariffs) because some types of quantity instruments (e.g. tradable green certificates) lead to price risks, which in turn increase financing costs (May and Neuhoff, 2019). However, since we do not want to tilt the comparison in favour of a particular approach, we will purposely abstract from such issues by assuming that (i) all technologies are perfect substitutes in yielding social benefits,[3] and (ii) investors are risk neutral. Relaxing these assumptions would favour (i) the technology-specific approach or technology banding over technology neutrality, and (ii) price instruments over quantity instruments that face investors with price volatility.

Our main objective is to provide a sufficiently general framework in which to understand, from a purely economic-regulatory perspective, when and why a particular approach should be preferred over another. Our model is simple but rich enough to properly weight some of the key factors involved in technology procurement design in practice. We consider two types of technologies, say, solar and wind,[4] and a continuum of suppliers of each technology. In order to model the planner's incomplete information, we assume that the supply curves are subject to positively or negatively correlated shocks across technologies. The planner's objective is to maximize (expected) social benefits minus total costs, subject to a budget constraint that captures the cost of public funds.

Equipped with this set up, we first consider the case of quantity regulation, i.e., procurement auctions. The planner can either procure a given number of units in a single technology-neutral uniform-price auction, or the same number of units divided in two separate technology-specific uniform-price auctions. Since a firm has no influence over clearing prices, a technology-neutral uniform-price auction is the optimal mechanism when the planner cannot discriminate suppliers according to their technologies. Does this result still hold when the planner can treat technologies differently?

We show that fully separating technologies in different auctions can sometimes dominate the full technology-neutral approach. In particular, (optimally) separating technologies allows to reduce the rents that are left with suppliers, an issue that does not arise in the presence of a single technology.[5] In contrast, setting technology-specific quantity targets might give rise to higher cost as the quantity allocation across technologies does not adjust to the realized

[3]This is in contrast to the analysis in Klemperer (2010) who assumes that the two goods, or the two technologies, are imperfect substitutes.

[4]The model could easily be extended to more than two technologies with similar conclusions.

[5]In a context of carbon trading accross countries, Martimort and Sand-Zantman (2016) also find that preventing trade across countries is part of the optimal mechanism, insofar it allows controlling rents going to the different countries.

cost shocks. Therefore, the planner should opt for the technology-neutral design only when the efficiency gain outweighs the rent loss from not running separate auctions.

What does this trade-off depend on? Not surprisingly, we find that a well informed regulator should always run separate auctions, with the technology-specific targets chosen so as to balance cost minimization and rent extraction (which results in the equalization of the social costs of both technologies). A similar prescription should be followed if the two technologies are subject to perfectly correlated shocks: cost minimization is not in danger either but technology separation allows to reduce rents. As incomplete information mounts, minimizing costs through technology separation becomes increasingly challenging as quantity targets do not adjust to the cost shocks. Eventually, technology neutrality may dominate technology separation unless the costs for the government of not discriminating technologies is too large. This ultimately depends on the amount of over-compensation to the more efficient suppliers – as captured by the cost difference across technologies – and the unit price of this over-compensation – as captured by the shadow cost of public funds.

Adding market power to the model brings in new insights. Under technology-specific auctions, market power makes it optimal to further distort the quantity targets, giving rise to more productive inefficiency as compared to the technology-neutral approach. While such quantity distortions also allow to reduce rents, the planner's ability to do so through technology separation is diminished the more market power there is. Hence, market power tends to favour the technology-neutral approach.

Since neither technology neutrality nor technology separation succeed in containing both costs and payments, one may argue in favour of a hybrid approach that allows for some partial separation between technologies. Indeed, a handful of countries currently rely on a partial separation approach (referred to as "technology banding") for setting renewable support. The idea is to run a single uniform-price auction with suppliers of the ex-ante inefficient technology (or less resourceful location) receiving a handicap in order to compete more effectively with suppliers of the ex-ante more efficient technology (or location).[6] Very often, banding is used to penalize technologies that are considered less valuable, or to incentivize the more valuable ones.[7] Yet, we show that banding can be useful as a payments containment device even in

[6]One example of technology banding is provided by the reference yield model for wind that has been in place in Germany since 2000. It relies on plant- and site-specific adjustment factors which favour investment in sites with less wind. The Renewable Obligation scheme that was in place in the United Kingdom (and which was very similar to the Renewable Portfolio Standard programs in the US) offers another example. Renewable producers are allowed to issue Renewable Obligation Certificates (ROC) which electricity suppliers have to buy to meet their obligations. While the default was that one ROC would be issued for each MWh of renewable output, the system was subsequently reformed so that some technologies were allowed to issue more, others less. For instance, in 2017, offshore wind installations were entitled to receive 1.8 ROCs per MWh, 0.9 ROCs per MWh for onshore wind installations or 1.4 for building mounted solar photovoltaics (UK Government, 2013).

[7]For instance, in the renewable auctions run in Mexico, plants that have a generation profile that matches the system's needs receive an additional remuneration, while plants whose production profile is less valuable get penalized (IRENA, 2019).

settings in which all technologies are equally valuable.

Whereas one may be speculate that the banding approach is superior relative to the two extremes of full neutrality or full separation, this is not always the case. Trivially, banding always dominates technology neutrality as one can always set a neutral handicap. However, through banding one cannot replicate the same outome as under technology separation, and we find that banding does not always dominate technology separation. Not only technology separation is better equipped at containing total payments, but more surprisingly, it might also lead to lower costs as compared to banding. The problem with banding is that the handicap that is designed to contain payments also distorts technology substitution away from the efficient allocation. Cost shock volatility coupled with convex costs, imply (through Jensen's inequality) that expected costs under banding might be higher than under technology separation. This is particularly the case when the correlation of cost shocks is sufficiently high.[8]

Another dilemma faced by regulators is whether to choose prices or quantities. Unlike quantities, choosing two prices (i.e., technology-specific approach) weakly dominates the choice of a single price (i.e., technology neutrality). This is so by construction, except when public funds are costless, in which case the two optimal prices are equal. So, in comparing prices versus quantities, we are simply left to considering the choice between posting two technology-specific prices and whatever is the preferred design under quantity regulation.

First, suppose that technology-specific auctions dominate technology-neutral auctions. In this case, the comparison of price versus quantity regulation gives rise to a modified version of Weitzman's (1974) seminal expression.[9] As it is well understood, a relatively more convex supply curve favors prices because "mistakes" on the supply side become costlier than on the benefit side. The presence of multiple technologies enhances the superiority of the price instrument relative to the quantity instrument since prices allow the quantities of the various technologies (and not just the total quantity) to better adjust ex-post to the cost shocks. Even if the regulator is concerned about rent extraction, the cost of public funds plays no role in the comparison given that both the technology-specific prices and quantities are equally suited to reduce suppliers' rents. However, the fact that public funds are costly is precisely what makes it relevant to compare the technology-specific approaches. Otherwise, the only relevant comparison would be between technology-neutral prices and quantities given that separation would bring no benefits in terms of rent extraction.[10]

Second, if the preferred design under quantity regulation involves technology-neutrality, the comparison of prices versus quantities explicitly includes a rent extraction term, plus the modified version of the Weitzman's effect. The former tilts the comparison in favour of choosing

[8]Using a similar framework but in the context of integrating pollution permit markets, Montero (2001) also finds that in some cases a corner solution (alike to technology separation in our set-up) may be optimal.

[9]The two expressions coincide only when the cost shocks are perfectly correlated, as in this case the two technologies behave just as one.

[10]For this reason, it is unclear (at least to us) why Weitzman (1974) contains an analysis with multiple-technologies (Section V). In any event, unlike us, he does not compare the technology-neutral versus the technology-specific solutions, which is the main focus of our analysis.

two prices, the more so the more valuable it is to discriminate across technologies. However, if public funds are not too costly, a single quantity target can dominate the choice of two prices because it allows for more quantity adjustment across technologies, therefore leading to higher efficiency.

The rest of the paper is organized as follows. Section 2 describes the model and characterizes the optimal solutions when the regulator uses a technology-neutral auction or two technology-specific auctions. Section 3 analyzes the case with technology banding. Section 4 adds market power to understand how it affects the comparison across approaches. Section 5 analyzes the solution under price regulation and compares it with the quantity solution, whether it involves a technology-neutral or a technology-specific approach. Section 6 illustrates the results of the model through a simulation of auctions for new investments in solar and wind capacity in the Spanish market. And section 7 concludes, with most proofs relegated to the Appendix.

2 The Model

There are two types of technologies, say, solar and wind, denoted by 1 and 2. Each technology $t = 1, 2$ can be supplied by a continuum of (risk-neutral) price-taking firms with unit capacity and whose mass is normalized to one.[11] Their unit costs are uniformly distributed over the interval $[\underline{c}_t, \bar{c}_t]$, where $\underline{c}_t = c_t + \theta_t$ and $\bar{c}_t = c_t + \theta_t + C''$.[12] Therefore, the aggregate cost of supplying $q_t \in [0, 1]$ units of technology t is given by the quadratic function

$$C_t(q_t, \theta_t) = (c_t + \theta_t)\, q_t + \frac{1}{2} C'' q_t^2, \tag{1}$$

where $C'' > 0$ is common to both technologies and θ_t is a "cost shock" that captures the planner's incomplete information about the costs of supplying technology t (both c_t and C'' are public information). We allow c_t and θ_t to differ across technologies, with $E[\theta_t] = 0$ and $E[\theta_t^2] = \sigma > 0$ for $t = 1, 2$. Furthermore, we allow cost shocks to be either positively or negatively correlated across technologies, i.e., $E[\theta_1\theta_2] = \rho\sigma$, with $\rho \in [-1, 1]$. Without loss of generality, we index technologies such that $c_1 \leq c_2$, implying that technology 1 is ex-ante more efficient than technology 2. We use $\Delta c \equiv c_2 - c_1 \geq 0$ and $\Delta\theta \equiv \theta_2 - \theta_1$.

The deployment of these technologies creates social benefits, which we also capture with a quadratic function of the form

$$B(Q) = bQ + \frac{1}{2} B'' Q^2,$$

where $Q = q_1 + q_2$ is the total number of units supplied, with $b > 0$ and $B'' < 0$.[13] From the social point of view, both technologies are perfect substitutes as they create the same social

[11] In Section 4 we add market power to the analysis.

[12] Unit costs are increasing and uncertain, partly because sites vary in quality, as also emphasized in Schmalensee (2012).

