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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

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Technology Neutral *vs.* Technology Specific Procurement*

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Abstract

An imperfectly-informed regulator needs to procure multiple units of some good (e.g., green energy, market liquidity, pollution reduction, land conservation) that can be produced with heterogeneous technologies at various costs. How should she procure these units? Should she run technology specific or technology neutral auctions? Should she allow for partial separation across technologies (technology banding or minimum technology quotas)? 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 renewable energies across the country, we illustrate how our theory can shed light on how to more effectively procure these technologies.

Keywords: public procurement, auctions, quantity regulation, price regulation, third-degree price discrimination, market power.

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1 Introduction

This past January, Spain introduced a novel auction design to procure 3000 MW of renewable energy: a joint auction for solar and wind but with minimum quotas of 1000 MW reserved for each technology.[1] Spain is just one among many countries resorting to renewable energy auctions to reduce carbon emissions at the lowest possible fiscal cost (Council of European Energy Regulators, 2018). A renewable energy auction revolution is under way worldwide (Fowlie, 2017). According to the International Renewable Energy Agency (2019), by the end of 2018, more than 100 countries had used auctions to procure renewable energy, i.e., a ten-fold increase in just one decade.[2] Remarkable in this "revolution" is the fact that no two auction designs look alike. They often differ in several dimensions, ranging from the pricing format to the contract duration, to name just two.

One key dimension, which is the focus of this paper, is whether auction designs are technology neutral, or whether they discriminate across technologies, either by type, location and/or scale.[3] Yet other auctions rely on hybrid designs that allow for some degree of competition across technologies while favouring some over others, e.g., by giving a handicap to some technologies, or by guaranteeing them a minimum quantity allocation, as recently done in Spain. Why is there such a large variation in auction designs regarding the treatment of the various technologies? What are the trade-offs involved? Is it possible to identify a technology approach that would perform better than the other formats currently in use? The objective of this paper is to provide a sufficiently general framework to understand, from a purely economic-regulatory perspective, when and why a particular procurement approach should be preferred over another.

Beyond this motivation, the question of how to procure goods or services 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., commercial banks) offer either strong or weak collateral in exchange for liquidity (Klemperer, 2010; Frost et al., 2015). In the past, central banks have considered different options, from posting prices (i.e., interest rates), to running separate auctions for each type of collateral, to running a joint auction for both types of collateral.[4] The choice between these

[1]The resulting prices have been highly competitive according to all international standards (IRENA, 2020). Two thirds of the total auctioned volume have been allocated to solar projects, just before triggering the minimum quota reserved for wind.

[2]Furthermore, many large corporations are also resorting to auctions to procure renewable power. For instance, from 2017-2019 Google purchased an amount of renewables equivalent to 100% of the company's total electricity use (Google, 2020).

[3]The European Union (2014)'s Guidelines on State aid for environmental protection and energy (currently under revision) require that auction schemes treat all technologies on a non-discriminatory basis (technology neutral), with only few exceptions allowed. This has prompted a shift for which the number of technology neutral auctions in Europe increased 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.

[4]Some joint auctions have followed the product-mix design of Klemperer (2010), where the auctioneer an-

approaches is also relevant in settings such as procurement of pollution reductions (Laffont and Tirole, 1996) and land conservation (Mason and Plantinga, 2013), among others.

As widely recognized in the literature of regulation and public procurement (Laffont and Tirole, 1993; Laffont and Martimort, 2002), procuring these goods faces the regulator with a trade-off between efficiency and rent extraction. Technology-neutral approaches are more effective for finding the cheapest technology sources, but they may result in over-compensation. Indeed, by not discriminating among heterogeneous sources, the authority may be leaving too much rents with the more efficient suppliers, unnecessarily increasing the costs of procurement. Without ex-ante knowledge of the costs of the various technologies, however, any attempt at differentiating technologies might not only result in inefficient but also more costly allocations.