[13] The linearity of marginal benefits is not needed for the analysis, but it is convenient to obtain closed-form solutions.

benefits. We assume that b and c_t are such that $b > c_t + \theta_t > 0$ for any realization of θ_t, making it always optimal to procure units from both technologies.

The risk-neutral planner's objective is to maximize (expected) social welfare subject to a budget constraint,

$$W(q_1, q_2) = E\left[B(q_1 + q_2) - C(q_1, q_2) - \lambda T(q_1, q_2)\right] \tag{2}$$

where $C(q_1, q_2)$ denotes the cost of supplying q_1 and q_2 units, $T(q_1, q_2)$ denotes the planner's total payment, and $\lambda \geq 0$ is the shadow cost of public funds (Laffont and Tirole, 1993). We will refer to $C(q_1, q_2) + \lambda T(q_1, q_2)$ as the *social cost*, which takes into account both the actual production costs as well as the costs of the fiscal distortions. This formulation is general enough to accommodate different procurement instruments. The functions $C(q_1, q_2)$ and $T(q_1, q_2)$ will take different forms as we move across these instruments.

We start with the case in which the planner chooses quantity targets. If the planner's target is to procure Q units, one option is to run a uniform-price auction that is open to both technologies. Suppliers would bid their true costs and the planner would pay the market-clearing price times the total quantity Q. As it turns out, this technology-neutral auction is the best mechanism to procure Q units when the planner cannot discriminate (price-taking) suppliers according to their technologies (see, for example, Segal 2003). Does it still hold that this technology-neutral auction is optimal when the planner can indeed separate suppliers according to their technologies? We address this question by first comparing a technology-neutral auction versus two technology-specific (uniform-price) auctions. We leave for later sections the comparison with other alternative mechanisms.

2.1 Technology-Neutral Auctions

Consider first a technology-neutral auction and denote by Q^N the planner's optimal quantity choice:[14]

$$Q^N = \arg\max_Q W(Q).$$

The planner is certain about the total quantity Q^N, but she does not know the allocation across technologies, which depends on the realized cost shocks. Indeed, market clearing implies that the marginal costs across technologies will be equalized, that is,

$$p^N = c_1 + \theta_1 + C'' q_1^N = c_2 + \theta_2 + C'' q_2^N, \tag{3}$$

where p^N denotes the market-clearing price. Using (3) and $Q^N = q_1^N + q_2^N$, the equilibrium contribution of each technology to total output is given by

$$q_1^N(Q^N, \theta_1, \theta_2) = \frac{Q^N + \Phi^N}{2} + \frac{\Delta\theta}{2C''} \tag{4}$$

$$q_2^N(Q^N, \theta_1, \theta_2) = \frac{Q^N - \Phi^N}{2} - \frac{\Delta\theta}{2C''}. \tag{5}$$

[14]Note that technology neutrality is also achieved under technology-specific auctions followed by a secondary market where the good can be freely traded.

where

$$\Phi^N \equiv E\left[q_1^N(Q^N,\theta_1,\theta_2)\right] - E\left[q_2^N(Q^N,\theta_1,\theta_2)\right] = \frac{\Delta c}{C''} \tag{6}$$

denotes the difference between the expected quantities allocated to each technology. The ex-ante more efficient technology is allocated a higher quantity, the more so the greater its cost advantage and the flatter the aggregate supply curve. Note that if cost shocks are perfectly and positively correlated, i.e., $\theta_1 = \theta_2$, then the planner can perfectly anticipate the allocation to each technology. Otherwise, these allocations remain uncertain.

Using equations (3) to (5), one can also obtain the market-clearing price as a function of the cost shocks,

$$p^N(Q^N,\theta_1,\theta_2) = \frac{c_1+c_2+\theta_1+\theta_2}{2} + \frac{C''Q^N}{2}, \tag{7}$$

which reaches the maximum level of uncertainty when shocks are perfectly and positively correlated, and the minimum when shocks are perfectly and negatively correlated (i.e., $\theta_1 = -\theta_2$), in which case there is no price uncertainty.

With these expressions, one can compute total costs in equilibrium,

$$C\left(q_1^N,q_2^N\right) \equiv \sum_{t=1,2} C_t(q_t^N(Q^N,\theta_t,\theta_{-t}),\theta_t)),$$

as well as total equilibrium payments,

$$T\left(q_1^N,q_2^N\right) \equiv p^N(Q^N,\theta_1,\theta_2)Q^N.$$

Taking expectations and using equations (4), (5) or (7), we obtain

$$E[C\left(q_1^N,q_2^N\right)] = \frac{c_1+c_2}{2}Q^N + C''\left(\frac{Q^N}{2}\right)^2 - \frac{(\Delta c)^2 + E[(\Delta\theta)^2]}{4C''} \tag{8}$$

and

$$E\left[T\left(q_1^N,q_2^N\right)\right] = \frac{c_1+c_2+C''Q^N}{2}Q^N. \tag{9}$$

For future reference, let

$$W_q^N \equiv B(Q^N) - E[C(q_1^N,q_2^N)] - \lambda E[T(q_1^N,q_2^N)]$$

be expected welfare under a technology-neutral auction.

2.2 Technology-Specific Auctions

Consider now a mechanism that exploits the planner's ability to discriminate suppliers according to their technologies. In particular, consider two technology-specific (uniform-price) auctions and denote by q_1^S and q_2^S the planner's optimal choices:

$$(q_1^S,q_2^S) = \arg\max_{q_1,q_2} W(q_1,q_2),$$

with $Q^S = q_1^S + q_2^S$. The market-clearing price in auction $t = 1, 2$, denoted p_t^S, is equal to marginal cost,

$$p_t^S(q_t^S, \theta_t) = C'' q_t^S + c_t + \theta_t. \tag{10}$$

Using (3) and $Q^S = q_1^S + q_2^S$, the equilibrium contribution of each technology to total output is given by

$$q_1^S = \frac{Q^S + \Phi^S}{2} \tag{11}$$

$$q_2^S = \frac{Q^S - \Phi^S}{2} \tag{12}$$

where

$$\Phi^S \equiv q_1^S - q_2^S = \frac{\Delta c}{C''} \frac{1+\lambda}{1+2\lambda} < \Phi^N \tag{13}$$

denotes the difference in the quantity targets across technologies. This difference is narrower than in the technology-neutral case, the more so the higher λ.

Similarly as above, one can compute total costs and total payments in equilibrium, which are respectively given by

$$C(q_1^S, q_2^S) \equiv \sum_{t=1,2} C_t(q_t^S, \theta_t)$$

$$T(q_1^S, q_2^S) \equiv \sum_{t=1,2} p_t^S(q_t^S, \theta_t) q_t^S.$$

As compared to the technology-neutral case, the equilibrium prices in the two auctions need not coincide, which matters for total payments.

With these expressions, one can also compute the expected welfare under technology-specific auctions,

$$W_q^S \equiv B(Q^S) - E[C(q_1^S, q_2^S)] - \lambda E[T(q_1^S, q_2^S)],$$

which is invariant to shocks.

Our first lemma greatly facilitates the comparison of technology-neutral and technology-specific auctions.

Lemma 1 *The optimal total quantity in a technology-neutral auction and in technology-specific auctions is the same, $Q^N = Q^S$, but the expected quantities allocated to each technology are not, with $q_1^S \leq E\left[q_1^N\right]$ and $q_2^S \geq E\left[q_2^N\right]$.*

Proof. See the Appendix. ■

Lemma 1 above points at two important results. First, under either mechanism, the planner procures the exact same total quantity. The reason is that, because the marginal social costs are equalized at the margin, procuring an extra unit of output under either instrument is expected to cost the same to society, taking into account both the actual costs, $C(q_1, q_2)$, as well as the fiscal distortions, $\lambda T(q_1, q_2)$.

The fact that the marginal social costs are the same does not imply however that the social costs are also the same. Indeed, they are not. The second result of Lemma 1 establishes that actual costs and payments are expected to differ because individual quantities are likely to be different; not only ex-post, once the cost shocks are realized, but more interestingly, ex-ante. Indeed, using the expressions (4)-(5) and (11)-(12), as well as $Q^N = Q^S$,

$$q_1^S - E\left[q_1^N\right] = E\left[q_2^N\right] - q_2^S = \Phi^S - \Phi^N < 0.$$

In words, as compared to the technology-neutral design, the planner now procures less of the ex-ante more efficient technology (technology 1) and more of the ex-ante less efficient technology (technology 2) in order to reduce payments.[15] Indeed, by increasing the allocation to the ex-ante less efficient technology, the planner can now reduce the over-compensation to the more efficient technology. Since the reduction in the rents going to technology 1 dominates over the increase in the rents going to technology 2, total payments decrease. Therefore, as compared to the technology-neutral design, the reduction in expected payments under the technology-specific design is fundamentally linked to the quantity distortion, as reflected in

$$E\left[T(q_1^S, q_2^S)\right] - E\left[T(q_1^N, q_2^N)\right] = \frac{C''}{2}\left(\Phi^S - \Phi^N\right)\Phi^S < 0. \tag{14}$$

However, this payment reduction comes at the expense of increasing costs, as captured by the first term of the right-hand-side in the next expression,

$$E\left[C(q_1^S, q_2^S)\right] - E[C(q_1^N, q_2^N)] = \frac{C''}{4}\left(\Phi^S - \Phi^N\right)^2 + \frac{E[(\Delta\theta)^2]}{4C''}. \tag{15}$$

The second term in (15) captures the fact that under cost uncertainty, costs are minimized under a technology-neutral approach as, unlike the technology-specific approach, quantities adjust to the actual cost shocks.

2.3 Comparison

Expressions (14) and (15) capture the basic trade-off faced by the planner who must decide whether to keep technologies competing together in the same auction, or to separate them. The former approach favors cost efficiency while the latter allows to reduce payments. This trade-off is at the heart of our first proposition.

Proposition 1 *The planner should favor a technology-neutral auction over technology-specific auctions if and only if*

$$W_q^N - W_q^S \equiv \Delta W_q^{NS} = \frac{1}{4C''}\left[2\sigma(1-\rho) - \frac{\lambda^2}{1+2\lambda}(\Delta c)^2\right] > 0. \tag{16}$$

[15] Note that if it were costless to raise public funds ($\lambda = 0$), $\Phi^S = \Phi^N$ and there would be no quantity distortion.

Proof. It follows immediately from comparing W_q^N and W_q^S and using $E[(\Delta\theta)^2] = 2\sigma(1-\rho)$ and the expressions for Φ^S and Φ^N. ■

According to the proposition, the planner should opt for the technology-neutral design when the efficiency loss of not doing so - as captured by first term in brackets in (16) - is more important than the additional rents left with suppliers from not running separate auctions - as captured by the second term. Expression (16) tells us that a well informed regulator (which here is equivalent to assuming $\sigma \to 0$) should always run separate auctions, with q_1^S and q_2^S chosen in a way to balance the minimization of costs and payments. A similar prescription should be followed if the two technologies are subject to similar shocks (i.e., $\rho \to 1$), because in this case ex-post cost minimization is no longer an issue. As incomplete information mounts, however, she may reverse her decision in favour of technology neutrality unless the cost for the planner of leaving high rents to the suppliers is too large. This ultimately depends on the amount of over-compensation to the more efficient suppliers - as captured here by the cost difference Δc - and the unit price of this over-compensation - as captured here by the shadow cost of public funds, λ (note that $\lambda^2/(1+2\lambda)$ is increasing in λ).

One option to avoid this rent efficiency trade-off under the technology-specific approach is to allow the auctioneer to choose the quantities ex-post, once bidders have submitted their bids. This would allow the auctioneer to reduce payments relative to technology neutrality without incurring in unintended productive inefficiencies.[16] Indeed, this would be equivalent to assuming $\sigma \to 0$, in which case the technology-specific approach dominates, as argued above. However, for reasons outside the model, there are many settings in which ex-post quantity adjustments are not feasible.[17] In all such settings, the rent-efficiency trade off highlighted above applies.

3 Technology Banding

Since neither technology neutrality nor technology separation succeed in containing both costs and payments, one may argue for a "more flexible" mechanism that could better accommodate both objectives. Technology banding appears to be one such mechanism, as currently implemented in a handful of countries for renewable support mechanisms. The idea is to run a single uniform-price auction with suppliers of the ex-ante inefficient technology (technology 2) receiving a handicap $\alpha > 1$ in order to compete more effectively with suppliers of the ex-ante

[16]The ability to change the quantities ex-post is well known in the literature as a way to mitigate market power (Back and Zender, 2001; Damianov *et al.*, 2010). In the presence of multiple technologies, our results show that, even in the absence of market power, ex-post quantity adjustments are also a useful tool to reduce bidder payments without incurring into productive inefficiencies.

[17]Such reasons might include requirements for transparency, attempts to promote bidders' participation (which might be at risk if quantities are uncertain), or simply the fact that the the two auctions are not run simultaneously or by different auctioneers, among others. Similarly, in other settings, the way markets work simply makes such adjustment impossible. This is for instance the case under Cap and Trade programs, in which a number of emission permits equal to the cap are issued first and only then are market participants allowed to trade them.

more efficient technology (technology 1). This means that if p^B is the market-clearing price under banding, technology 2 gets a price of αp^B for each unit supplied, while technology 1 just gets p^B. Thus, at every price, suppliers of technology 2 are willing to offer a greater quantity the higher the handicap α.[18]

The planner's optimal banding choice is:

$$(\alpha^B, Q^B) = \arg\max_{\alpha,Q} W(\alpha, Q),$$

where $Q^B = q_1^B + q_2^B$. From the market clearing condition,

$$p^B = c_1 + \theta_1 + C'' q_1^B = \frac{1}{\alpha^B}(c_2 + \theta_2 + C'' q_2^B),$$

one can obtain the equilibrium contribution of each technology,

$$q_1^B(Q^B, \alpha^B, \theta_1, \theta_2) = \frac{Q^B}{1+\alpha^B} + \frac{c_2 + \theta_2 - \alpha^B (c_1 + \theta_1)}{(1+\alpha^B) C''} \tag{17}$$

and

$$q_2^B(Q^B, \alpha^B, \theta_1, \theta_2) = \frac{\alpha^B Q^B}{1+\alpha^B} - \frac{c_2 + \theta_2 - \alpha^B (c_1 + \theta_1)}{(1+\alpha^B) C''}. \tag{18}$$

In turn, the equilibrium market-clearing price as a function of the shocks is given by

$$p^B(Q^B, \alpha^B, \theta_1, \theta_2) = \frac{c_1 + c_2 + \theta_1 + \theta_2 + C'' Q^B}{1+\alpha^B}. \tag{19}$$

Thus, the expected welfare under a quantity regime governed by a banding auction, denoted W_q^B, is given by

$$W_q^B \equiv B(q_1^B + q_2^B) - E[C(q_1^B, q_2^B)] - \lambda E[T(q_1^B, q_2^B)],$$

where $C(q_1^B, q_2^B) = \sum_{t=1,2} C_t(q_t^B(\cdot), \theta_t)$ and $T(q_1^B, q_2^B) = p^B(\cdot) q_1^B(\cdot) + \alpha^B p^B(\cdot) q_2^B(\cdot)$.

Since α can always be set equal to one (and Q^B equal to Q^N), the banding design is by construction superior to the technology-neutral design. Less evident is whether a banding design can also be superior to a technology-specific design, and if so, under what circumstances. To explore this possibility, it helps to start with the following intermediate result.

Lemma 2 *In the absence of uncertainty, i.e., $\sigma \to 0$, the banding design replicates the technology-specific design, with $Q^B = q_1^S + q_2^S$ and $\alpha^B = p_2^S / p_1^S$. Either design dominates the technology-neutral design, i.e., $W_q^B = W_q^S > W_q^N$.*

Proof. It follows immediately from comparing W_q^B and W_q^S when $\theta_1 = \theta_2 = 0$ and from Proposition 1. ■

[18] This price adjustment is also often used whenever the two goods are considered to be of different qualities; e.g. liquidity auctions, backed by good or bad collateral. In this case, the high quality good is given a handicap, or a supplement on top of the market price. The product mix auctions proposed by Klemperer (2010) are an alternative. However, they cannot be applied to settings like ours in which the two goods are perfect substitutes.

In the absence of uncertainty, the planner is indifferent between technology banding and technology separation since in either case she has two instruments at her disposal. Matters change, however, as we introduce uncertainty. One may speculate that under uncertainty one should lean in favor of the banding option since, by allowing for some technology substitution, it appears better equipped at containing total costs. But, akin to Proposition 1, allowing for this substitution may come at the expense of leaving higher rents with suppliers, to the extent that technology separation may nevertheless prevail as the best option.

Proposition 2 *Suppose that technology-specific auctions are superior to technology-neutral auctions, i.e.,* $W_q^S > W_q^N$. *There exists a correlation cut-off,* $\bar{\rho} < 1$, *above which technology-specific auctions also dominate technology banding, i.e.,* $W_q^S > W_q^B$.

Proof. See the Appendix. ■

To convey the intuition of Proposition 2, let us go through some key steps of the proof. To start, note that there is no point in comparing technology banding to technology separation if the latter is dominated by technology neutrality. In that case, banding would be automatically superior, by construction. Therefore, suppose that λ is large enough so that technology separation dominates technology neutrality, i.e., equation (16) in Proposition 1 does not hold.

Building from Lemma 2, suppose for now that $Q^B = q_1^S + q_2^S$ for any level of uncertainty (we will shortly comment on this). This reduces the comparison between banding and separation to one dimension: how uncertainty affects expected costs and payments across designs. Under technology separation, expected costs and payments are invariant to uncertainty (see section 3.2). Hence, we basically just need to understand how uncertainty affects expected costs and payments under banding. Assuming $\alpha^B = E[p_2^S]/E[p_1^S]$, we can use (17) and (18) to obtain expressions for these two components as follows

$$E\left[C^B(Q^B, \alpha^B)\right] = E\left[C^S(q_1^S, q_2^S)\right] + \frac{\sigma[\rho(1 + (\alpha^B)^2) - 2\alpha^B]}{C''\left(1 + \alpha^B\right)^2}, \tag{20}$$

and

$$E\left[T^B(Q^B, \alpha^B)\right] = E\left[T^S(q_1^S, q_2^S)\right] + \frac{\sigma\left(1 + \rho\right)\left(\alpha^B - 1\right)^2}{C''\left(1 + \alpha^B\right)^2}, \tag{21}$$

where $Q^B = q_1^S + q_2^S$. Consistent with Lemma 2, as $\sigma \to 0$ (and $\alpha^B \to p_2^S/p_1^S$), $E\left[C^B(\cdot)\right] \to E\left[C^S(\cdot)\right]$ and $E\left[T^B(\cdot)\right] \to E\left[T^S(\cdot)\right]$, so that the two technology designs become no different.

As we increase σ, however, two things occur: expected costs can go up or down, depending on ρ and α^B, and expected payments can only go up, except when $\rho = -1$. To be more precise about the implications for the welfare comparison, it helps to focus on two extreme values of ρ. Consider first the case of perfectly and negatively correlated cost shocks, i.e., $\rho = -1$. From expressions (20) and (21), banding is unambiguously superior to separation because expected costs are lower under banding while expected payments are the same as under separation. It is easy to understand why payments coincide: when $\rho = -1$, the market-clearing price under banding (19) becomes certain (just like the market-clearing price under separation), thereby making the planner's expected payments certain as well.

On the other hand, expected costs are lower under banding because it allows for substitution across technologies, albeit incompletely since $\alpha^B > 1$, when it is most valuable from a cost containment point of view. Interestingly, the value of this substitution is complete at $\rho = -1$, despite $\alpha^B > 1$. In fact, expected cost savings under banding relative to separation, which add to σ/C'', are exactly the same as under technology neutrality relative to separation (see Proposition 1). However, as ρ departs from -1, cost savings under banding are not as large as under technology neutrality because of the efficiency distortion introduced by setting $\alpha^B > 1$.

Consider now the other correlation extreme, $\rho = 1$. Unlike the previous case, separation is now unambiguously superior to banding because both expected costs as well as expected payments are lower under separation. The fact that payments are higher under banding is not very surprising because $\rho = 1$ gives rise to highly uncertain market-clearing prices, leading to highly uncertain payments. More intriguing is the fact that banding fails to provide any cost containment at all. Part of the reason for this was already alluded to in the previous paragraph. From Proposition 1, we know that allowing for technology substitution when $\rho = 1$ does not provide any cost containment advantage at all. The problem with banding, however, is that technology substitution is distorted by the fact that $\alpha^B > 1$. And this distortion has a price. From equations (17) and (18) we can see that under a positive cost shock, $\theta_1 = \theta_2 > 0$, quantities procured of each technology move further away from their cost-minimizing levels (q_2 moves further up and q_1 further down). Under a similar but negative cost shock, quantities move instead closer to their cost-minimizing levels. But costs are convex, so the first effect dominates the second, as Jensen's inequality predicts. If α^B were equal to one, these two effects would cancel each other out.[19]

Going over these extreme correlation scenarios allows us to establish, by continuity, the existence of a correlation cut-off $\bar{\rho} < 1$ that leaves the planner indifferent between technology separation and banding. Using the planner's indifference condition, $W_q^S = W_q^B$, this cutoff is given by[20]

$$\bar{\rho} = \frac{2\alpha^B - \lambda(\alpha^B - 1)^2}{1 + (\alpha^B)^2 + \lambda(\alpha^B - 1)^2} < 1. \tag{22}$$

For $\rho > \bar{\rho}$, separation dominates banding, and viceversa.