Although this rent-efficiency trade-off has been already recognized in the realm of renewable energy procurement (EC, 2013; CEER, 2018), its impact on the preferred regulatory instrument to procure renewables and other resources has not been systematically analyzed. In this paper, we develop a simple, yet rich enough, model to properly weigh some of the key factors involved in technology procurement design in practice. We consider two types of technologies, say, solar and wind,[5] and a continuum of suppliers of each technology.[6] We capture the regulator's incomplete information by assuming that supply curves are subject to positively or negatively correlated shocks across technologies. The regulator's objective is to maximize (expected) social benefits minus total costs, subject to a budget constraint that gives rise to costly public funds. In solving the regulator's problem, we restrict attention to procurement formats that rely on uniform pricing.

We start our analysis by showing that the optimal mechanism is a product-mix auction *à la* Klemperer (2010), i.e., a single auction where the regulator commits to a demand schedule that is contingent on the bids submitted for the two technologies. Whenever the regulator cares about payments (i.e., public funds are costly), this mechanism results in different prices for the two technologies, despite delivering the same benefits – a result which is reminiscent of third-degree price discrimination (Bulow and Roberts, 1989). Importantly, the quantity allocation across technologies departs from the cost-minimizing solution in order to reduce payments. Hence, the optimal mechanism is technology neutral – in that both technologies compete within the same auction and are treated symmetrically ex-ante – but at the same time it is technology specific – in that both technologies receive different prices, with the allocated quantities departing from

nounces demand schedules for the different products. We come back to this design shortly.

[5]Manzano and Vives (2020) also consider a divisible good uniform-price auction with two groups of identical bidders. In their model, bidders compete in demand schedules and do not know their own costs. The attempt to learn costs from the market price shapes their bidding behaviour, leading them to submit flatter or steeper demand functions. Another key difference with our model is that their welfare analysis does not incorporate the social cost of public funds.

[6]Price-taking behaviour not only facilitates the analysis but also captures, to a large extent, what we have seen in recent renewable auctions (the latest renewable auction in Spain, for example, had 84 different bidders, offering more than three times the auctioned amount, with a final number of 32 winners). In any event, in Section 5 we discuss whether and to what extent market power may change some of our results.

a pure cost ranking.[7]

While the optimal mechanism allows the regulator to fully overcome her information asymmetry, and thus avoid the rent-efficiency trade-off, it has never been used in practice (at least not in the realm of resource and renewable-energy auctions, as our discussion above attests). Instead, regulators often rely on simpler policy designs that adjust only partially to actual cost realizations. Under these simpler mechanisms, regulators cannot escape the rent-efficiency trade-off described above, which is a centerpiece in the rest of our analysis.

Motivated by the renewable-auction "revolution", we first consider the case of quantity regulation, i.e., procurement auctions. We start with two of the simplest designs found in practice: the regulator has to commit ex-ante to procure a given number of units in either a single technology neutral uniform-price auction or in two technology specific uniform-price auctions. 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 (this replicates the outcome of the optimal mechanism). A similar prescription should be followed if the two technologies are subject to perfectly correlated shocks: in this case, cost minimization is not in danger either, but technology separation allows to reduce rents.

As incomplete information mounts, however, 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 are too large. This ultimately depends on the amount of over-compensation to the more efficient suppliers – as captured by the expected cost difference across technologies – and the unit price of this over-compensation – as captured by the shadow cost of public funds.[8]

Since neither technology neutrality nor technology separation succeed in containing both costs and payments, one may argue in favour of hybrid approaches that allow 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 (Myerson, 1981).[9]

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

[8]Adding market power to the model brings 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 regulator'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.