One key component in the cutoff expression (22) is the cost of public funds, λ. A lower value

[19]As we explain in the Appendix, the case of $\rho = 1$ requires of an additional step before one can formally establish that $W_q^S > W_q^B$. Unlike when $\rho = -1$, both α^B and Q^B are indeed not invariant to the introduction of uncertainty, which implies that the deterministic compononent in W_q^B is not longer equal to $W_q^S = W(q_1^S, q_2^S)$. But since under separation q_1 and q_2 can always be chosen to exactly replicate the deterministic component in W_q^B, it must be true that the deterministic component in W_q^B falls with uncertainty. Hence, the superiority of separation at $\rho = 1$ is only reinforced as we introduce uncertainty.

[20]Note that this cutoff expression is strictly valid as $\sigma \to 0$. As σ increases, two things happen: α^B goes down and the deterministic component of W_q^B also goes down. These factors act in opposing directions, but in the Appendix we show that the first factor dominates, so $\bar{\rho}$ goes up with uncertainty but remains away from 1.

of λ pushes $\bar{\rho}$ further up, making banding more attractive. The reason is that the planner's payments do not weigh as much, thereby mitigating the advantage of separation in reducing rents. The other key component in (22) is α^B. A lower value of α^B also pushes $\bar{\rho}$ further up, making banding more attractive. Again, a lower α^B means that rent extraction is less important and that the potential cost distortions from imperfect substitution across technologies under banding will not be as large.

The factors that contribute to a lower α^B are very intuitive as well. As shown in the Appendix, α^B is weakly decreasing with uncertainty, which is when (cost) efficiency considerations become more important, thereby enhancing the value of banding. In the same Appendix we also show that as uncertainty vanishes, α^B reduces to[21]

$$\alpha^B(\sigma \to 0) = 1 + \frac{2\lambda\Delta c}{\Delta c\,(1+\lambda) + C''Q^B\,(1+2\lambda)} < \frac{5}{3}, \tag{23}$$

which serves to show that α^B falls with lower values of λ and Δc and higher values of C''. Lower values of λ and Δc make rent extraction less important, the former by lowering its weight in the planner's problem, the latter by reducing its magnitude. Last, a high C'' also favors a lower α^B because the cost distortions are far costlier under a more convex cost curve.

4 Adding Market Power

So far we have assumed that suppliers behave competitively by offering their units at marginal cost. In this section, we revisit our previous analysis of technology-neutral and technology-specific auctions by adding market power to the model.[22] In particular, since we do not want to introduce further asymmetries across technologies, we assume a symmetric market structure for both, with one dominant firm (d) controlling a share ω of each unit, while the remaining share, $1-\omega$, belongs to a fringe of competitive firms (f). Aggregate costs remain unchanged, while the costs faced by the dominant firm and the fringe now differ. In particular, the costs for each $i = d, f$ are given by

$$C_{it}(q_{it}, \theta_t) = (c_t + \theta_t)\,q_{it} + \frac{1}{2}\frac{C''}{\omega_i}q_{it}^2,$$

with $\omega_d = \omega$ and $\omega_f = 1-\omega$. Accordingly, the higher ω the more efficient is the dominant firm relative to the fringe, and the stronger is its market power.[23]

[21] Note from (5), for example, that an interior solution –that both technologies are always procured in equilibrium– requires $C''Q^B > \Delta c$, setting an upper bound for α^B of 5/3.

[22] Similar conclusions would be obtained if we also compared these to banding.

[23] The presence of a dominant firm opens up the door for non-linear mechanisms; for instance, they could involve menus with quantity discounts (premia, in this case). On the one hand, it could be the case that our finding below (Proposition 3) – i.e, that market power favors the neutral approach over the specific one – applies in the context of non-linear menus. On the other, it could also be the case that menus' incentive compatibility constraints are cheaper to handle under separation than under neutrality. However, exploring this possibility in detail is out of the scope of this paper.

While the fringe behaves competitively, the dominant firm sets prices in order to maximize its profits over the residual demand. Under technology-neutrality, the market clearing price now becomes

$$p^N(Q, \theta_1, \theta_2) = \frac{c_1 + c_2 + \theta_1 + \theta_2}{2} + \frac{C''}{1 - \omega^2}\frac{Q}{2},$$

which corresponds to our previous solution for $\omega = 0$, equation (3). For higher values of ω, the slope of the price equation becomes steeper.

The resulting expected allocation across firms is,

$$E\left[q_d^N\right] = \frac{\omega}{1+\omega}Q^N < E\left[q_f^N\right] = \frac{1}{1+\omega}Q^N,$$

with both firms ex-post allocating their production across technologies in order to equalize their marginal costs. The market share of the dominant firm is smaller as it withholds output in order to push prices up.

Likewise, under technology-specific auctions, the market clearing price becomes, for $t = 1, 2$,

$$p_t^S(q_t, \theta_t) = c_t + \theta_t + \frac{C''}{1 - \omega^2}q_t$$

and the resulting allocation across firms is,

$$q_{dt}^S = \frac{\omega}{1+\omega}q_t^S < q_{ft}^S = \frac{1}{1+\omega}q_t^S.$$

Similarly to our first lemma, Lemma 3 below compares the quantity choices under technology-neutral and technology specific auctions in the presence of market power.

Lemma 3 *For all ω, the optimal total quantities in a technology-neutral auction and in technology-specific auctions are the same, i.e., $Q^N(\omega) = Q^S(\omega)$, but the expected quantities allocated to each technology are not: $q_1^S(\omega) < E\left[q_1^N(\omega)\right]$ and $q_2^S(\omega) > E\left[q_2^N(\omega)\right]$. In turn, $Q^N(\omega)$ and $Q^S(\omega)$ are decreasing in ω and the allocative distortions $E\left[q_1^N(\omega)\right] - q_1^S(\omega)$ and $q_2^S(\omega) - E\left[q_2^N(\omega)\right]$ are increasing in ω.*

Proof. See the Appendix. ■

As in perfectly competitive auctions, the planner chooses the same aggregate quantity across the two approaches, but distorts the technology-specific targets from the ex-ante efficient solution. Interestingly, market power adds new twists. First, in the presence of market power, increasing the total quantity involves higher marginal costs given that market power distorts the quantity allocation across firms. It also increases payments more, as market power results in higher prices and makes the price curve steeper. Since the marginal benefits are unchanged, it follows that the total quantity procured is lower the greater the degree of market power.

Second, market power affects the distortion in the technology-specific targets. There are two forces moving in opposite directions. Because the price curves are steeper, marginally moving quantity from the low cost to the high cost technology reduces payments relatively more than in the absence of market power. However, because market power distorts the quantity allocation across firms, distorting the allocation across technologies increases costs more than in the absence of market power. The first effect dominates, however, leading to more quantity distortion across technologies as market power goes up.

The comparison between technology neutrality and separation still reflects a rent-efficiency trade-off, with the former being more effective at reducing costs and the latter being more effective at containing payments. Market power affects these two objectives, increasing costs and payments under both approaches. However, the comparison is tilted in favour of technology-neutrality. The reason is two-fold. First, through the effect of market power on the quantity distortion, the cost increase is higher under technology separation than under technology neutrality. And second, separation is increasingly less effective in reducing overall payments becomes as market power goes up. This is stated in our last proposition.

Proposition 3 *Market power reduces welfare under both approaches, but the welfare reduction is greater under technology-specific auctions, i.e.,* ΔW_q^{NS} *is increasing in* ω*.*

Proof. See the Appendix. ■

To gain some intuition, consider the extreme case of a monopolist facing either one or two inelastic quantity targets. In either case, the monopolist would charge the highest possible prices, fully offsetting the possibility to reduce payments through separation. Hence, expected payments would be equal under both types of auctions. However, unlike technology separation, technology neutrality would allow the monopolist to freely allocate its production across technologies. As this reduces total costs, the presence of a monopolist does not hurt welfare as much under technology neutrality as under separation. For not so extreme degrees of market power, the technology-specific approach may still dominate technology-neutrality, but the range of parameter values for which this is the case is narrower than in Proposition 1.

5 Price Regulation

So far we have considered a planner who procures a total of $Q = q_1 + q_2$ units of some good under different auction formats. While we have worked under the assumption that Q is chosen to maximize welfare (2), there may be instances in which Q is not under the planner's control but rather exogenously given. For instance, Q may respond to a higher-level country commitment to reduce carbon emissions in a particular sector. In cases like these, in which Q is exogenously given, the planner's problem may reduce to choosing the auction format – technology-neutral or technology-specific – that minimizes the sum of costs and payments, $C(q_1, q_2) + \lambda T(q_1, q_2)$. It should be clear that all our results go through even in this case.

The case of an endogenous Q opens a new set of questions, however. In particular, it may no longer be optimal to rely on the quantity-based instruments we have considered so far, but rather on price-based instruments. In the presence of uncertainty, this gives rise to a new trade-off: under a quantity-based instrument the total quantity is fixed but prices vary according to shocks; whereas under a price-based instrument prices are fixed but quantities vary according to shocks.

If the regulator cannot discriminate across the different technologies, the best she can do within the family of price-based instruments is to post a single price at which she is ready to buy whatever is supplied of each technology. But if she can discriminate suppliers according to their technologies, as assumed throughout, she can do better by posting two prices, p_1 and p_2.

Since two prices are by construction superior to a single price (unless $\lambda = 0$, in which case they are welfare equivalent), the planner's optimal pricing choice is

$$(p_1^*, p_2^*) = \arg\max_{p_1, p_2} W(q_1(p_1), q_2(p_2)),$$

where quantities $q_t(p_t, \theta_t)$ adjust so that prices equal marginal costs

$$p_t = c_t + \theta_t + C'' q_t$$

for $t = 1, 2$. In expected terms, this price is analogous to (10), $p_t^* = E[p_t^S] \equiv c_t + C'' q_t^*$, confirming that under certainty a regime of two separate prices is not different from a regime of two separate quantities.