[9]Very often, banding is also used to penalize technologies that are considered less valuable, or to incentivize the more valuable ones. For instance, in the renewable auctions in Mexico, plants that have a generation profile that matches the system's needs receive an additional remuneration, while plants with less valuable production profiles are penalized (IRENA, 2019). Yet, we show that banding can be useful as a payment containment device

Whereas one may 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 dominates technology neutrality as one can always set a neutral handicap. However, through banding one cannot replicate the same outcome as under technology separation. Indeed, we find that banding does not always dominate the technology specific approach. Not only the latter 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, implies (through Jensen's inequality) that expected costs under banding might be higher than under the technology specific approach. This is particularly the case when the correlation of cost shocks is sufficiently high.[10]

Another hybrid approach, used in the latest renewable auction in Spain, is the establishment of minimum technology quotas (MTQs) in otherwise technology neutral auctions.[11] Unlike banding, MTQs can be designed to replicate the two extremes of technology neutrality and technology separation, and should thus be (weakly) preferred. By separating technologies for the more extreme cost realisations, MTQs are effective in containing payments when this is most needed. Likewise, by allowing for neutrality when costs shocks make technologies more symmetric, it is effective in avoiding cost inefficiencies. However, this does not mean that MTQs are always superior to banding. Indeed, we show that banding may dominate MTQs when one technology is clearly more efficient than the other and their costs are not too positively correlated.

In order to uncover the potential auction results under several scenarios, we perform simulations using detailed data on renewable investments in Spain. We find that, given the existing cost differences between solar and wind investments, technology separation outperforms both technology neutrality as well as banding. The main reason is that technology separation allows to contain payments, even if this implies increased costs. However, technology separation is dominated by MTQs, as the latter also help in containing payments but at a lower cost in terms of efficiency losses. In sum, these results suggest that Spain's novel auction design might have been a good choice given the current state of technologies.[12]

So far we have considered a regulator who procures a given number of units, say Q, under different auction formats. Those scenarios can arise when Q is not under the regulator's control

even in settings in which all technologies are equally valuable.

[10]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.

[11]Yet another hybrid option is to introduce technology specific reserve prices instead of minimum quotas (reserve prices have been used in the auctioning of pollution permits for instance; see, Borenstein et al., 2019). As this hybrid option might result in the total quantity not being fully allocated, we do not cover this case in our analysis. It is tangentially covered when we discuss "prices vs. quantities" in Section 6.

[12]For completeness, the Spanish design differed in other dimensions not considered in our simulations, so actual and simulated results are not readily comparable. An empirical analysis of the actual auction's outcome is left for future work once bid data becomes available.

but rather exogenously given; for instance, in response to a higher-level country commitment to reduce carbon emissions. The case of an endogenous Q opens a new set of questions. In particular, it may no longer be optimal to rely on quantity-based instruments (e.g., auctions) but rather on price-based instruments (e.g., Feed-in Tariffs). To study this additional instrument choice problem, we extend Weitzman's (1974) seminal work by considering multiple technologies and costly public funds. New insights emerge.

If, on the one hand, technology specific auctions happen to dominate a technology neutral auction, the comparison of "prices versus quantities" gives rise to a modified version of Weitzman's (1974) seminal expression.[13] In this case, the presence of multiple technologies enhances the superiority of prices over quantities since the former allow the quantities of the various technologies (and not just the total quantity) to better adjust to cost shocks. If, on the other hand, a technology neutral auction happens to dominate technology specific auctions, the comparison of prices versus quantities includes an additional term: a rent-extraction term. When public funds are not too costly, such that the rent-extraction term is not too large, a single quantity target may still dominate two prices as it allows for more quantity adjustment across technologies.

The rest of the paper is organized as follows. Section 2 describes the model and characterizes the optimal mechanism. Section 3 compares technology neutral and technology specific auctions in their simplest formats. Section 4 analyzes hybrid schemes: technology banding and minimum technology quotas. Section 5 adds market power. Section 6 analyzes price regulation. Section 7 contains the simulation exercise using solar and wind data from the Spanish market. Section 8 concludes. Lengthy proofs are relegated to the Appendix.

2 The Model

2.1 Model Description

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.[14] Their unit costs are uniformly distributed over the interval $[\underline{c}_t, \bar{c}_t]$, where $\underline{c}_t = c_t + \theta_t$ and $\bar{c}_t = c_t + \theta_t + C''$.[15] 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 $\theta_t \in [\underline{\theta}_t, \bar{\theta}_t]$ is a "cost shock" that captures the regulator's incomplete information about the costs of supplying technology t (both c_t and

[13]Our expression coincides with Weitzman's (1974) only when the cost shocks are perfectly correlated, as in this case the two technologies behave just as one.