Thus, the expected welfare under a price regime governed by two posted prices, denoted W_p^S, is given by

$$W_p^S = B(q_1(p_1^*) + q_2(p_2^*)) - E[C(q_1(p_1^*), q_2(p_2^*))] - \lambda E[T(q_1(p_1^*), q_2(p_2^*))]$$

where $C(\cdot) = \sum_{t=1,2} C_t(q_t(p_t^*, \theta_t), \theta_t)$ and $T(\cdot) = \sum_{t=1,2} p_t^* q_t(p_t^*, \theta_t)$. For future reference, denote by W_p^N the expected welfare under a price regime governed by a single posted price (i.e., a technology-neutral price).

The welfare comparison between prices and quantities yields the following proposition.

Proposition 4 *Two posted prices dominate two technology-specific auctions if and only if*

$$W_p^S - W_q^S \equiv \Delta W_{pq}^S = \frac{\sigma(1+\rho)}{(C'')^2} \left(B'' + \frac{C''}{2} \frac{2}{1+\rho} \right) > 0. \tag{24}$$

Proof. See the Appendix. ■

When shocks θ_1 and θ_2 are perfectly correlated, $\rho = 1$, equation (24) reduces to nothing but Weitzman (1974)'s seminal "prices *vs.* quantities" expression (just note that $C''/2$ is the combined slope of the two supply curves, each with a slope C''). The intuition of his result is well known: a relatively more convex supply curve favors prices because "mistakes" on the supply side become costlier than on the benefit side. This analogy with Weitzman (1974) should not be surprising as $\rho = 1$ implies that the two technologies behave just as one.

As we move away from this extreme case, however, the price instrument performs better than the quantity instrument, i.e., ΔW_{pq}^S is more likely to be positive than in the single technology case. For imperfectly correlated shocks, prices allow the quantities allocated to the various technologies to better adjust ex-post to the cost shocks, which helps to contain production costs while reducing uncertainty on the benefit side. Thus, because of technology substitution, the slope of the relevant marginal cost curve becomes flatter under price regulation, thereby favouring the price approach. In fact, when shocks are perfectly and negatively correlated, $\rho \to -1$, prices are unambiguously superior to quantities because there is no longer uncertainty on the benefit side.[24]

With two prices or two quantities, expected government payments are independent of the degree of cost correlation ρ and the degree of uncertainty σ. Since under certainty, prices and quantities are equally suited to reduce suppliers' rents, it follows that under uncertainty expected government payments are also the same with two prices or two quantities, which explains why λ is absent from expression (24). This result does not mean, however, that price regulation should always be preferred to quantity regulation when expression (24) holds. It may still be optimal to opt for quantity regulation, in particular, for a technology-neutral auction. According to our next proposition, this may happen when λ is relatively small.

Proposition 5 *Two posted prices dominate a technology-neutral auction if and only if*

$$W_p^S - W_q^N = \frac{\lambda^2}{1+2\lambda}\left(\frac{\Delta c}{2C''}\right)^2 + \frac{\sigma(1+\rho)}{(C'')^2}\left(B'' + \frac{C''}{2}\right) > 0. \tag{25}$$

Proof. Immediate from the proofs of Propositions 1 and 4. ■

To convey some intuition, it helps to decompose $\left(W_p^S - W_q^N\right)$ in two terms: $(W_p^S - W_p^N) + (W_p^N - W_q^N)$. The first term, $\left(W_p^S - W_p^N\right)$, is the rent-extraction gain from using two prices as opposed to a single price. This is exactly captured by the first term in (25). The second term, $\left(W_p^N - W_q^N\right)$, is the Weitzman's trade-off between using a (single) price and a (single) quantity. This is exactly captured by the second term in (25).

Since $B'' + C''/2 \leq B'' + C''/(1+\rho)$, it is clear from the comparison of (24) and (25) that if $\lambda = 0$, $W_p^S > W_q^S$ implies $W_p^S > W_q^N$. The reason is, as already argued, that two prices are equally effective in extracting rents than two quantities, but two prices are always more effective at accommodating cost shocks than two quantities (except in the extreme case of $\rho = 1$). However, with costly public funds, $W_p^S > W_q^S$ no longer implies $W_p^S > W_q^N$. Indeed, when λ is not too large (meaning that main objective is to minimize costs), it can well be the case that a technology neutral auction dominates over the rest, $W_q^N > W_p^S > W_q^S$. The reason is that, while two prices allow for more quantity adjustment than two quantities, technology neutrality is the only instrument that allows quantities to fully adjust.

[24] While this multiple-technology analysis was already in Weitzman (1974), it is unclear why he compares technology-specific prices and quantities given that in the absence of costly public funds technology separation brings no additional benefit. In fact when $\lambda = 0$, technology neutrality dominates separation, strictly so under quantity regulation (Proposition 1) and weakly so under price regulation. Hence, the only meaningful comparison is between a single quantity and a single price.

6 Simulations

In this section we use actual market and cost data to illustrate the main results of the model. In particular, with detailed information on the ongoing solar and wind investments in Spain, we perform the following counterfactual exercise: if these projects were to compete for the right to access the market through an auction for an exogenously given amount Q of green energy, what would the differences be between running a single technology-neutral auction, a single technology-neutral auction with banding, or two separate technology-specific auctions, one for solar and one for wind? In particular, what would the implications be for investment efficiency and payments?

Thanks to access to the Registry of Renewables Installations in Spain (RIPRE), we have collected data on all the renewable investment projects that applied for planning permission from January 2019 until March 2020. These dataset specifies several project characteristics, namely, their technology (either solar PV or wind), their maximum production capacity, and their location, among others. Using historic data on renewable production across the fifty Spanish provinces,[25] we have computed the expected production of each investment project over its lifetime (which we assume equal to twenty five years).[26] We denote it as q_{itl}, for project i of technology t located in province l. A project's average cost is given by the ration between its investment cost, denoted $c(\theta_t, k_i)$, and q_{itl}. By ranking the projects of the same technology in increasing average cost order, we construct the aggregate cost curve of such technology, i.e., analogously to expression (1).

We parametrize the investment cost function of each project as follows

$$c(\theta_t, k_i) = [c_t + \beta\theta_t] \, k_i^{\gamma},$$

where c_t is the cost parameter of technology t, θ_t is a cost shock for technology t, and k_i is the capacity of project i.[27] We set γ equal to 0.9 to capture mild scale economies.[28] Regarding the parameter c_t, we set it up so that the average costs of all the projects in our sample equal the average costs of that technology, as reported by the International Renewable Association (IRENA) for 2018.[29] Even if average costs are set at this level, heterogeneity in locations and plant sizes gives rise to variation in average costs across projects.

[25] These data are obtained from Red Eléctrica, which is the Spanish electricity system operator.

[26] That is the expected lifetime of most installations. If we instead assume a shorter life-time (say, twenty years) the main conclusions of this analysis would remain unchanged as long as we apply that number to both technologies.

[27] Note that in the model described in Section 2 we had implicitly assumed that all projects had unit capacity, $k_i = 1$. This difference is inconsequential, but allows us to introduce scale economies in project size.

[28] Setting $\gamma = 1$ would imply that differences in the average cost of each project would only arise due to their different locations. Setting γ at lower values would make the average cost curves steeper, while the average cost would remain fixed at the same value reported by IRENA.

[29] In detail, IRENA reports that the investment cost of solar PV was 1,113 \$/kW and 1,833\$/kW for wind (we use an exchange rate \$/Euro equal to 1.12). These parameters come from IRENA's 2018 report, for Germany (no cost is reported for the investment cost of solar PV in Spain).

Regarding the cost shock θ_t, we assume that it is distributed according to a standard normal distribution, with a correlation coefficient ρ across the cost shocks for the two technologies. To understand the role of cost correlation, we use three alternative assumptions: $\rho \in \{-0.8, 0, 0.8\}$. The parameter β simply allows to change the weight of cost shocks on total costs; we set it equal to 900, which which implies that cost shocks move average costs by 5%, upwards or downwards. For each value of ρ, we consider 100 independent draws of the cost parameters (θ_1, θ_2) , i.e., for solar and wind. For comparability purposes, we use the same realizations under all three technology approaches.

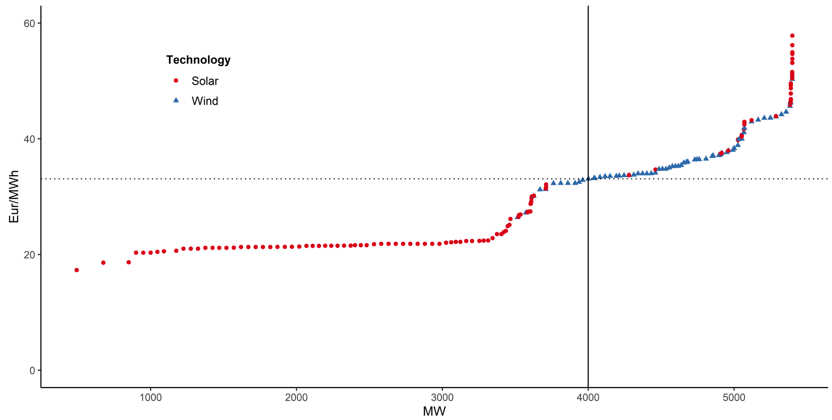
Technology-neutral approach Under technology-neutrality, for each realized pair (θ_1, θ_2), we construct the industry average cost curve by ranking the projects of both technologies in increasing average cost order, with their corresponding capacity. The intersection between the industry average cost curve and $Q = 4000$ gives the expected market clearing price under technology neutrality as well as the quantity allocation across technologies.[30] With this, we compute realized payments and costs; multiplying payments by $\lambda \in \{0, 0.2, 0.4\}$ and summing costs, we obtain total social costs. The average across all cost realizations gives us expected payments, expected costs, and expected social costs.

Figure 1a plots the aggregate technology-neutral average cost curve for a given cost-shock realization (θ_1, θ_2) . As it can be seen, the average costs of solar plants (denoted by red dots) tend to be lower than the average costs of wind plants (denoted by blue dots). However, the average cost curve of solar plants becomes very steep as we approach the capacity constraint, given that the most expensive projects are the small ones located in the least sunny regions. The average cost curve of wind plants tends to be higher but flatter, as all wind projects tend to be similar in size and they tend to be located in the most windy regions only. Therefore, for a total investment of $Q = 4000$, it is optimal to procure both solar as well as wind projects. Cost shocks move these curves up and down, which leads to price changes and smooth adjustments in the total quantity allocated to each technology.