[14]In Section 5 we add market power to the analysis.

[15]Unit costs are increasing and uncertain, partly because sites vary in quality, as captured in our simulation exercise and also emphasized in Schmalensee (2012).

C'' are public information). We allow c_t and θ_t to differ across technologies. In particular, we assume cost shocks to be jointly distributed according to the pdf $g(\theta_1, \theta_2)$, with $E[\theta_t] = 0$ and $E[\theta_t^2] = \sigma > 0$ for $t = 1, 2$, and $E[\theta_1\theta_2] = \rho\sigma$, with $\rho \in [-1, 1]$. Thus, we allow cost shocks to be either positively or negatively correlated across technologies. 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 $\Delta\theta \equiv \theta_2 - \theta_1$. We further assume that cost shocks belong to finite intervals so that in any equilibrium both technologies are deployed.

The deployment of these technologies creates social benefits, which we also capture with a quadratic function of the form (strictly speaking, the quadratic specification is not used until Section 6)

$$B(q_1, q_2) = B(Q) = bQ + \frac{1}{2}B''Q^2,$$

where $Q = q_1 + q_2$ is the total number of units supplied, with $b > 0$ and $B'' < 0$. From the social point of view, both technologies give rise to the same social benefits even though they are differentiated from the supply side.[16] We assume that b is large enough so it always optimal to procure some units.

The risk-neutral regulator'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 regulator'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 for the various instruments.

The timing of the procurement game is as follows. At date 1, the regulator announces the procurement format and its clearing rules. We restrict attention to formats that rely on uniform pricing, regardless of whether the regulator is using quantity or price schemes. At date 2, firms submit their bids. Since truthful bidding is a weakly dominant strategy for a price-taking firm, we adopt cost bidding as equilibrium strategy (unless explicitly mentioned otherwise).

2.2 Optimal Mechanism

Within the class of mechanisms that rely on uniform pricing, the optimal mechanism is a "product-mix" auction (Klemperer, 2010).

[16] We adopt this assumption so as not to bias the analysis in favour of technology specific approaches. This assumption could be easily relaxed, as indicated below.

Lemma 1 *The optimal product-mix auction is characterized by the regulator's announcement of demand schedules*

$$P_t^d(q_1, q_2) = \frac{B'(q_1 + q_2) - \lambda C'' q_t}{1 + \lambda} \tag{3}$$

with firms' bids organized according to technology specific supply schedules, $P_t^s(q_t)$ *for* $t = 1, 2$.

Proof. Truthful bidding leads to supply schedules given by the marginal cost of each technology, i.e.,

$$P_t^s(q_t) = C_t'(q_t; \theta_t) = c_t + \theta_t + C'' q_t.$$

for $t = 1, 2$. It is then straightforward to show that the resulting prices and quantities in the product-mix auction, which are obtained from the system $P_t^d(q_1, q_2) = P_t^s(q_t)$ for $t = 1, 2$, solve the same problem of a regulator who observes θ_1 and θ_2. ■

Even if the two technologies are perfectly homogeneous on the benefit side, the product-mix auction delivers different prices for the two products (i.e., technologies) whenever the regulator cares about payments, i.e., whenever $\lambda > 0$ (unless, of course, shocks are such that $c_1 + \theta_1 = c_2 + \theta_2$, which is virtually impossible). This should not be surprising, since these technology specific prices respond to a standard third-degree price discrimination motive. Furthermore, the optimal quantities allocated to both technologies depart from the cost minimizing ones, and more so the higher λ. Adding product differentiation on the benefit side (i.e., letting $\partial B(q_1, q_2)/\partial q_1 \neq \partial B(q_1, q_2)/\partial q_2$), as in Klemperer (2010), would only change equilibrium prices and quantities through changes in demand schedules, in which case $B'(q_1 + q_2)$ would simply be replaced by $\partial B(q_1, q_2)/\partial q_t$ in expression (3). These changes may result in more or less price divergence across the two technologies, and in a larger or smaller departure from the cost-minimizing solution, depending on the regulator's preferences and the cost of supplying the different technologies. However, the key result would remain unchanged: the optimal mechanism delivers two (technology specific) prices, with or without differences on the benefit side.