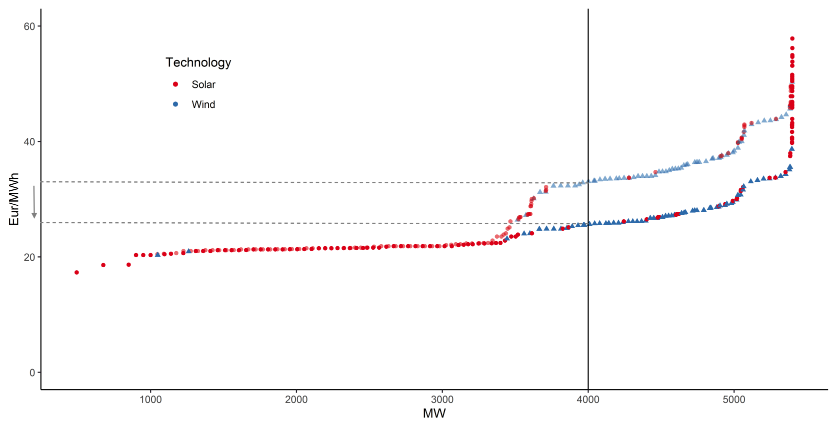
Technology-banding approach The technology neutral approach can be modified through technology banding. Since wind is the high cost technology, we give it a handicap α. Figure 1b illustrates how the aggregate supply curve shifts down from technology neutrality (which is equivalent to setting $\alpha = 1$) to technology banding with $\alpha = 1.3$. As the wind plants are willing to bid at their average costs deflated by α, the resulting market clearing share for wind goes up (and that of solar goes down) and the market clearing price goes down.

For each set of parameters (ρ, λ), we compute the market equilibrium for each pair of cost shocks realizations (θ_1, θ_2), and for all values $\alpha \in \{0, 0.1, ...1.9, 2\}$. We choose the optimal

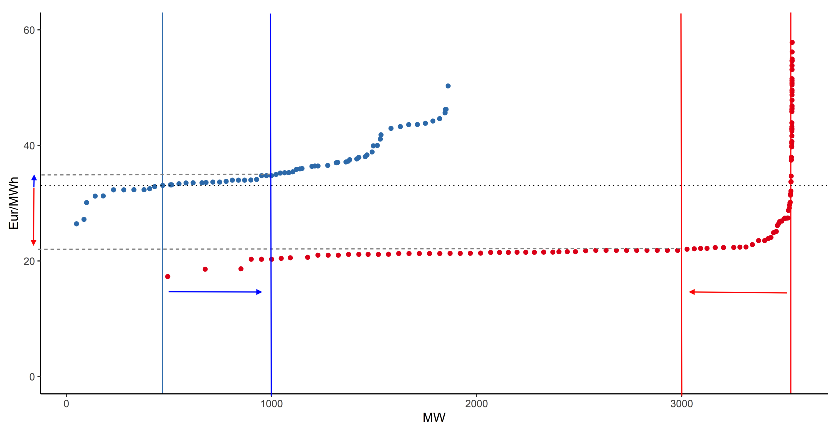
[30] To provide some orders of magnitude about the cost uncertainty implicit in our simulations, the market clearing price under technology neutraility is 33-34 Euro/MWh with a standard deviation of 5-6 Euro/MWh, i.e., 14-19 percent from the mean.



(a) Technology Neutral



(b) Technology Banding ($\alpha = 1.3$)



(c) Technology Specific

Figure 1: Bidding Results for Different Auction Designs

Notes: These figures display average supply bid curves under three auction designs. Red dots correspond to solar projects and blue triangles to wind projects. Under technology neutrality (Figure 1a), all projects are ranked in increasing average cost order. Under technology banding (Figure 1b), wind projects are given a handicap $\alpha = 1.3$. Under the technology-specific approach (Figure 1c), projects are ranked separately within each technology. The vertical lines represent how the allocation across technologies is distorted relative to technology neutrality.

Table 1: Technology-banding relative to technology-neutrality

ρ	λ	**Costs**	**Payments**	**Social Costs**	**Banding** α
-0.8	0	1.00	1.00	1.00	1.0
-0.8	0.2	1.01	0.87	0.98	1.3
-0.8	0.4	1.02	0.86	0.96	1.4
0	0	1.00	1.00	1.00	1.0
0	0.2	1.01	0.86	0.97	1.3
0	0.4	1.02	0.84	0.95	1.4
0.8	0	1.00	1.00	1.00	1.0
0.8	0.2	1.01	0.82	0.97	1.3
0.8	0.4	1.01	0.82	0.94	1.3

handicap, i.e., the value of α that minimizes the expected social cost. Table 1 summarizes the results. For each (ρ, λ) pair, it reports the ratio of the relevant outcomes (costs, payments and social costs) under banding relative to technology neutrality. As compared to technology neutrality, banding leads to higher costs, but also to lower payments. Since the latter effect dominates, the optimal degree of banding (reported on the last column) is always positive (unless the regulator is not concerned about rents, $\lambda = 0$), and it goes up the greater the concern for rents (i.e., the higher λ).

Technology-specific approach To analyze the technology specific approach, we run the same exercise as under technology-neutrality but at the technology level. For given values of ρ and λ, we identify the ex-ante allocation across the two technologies $\left(q_1^S, q_2^S\right)$ that minimizes expected social costs, subject to the constraint that the two must sum up to $Q = 4000$. For this ex-ante optimal allocation, we compute expected payments, expected costs, and expected social costs.

Figure 1c illustrates the effects of distorting the ex-ante optimal allocation away from the technology neutral outcome. By reducing the quantity allocated to solar and increasing the one allocated to wind, it is possible to reduce total payments: the strong price reduction for solar projects more than compensates the mild price increase for wind. This creates investment inefficiencies, as the average costs of some of the wind projects that are now procured exceed the average costs of some of the solar projects that are no longer procured. The potential for investment inefficiencies increases as one adds cost shocks to these figures, given that the ex-ante allocation under the technology-specific approach does not adjust for those shocks. Hence, the choice between the two approaches must strike a balance between the objective to minimize payments and the objective to maximize investment efficiency.

This trade-off is illustrated in Table 2, which reports the results under the technology-specific approach relative to technology-neutrality. Similarly to banding, costs under the technology-specific approach tend to always be higher and payments lower relative to technology-neutrality. On the one hand, the relative cost efficiency of technology-neutrality increases for higher values of λ, as the quantity distortion under the technology-specific approach gets larger. On the other, this also enlarges the payment gap between the two approaches. Note also that the efficiency distortion under the technology-specific approach is lower in the case of positive cost correlation. Overall, for all positive values of λ, this trade-off favours the technology-specific approach as it always gives rise to lower social costs relative to the technology-neutral approach.

Comparing Tables 1 and 2 allows to assess the technology-specific approach relative to banding. For all (ρ, λ) pairs, the cost distortion is (weakly) greater under the technology-specific approach, but payments are also lower. Since the latter effect dominates, the technology-specific approach always results in lower social costs as compared to banding.

Table 2: Technology-specific auctions relative to technology-neutrality

ρ	λ	**Costs**	**Payments**	**Social Costs**
-0.8	0	1.03	0.73	1.03
-0.8	0.2	1.04	0.72	0.96
-0.8	0.4	1.04	0.71	0.91
0	0	1.02	0.75	1.02
0	0.2	1.02	0.75	0.95
0	0.4	1.03	0.72	0.91
0.8	0	1.00	0.88	1.00
0.8	0.2	1.01	0.76	0.95
0.8	0.4	1.02	0.74	0.91

We have performed several robustness checks by choosing different values for the parameters. Overall, the main conclusions of the analysis remain intact. The technology-specific approach dominates over technology-neutrality and technology-banding when the regulator cares about consumer payments. Even though technology banding allows to combine the two positive properties of the other two pure approaches - i.e., higher productive efficiency than under the technology-specific approach and lower payments than under technology neutrality - it is still dominated by the technology-specific approach. The driving force is the large asymmetries between the costs of solar and wind projects in the Spanish electricity market, which give rise to large rents unless they are treated separately. In other contexts, if such asymmetries are milder, or if the slope of the solar curve becomes flatter while that of wind becomes steeper, the results could well change in favour of technology banding, or even technology neutrality.

7 Conclusions

Our paper analyzes an issue which is at the heart of a successful energy transition; namely, whether and when to favour a technology-neutral versus a technology-specific approach, and whether and when to do so under price or quantity regulation. Regulators worldwide have favoured one approach or another without there being a former analysis of the trade-offs involved; particularly so, when one takes into account the budget constraint faced by regulators. We have shown that there does not exist a one-size fits all solution: the preferred instrument should be chosen on a case-by-case basis, depending on the characteristics of the technologies and the information available to the regulator.

We have shown that the comparison of a technology-neutral versus technology-specific approach is faced with a fundamental trade-off. By allowing quantities to adjust to cost shocks, the technology-neutral approach achieves cost efficiency at the cost of leaving high rents with inframarginal producers. In contrast, the technology-specific approach sacrifices cost efficiency in order those reduce rents. Therefore, whether one approach dominates over the other depends on the specifics of each case.

In particular, technology-specific auctions tend to dominate technology-neutral auctions when technologies are fairly asymmetric —as in our simulation exercise based on information from ongoing solar and wind investments in Spain— and the costs of public funds are large, which is when the rent extraction motive is stronger. The opposite is true when cost uncertainty is large and cost shocks are negatively correlated, which is when the concerns for cost efficiency matter most. Market power tilts the comparison in favour of technology neutrality, mainly driven by the efficiency implications of the wider quantity distortions it creates under the technology-specific approach. However, technology-neutrality is always dominated by technology banding, which in turn dominates technology separation but only when cost shocks are sufficiently negatively correlated. Last, while technology-specific prices always dominate a technology-neutral price, the comparison with the quantity instruments again depends on parameter values. A convex cost curve relative to the benefit curve favours the price approach, while small cost asymmetries across technologies and low costs of public funds tend to further favour the choice of a single quantity target over the choice of technology-specific prices.

We believe that the procurement of green technologies is a most natural application of our analysis. Beyond the reasons we already discussed in the introduction, we want to conclude by highlighting a key fact: namely, in the energy sector, there is typically a single principal (e.g. the national or the supranational regulator). This means that, if she opts for technology separation, she decides on the quantity targets or the prices for each technology, while internalizing the overall effect of such choices on total expected costs and payments. Otherwise, in the presence of multiple principals, there would be no reason to expect that the separation of technologies would be done optimally. Indeed, as we have shown in our analysis of procurement auctions, the quantity target of the less efficient technology is distorted upwards in order to reduce total payments, at the expense of increasing the rents left with the inefficient suppliers.

For this reason, with two principals, each deciding on a separate auction, the optimal solution would likely not be implemented. Beyond the presence of a single versus multiple principals, the fine tuning that is needed to implement the optimal solution under technology separation might not always be feasible in practice. Indeed, political economy reasons of all sorts (distributional concerns, pressure of lobby groups, industrial policy considerations, fairness, etc.) might constrain the implementation of the optimal solution under separation. These reasons might explain why in several settings to which our model applies (notably, emissions markets involving various jurisdictions) the separation solution is doomed to fail.

Appendix

Proof of Lemma 1

The welfare maximizing solution under technology neutrality, Q^N, solves

$$\frac{\partial B\left(Q^N\right)}{\partial Q} = E\left[\sum_{t=1,2} \frac{\partial C_t\left(q_t^N\right)}{\partial q_t} \frac{\partial q_t^N(Q)}{\partial Q}\right] + \lambda E\left[\frac{\partial p^N(Q)}{\partial Q} Q^N + p^N(Q) \sum_{t=1,2} \frac{\partial q_t^N(Q)}{\partial Q}\right] \tag{26}$$

where $p^N(Q)$ is the equilibrium price and $\partial C_t(q_t^N)/\partial q_t = c_t + \theta_t + C'' q_t^N$.

By construction (i) $\sum_{t=1,2} q_t^N(Q) = Q$, so (ii) $\sum_{t=1,2} \partial q_t^N(Q)/\partial Q = 1$. Moreover, cost-minimization implies that (iii) $\partial C_1\left(q_1^N\right)/\partial q_1 = \partial C_2\left(q_2^N\right)/\partial q_2 = p^N(Q)$, so (iv) $C''\partial q_1^N/\partial Q = C''\partial q_2^N/\partial Q$ and (v) $\partial p^N(Q)/\partial Q = C''\partial q_t^N/\partial Q$. But from (ii) and (iii) we have that $\partial q_1^N/\partial Q = \partial q_2^N/\partial Q = 1/2$, so (vi) $\partial p^N(Q)/\partial Q = C''/2$. Plugging conditions (iii) through (vi) into (26) leads to the first-order condition (FOC)

$$\frac{\partial B\left(Q^N\right)}{\partial Q} = (1+\lambda)\frac{\partial C_t\left(q_t^N\right)}{\partial q_t} + \lambda \frac{C''}{2} Q^N$$

for $t = 1, 2$. Summing the two FOCs, taking expectations and dividing by 2, we arrive at

$$\frac{\partial B\left(Q^N\right)}{\partial Q} = \frac{1}{2}(1+\lambda)(c_1+c_2) + \frac{1}{2}(1+2\lambda)C''Q^N. \tag{27}$$

Consider now technology separation. The welfare maximizing solution under technology separation, q_1^S and q_2^S, solves

$$\frac{\partial B\left(q_1^S + q_2^S\right)}{\partial q_t} = E\left[\frac{\partial C_t\left(q_t^S\right)}{\partial q_t^S}\right] + \lambda E\left[p_t^S(q_t^S) + \frac{\partial p_t^S(q_t^S)}{\partial q_t} q_t^S\right] \tag{28}$$

where $p_t^S(q_t)$ is the equilibrium price in t's technology-specific auction and $\partial C_t(q_t^S)/\partial q_t = c_t + \theta_t + C'' q_t^S$ for $t = 1, 2$.

Using $\partial C_t\left(q_t^S\right)/\partial q_t = p_t^S(q_t)$, summing the two FOCs, taking expectations and dividing by two, we arrive at

$$\frac{\partial B\left(q_1^S + q_2^S\right)}{\partial q_t} = \frac{1}{2}(1+\lambda)(c_1+c_2) + \frac{1}{2}(1+2\lambda)C''Q^S \tag{29}$$

where $Q^S = q_1^S + q_2^S$. Comparing (27) and (29) yield $Q^N = Q^S$.

We now want to show that the expected quantity allocations under neutrality are different than the allocations under separation. Argue by contradiction and assume $q_1^S = E\left[q_1^N\right]$ and $q_2^S = E\left[q_2^N\right]$. Since under neutrality $C_1'\left(q_1^N\right) = C_2'\left(q_2^N\right) = p^N(Q^N)$, we have, after taking expectations, that (vii) $c_1 + C''E\left[q_1^N\right] = c_2 + C''E\left[q_2^N\right]$; hence $E\left[q_1^N\right] > E\left[q_2^N\right]$ since $c_1 < c_2$. On the other hand, the FOCs (28) under separation lead to a similar equilibrium condition (viii) $c_1 + (1+2\lambda)C''q_1^S = c_2 + (1+2\lambda)C''q_2^S$. Using $q_1^S = E\left[q_1^N\right]$ and $q_2^S = E\left[q_2^N\right]$, and subtracting (vii) from (viii), we arrive at $q_1^S = q_2^S$; a contradiction with $E\left[q_1^N\right] > E\left[q_2^N\right]$ given that $\lambda > 0$.

Finally, we want to compute the direction of the quantity distortion. Again, assess the FOCs (28) at $q_1^S = E\left[q_1^N\right]$ and $q_2^S = E\left[q_2^N\right]$. Since $E\left[q_1^N\right] > E\left[q_2^N\right]$, it follows from (vii) that the FOC for technology 1, FOC1, is greater than FOC2

$$c_1 + (1+2\lambda)C''E\left[q_1^N\right] > c_2 + (1+2\lambda)C''E\left[q_2^N\right].$$

Since the FOC is increasing in q_t^S, for the two FOCs to be equal to the marginal benefit (and therefore to each other), we require $E\left[q_1^N\right] > q_1^S$ and $E\left[q_2^N\right] < q_2^S$.

Proof of Proposition 2

From expressions (20) and (21) in the main text, we can write the expected welfare under banding as

$$W_q^B = \bar{W}_q^B(\alpha^B, Q^B) - \frac{\sigma[\rho(1+(\alpha^B)^2) - 2\alpha^B + \lambda\,(1+\rho)\left(\alpha^B - 1\right)^2]}{C''\,(1+\alpha^B)^2},$$

where $\bar{W}_q^B(Q^B, \alpha^B)$ corresponds to the deterministic part of the welfare expression and $\{\alpha^B, Q^B\} = \arg\max_{\alpha,Q} W_q^B(\alpha, Q; \sigma, \rho)$.

According to Lemma 2, $\bar{W}_q^B(\alpha, Q)$ is a concave function that reaches its peak when $\alpha = p_2^S/p_1^S = \alpha^B(\sigma = 0) \equiv \alpha_0^B$ and $Q = q_1^S + q_2^S = Q^B(\sigma = 0) \equiv Q_0^B$, that is, when $\bar{W}_q^B(\alpha_0^B, Q_0^B) = W_q^S$ (this is because W_q^S is invariant to shocks). When $\sigma > 0$, $\bar{W}_q^B(\alpha^B, Q^B) < \bar{W}_q^B(\alpha_0^B, Q_0^B)$ and the first-order condition that solves for $\alpha^B(\sigma > 0)$ is given by

$$\frac{\partial \bar{W}_q^B(\alpha^B, Q^B)}{\partial \alpha} - \frac{2\sigma(1+\rho)(2\lambda+1)(\alpha^B - 1)}{C''(1+\alpha^B)^3} = 0.$$

Since the second term is negative, $\partial \bar{W}_q^B(\alpha^B, Q^B)/\partial\alpha > 0$ and, therefore, $\alpha^B < \alpha_0^B$.

Conditions (i) $\bar{W}_q^B(\alpha^B, Q^B) < \bar{W}_q^B(\alpha_0^B, Q_0^B) = W_q^S$ and (ii) $\alpha^B < \alpha_0^B$ act in different directions as to their impacts on $\bar{\rho}$. While (i) calls for a lower $\bar{\rho}$, (ii) calls for a higher one. To see which effect dominates, take the condition that defines $\bar{\rho}$, i.e.,

$$\bar{W}_q^B(\alpha^B, Q^B) - \frac{\sigma[\bar{\rho}(1+(\alpha^B)^2) - 2\alpha^B + \lambda\,(1+\bar{\rho})\left(\alpha^B - 1\right)^2]}{C''\,(1+\alpha^B)^2} = W_q^S, \tag{30}$$

and totally differentiate it with respect to σ. Using the envelope theorem yields (note that ρ only enters indirectly in $\bar{W}_q^B$, through its effects on α^B and Q^B)

$$\frac{d\bar{\rho}}{d\sigma} = \frac{-[\bar{\rho}(1+(\alpha^B)^2) - 2\alpha^B + \lambda\,(1+\bar{\rho})\left(\alpha^B - 1\right)^2]}{\sigma[1+(\alpha^B)^2 + \lambda\,(\alpha^B-1)^2]} > 0.$$

Recall that the numerator is positive because of (i).

It remains to show that $\bar{\rho}$ is bounded away from 1, regardless of σ. We proceed by contradiction. If $\bar{\rho}$ were to approach the unity for some value of σ, then, from (30), we would obtain that $\bar{W}_q^B(\alpha^B, Q^B) > W_q^S$; a contradiction.

Proof of Lemma 3

To show that $Q^N(\omega) = Q^S(\omega)$, we start by considering the first-order condition (FOC) that solves for $Q^N(\omega)$,

$$\begin{aligned} \frac{\partial B\left(Q^N\right)}{\partial Q} \quad = \quad & E\left[\sum_{i=f,d}\sum_{t=1,2}\frac{\partial C_{ti}\left(q_{ti}^N\right)}{\partial q_{ti}}\frac{\partial q_{ti}^N(Q)}{\partial Q}\right] - \\ & \lambda E\left[\frac{\partial p^N(Q)}{\partial Q}Q^N + p^N(Q)\sum_{i=f,d}\sum_{t=1,2}\frac{\partial q_{ti}^N(Q)}{\partial Q}\right] \end{aligned} \tag{31}$$

where $p^N(Q)$ is the equilibrium price and $\partial C_{ti}(q_{ti}^N)/\partial q_{ti} = c_t + \theta_t + C'' q_{ti}^N/\omega_t$.

Expression (31) can be simplified using several conditions that must hold in equilibrium, such as the balance condition (i) $Q = \sum_i \sum_t q_{ti}^N(Q)$ and the cost-minimizing condition (ii) $\partial C_{ti}(q_{ti}^N(Q))/\partial q_{ti} = \partial C_{-ti}(q_{-ti}^N(Q))/\partial q_{-ti}$ for $t = 1,2$ and $i = f, d$. Totally differentiating these two conditions with respect to Q adds two further conditions: (iii) $1 = \sum_i \sum_t \partial q_{ti}^N(Q)/\partial Q$ and (iv) $\partial q_{1i}^N(Q)/\partial Q = \partial q_{2i}^N(Q)/\partial Q$ for $i = f, d$, respectively. In addition, we have the fringe's price-taking condition (v) $p^N(Q) = \partial C_{tf}(q_{tf}^N(Q))/\partial q_{tf}$ for $t = 1,2$, which, in turn, lead to condition (vi) $\partial p^N(Q)/\partial Q = C''/(1-\omega) \times \partial q_{tf}^N(Q)/\partial Q$ for $t = 1,2$. Finally, we have the dominant firm's profit-maximization condition

$$\{q_{1d}^N, q_{2d}^N\} = \arg\max\{p^N(Q)(q_{1d}^N + q_{2d}^N) - C_{1d}\left(q_{1d}^N\right) - C_{2d}\left(q_{2d}^N\right)\}, \tag{32}$$

subject to (i) and (v).

Solving (32) we arrive at the FOC

$$q_{1d}^N(Q) + q_{1d}^N(Q) - 2\,(1-\omega)\left(\frac{1}{1-\omega}q_{tf}^N(Q) - \frac{1}{\omega}q_{td}^N(Q)\right) = 0, \tag{33}$$

for $t = 1,2$. Totally differentiating (33) with respect to Q and using (iv) we obtain condition (vii) which reads $\partial q_{td}^N(Q)/\partial Q = \omega \partial q_{tf}^N(Q)/\partial Q$ for $t = 1,2$. Furthermore, condition (vii) together with (iii) and (iv) lead to condition (viii): $\partial q_{tf}^N(Q)/\partial Q = 1/2(1+\omega)$ and $\partial q_{td}^N(Q)/\partial Q = \omega/2(1+\omega)$ for $t = 1,2$. And since $\partial q_{1i}^N(Q)/\partial Q = \partial q_{2i}^N(Q)/\partial Q$ from (iv), integrating yields

$$q_f^N(Q) = \frac{1}{1+\omega}Q \quad \text{and} \quad q_d^N(Q) = \frac{\omega}{1+\omega}Q \tag{34}$$

where $q_f^N(Q) = q_{1f}^N(Q) + q_{2f}^N(Q)$ and $q_d^N(Q) = q_{1d}^N(Q) + q_{2d}^N(Q)$. Note that while $q_i^N(Q)$ is deterministic, $q_{1i}^N(Q)$ and $q_{2i}^N(Q)$ are not.

Plugging (viii) into (31) yields

$$\frac{\partial B\left(Q^N\right)}{\partial Q} = E\left[\frac{\partial C_{tf}(q_{tf}^N)}{\partial q_{tf}}\frac{1}{1+\omega} + \frac{\partial C_{td}\left(q_{td}^N\right)}{\partial q_{td}}\frac{\omega}{1+\omega}\right] + \lambda E\left[\frac{\partial C_{tf}(q_{tf}^N)}{\partial q_{tf}} + \frac{1}{2}\frac{C''}{1-\omega^2}Q^N\right]$$

for $t = 1, 2$. Summing conditions for $t = 1$ and $t = 2$, using (34), taking expectations, and dividing by 2, we conveniently arrive at

$$\frac{\partial B\left(Q^N\right)}{\partial Q} = \frac{1}{2}(1+\lambda)(c_1+c_2) + \frac{1}{2}A(\omega)(1+2\lambda)C''Q^N \tag{35}$$

where

$$A(\omega) = \frac{1+2\lambda\,(1+\omega)+\omega(1-\omega)}{(1+2\lambda)\,(1-\omega)\,(1+\omega)^2} \tag{36}$$

with $A(0) = 1$ and $A'(\omega) > 0$ (note that $sign[A'(\omega)] = sign[4\lambda(1+\omega)+3\omega-\omega^2])$.

Consider now the FOCs that solve for $q_1^S(\omega)$ and $q_2^S(\omega)$

$$\frac{\partial B\left(q_1^S+q_2^S\right)}{\partial q_t} = E\left[\sum_{i=f,d}\frac{\partial C_{ti}(q_{ti}^S)}{\partial q_{ti}}\frac{\partial q_{ti}^S(q_t^S)}{\partial q_{ti}}\right] + \lambda E\left[p_t^S(q_t^S) + \frac{\partial p_t^S(q_t^S)}{\partial q_t}q_t^S\right], \tag{37}$$

for $t = 1, 2$ and where $p_t^S(q_t)$ is the equilibrium price in t's technology-specific auction and $\partial C_{ti}(q_{ti}^S)/\partial q_{ti} = c_t + \theta_t + C''q_{ti}^S/\omega_t$.

Proceeding as above, we obtain

$$q_{tf}^S(q_t^S) = \frac{1}{1+\omega}q_t^S \quad \text{and} \quad q_{td}^S(q_t^S) = \frac{\omega}{1+\omega}q_t^S, \tag{38}$$

where $q_f^S = q_{1f}^S + q_{2f}^S$ and $q_d^S = q_{1d}^S + q_{2d}^S$. Summing the two FOCs given by (37), one for each technology, using (38), taking expectations, and dividing by 2, yield

$$\frac{\partial B\left(q_1^S+q_2^S\right)}{\partial q_t} = \frac{1}{2}(1+\lambda)(c_1+c_2) + \frac{1}{2}A(\omega)(1+2\lambda)C''Q^S, \tag{39}$$

where $Q^S = q_1^S + q_2^S$.

Looking at (35) and (39), it is clear that the two expressions are the same, implying $Q^N(\omega) = Q^S(\omega)$ for all ω. Furthermore, that $Q^N(\omega)$ and $Q^S(\omega)$ are decreasing in ω follows directly form the concavity of $B(\cdot)$ and $A'(\omega) > 0$.

For the rest of the proof note, after some manipulation, that the presence of market power affects expressions (4), (5), (11) and (12) in the main text as follows

$$\begin{aligned}
q_1^N(\omega) &= \frac{Q^N(\omega)+\Phi^N}{2} + \frac{\Delta\theta}{2C''} \\
q_2^N(\omega) &= \frac{Q^N(\omega)-\Phi^N}{2} - \frac{\Delta\theta}{2C''} \\
q_1^S(\omega) &= \frac{Q^S(\omega)+\Phi^S(\omega)}{2} \\
q_2^S(\omega) &= \frac{Q^S(\omega)-\Phi^S(\omega)}{2},
\end{aligned}$$

where $\Phi^N = \Delta c/C''$ (see (6) in the main text) and

$$\Phi^S(\omega) = \frac{1}{A(\omega)}\Phi^S(0)$$

with $\Phi^S(0) = (1+\lambda)\Delta c/(1+2\lambda)C''$(see (13) in main text).

Since $\partial\Phi^S(\omega)/\partial\omega < 0$ (recall that $A'(\omega) > 0$) and $Q^S(\omega) = Q^N(\omega)$, the distortion

$$E\left[q_1^N\right] - q_1^S = q_2^S - E\left[q_1^N\right] = (\Phi^N - \Phi^S(\omega))/2$$

is also increasing in ω.

Proof of Proposition 3

We want to show that welfare falls with ω under both approaches, but more so under the technology-specific approach.

Using (15) in the main text and the expressions in Lemma 3 we can compute, after some algebra, the difference in expected costs as

$$\Delta C^{SN}(\omega) \equiv E\left[C^S(Q^S(\omega))\right] - E\left[C^N(Q^N(\omega))\right] = \Delta C^{SN}(0) + \Psi(\omega) > 0$$

where

$$\Psi(\omega) = \frac{\omega^3 C''[\Phi^S(0)]^2}{4\,(1+\omega)^2\,(1-\omega)} > 0$$

with $\Psi(0) = 0$ and $\Psi'(\omega) > 0$. This shows that as we increase market power the cost difference also goes up due to the further allocative distortion under separation.

Similarly, and following (14), the difference in payments can be written as

$$\Delta T^{SN}(\omega) \equiv E\left[T^S(Q^S(\omega))\right] - E\left[T^N(Q^N(\omega))\right] = \Delta T^{SN}(0)\Upsilon(\omega) < 0$$

where

$$\Upsilon(\omega) = \frac{1}{\lambda A(\omega)}\left[1 + 2\lambda - \frac{1+\lambda}{(1-\omega^2)\,A(\omega)}\right] > 0$$

with $\Upsilon(0) = 1$ and $A(\omega)$ given by (36). Since $A'(\omega) > 0$ and $\partial[(1-\omega^2)\,A(\omega)]/\partial\omega < 0$, $\Upsilon'(\omega) < 0$ in the relevant range, that is, when $\Upsilon(\omega) > 0$. And since $\Delta T^{SN}(0) < 0$, we have that $\Delta T^{SN}(\omega)$ is increasing in ω, reducing the advantage of separation from a payment perspective. It follows that welfare decreases more with ω under separation than under neutrality.

Proof of Proposition 4

Let p_1^* and p_2^* be the optimal posted prices, leading to equilibrium quantities

$$q_t(p_t^*) = \frac{1}{C''}(p_t - c_t - \theta_t)$$

and welfare

$$W_p^S = E\left[bQ_p + \frac{B''}{2}(Q_p)^2 - \sum_{t=1,2}\{(c_t+\theta_t)\,q_t(\cdot) - \frac{C''}{2}(q_t(\cdot))^2 - \lambda p_t^* q_t(\cdot)\}\right] \tag{40}$$

where $Q_p = q_1(p_1^*) + q_2(p_2^*)$. For the same reasons that the deterministic component under the (optimal) price design in Weitzman (1974) is equal to the deterministic component under the (optimal) quantity design, here the deterministic component of W_p^S is equal to W_q^S, therefore ΔW_{pq}^S is simply the stochastic component, which is

$$\frac{B''}{2[C'']^2} E\left[(\theta_1 + \theta_2)^2\right] + \frac{1}{2C''}\left(E\left[\theta_2^2\right] + E\left[\theta_1^2\right]\right)$$

or expression (24).

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