While the product-mix auction has the great advantage of indirectly solving the regulator's information problem, in reality, at least in the realm of resource and renewable-energy auctions, it has rarely been used, if ever. For the most part, regulators tend to rely on simpler policy designs that adjust only partially to actual cost realizations, whether fixing quantities ex-ante and letting prices adjust ex-post or, alternatively, fixing prices ex-ante and letting quantities adjust ex-post. Some may argue that these simpler designs leave less room for ex-post arbitrary adjustments. However, the product-mix auction is also immune to such concerns; it commits the regulator to act upon a pre-announced schedule. It is arguable whether schedules are easier to "manipulate" than quantities or prices, or the reverse.

Without delving into the political economy of why some instruments enjoy more support than others, in the rest paper we analyze procurement designs that have been used or proposed in practice, whether quantity- or price-based. In the presence of asymmetric information, none of these designs will approach the outcome of the optimal product-mix auction (Lemma 1);

unless, of course, $\lambda = 0$, in which case the product-mix auction converges to a technology neutral auction. Therefore, our goal is to understand whether and under what conditions some instruments may be superior to others.

3 Quantity-Based Procurement

We start our analysis with the case in which the regulator chooses quantity targets. If the regulator's target is to procure $Q = q_1 + q_2$ units, one option is to run a uniform-price auction that is open to both technologies. Suppliers would bid their true costs and the regulator would pay the market-clearing price times the total quantity Q. An alternative to this technology neutral auction, provided the regulator is allowed to discriminate across bidders, is to separate bidders according to their technologies and run technology specific auctions, say, for quantities q_1 and q_2, respectively. This time, the regulator would pay bidders according to two different market-clearing prices. We compare these two auction designs below and leave for the next section their comparison to hybrid schemes that introduce some flexibility into these designs.

3.1 Technology Neutral Auctions

Consider first a technology neutral auction and denote by Q^N the regulator's optimal quantity choice:[17]

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

Given Q^N, the ex-post allocation across technologies will depend on the realized cost shocks. Indeed, the quantity allocation will be such that the marginal costs of the two technologies will be equalized to the market-clearing price,

$$p^N = c_1 + \theta_1 + C'' q_1^N = c_2 + \theta_2 + C'' q_2^N, \tag{4}$$

Using (4) and $Q^N = q_1^N + q_2^N$, the equilibrium contribution of each technology to total output is given by

$$q_1^N(Q^N, \theta_1, \theta_2) = \frac{Q^N + \Phi^N}{2} + \frac{\Delta\theta}{2C''} \tag{5}$$

$$q_2^N(Q^N, \theta_1, \theta_2) = \frac{Q^N - \Phi^N}{2} - \frac{\Delta\theta}{2C''} \tag{6}$$

where

$$\Phi^N \equiv E\left[q_1^N(Q^N, \theta_1, \theta_2)\right] - E\left[q_2^N(Q^N, \theta_1, \theta_2)\right] = \frac{\Delta c}{C''} \tag{7}$$

denotes the difference between the expected quantities allocated to each technology. The expected allocation to the ex-ante more efficient technology is higher, the more so the greater its cost advantage and the flatter the aggregate supply curve. Note that if cost shocks are perfectly

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

and positively correlated, i.e., $\theta_1 = \theta_2$, then the regulator can perfectly anticipate the allocation to each technology. Otherwise, these allocations remain uncertain.

Using equations (4) to (6), one can also obtain the market-clearing price as a function of the cost shocks,

$$p^N(Q^N, \theta_1, \theta_2) = \frac{c_1 + c_2 + \theta_1 + \theta_2}{2} + \frac{C''}{2} Q^N, \tag{8}$$

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.

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.

3.2 Technology Specific Auctions

Consider now a mechanism that exploits the regulator'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 regulator's optimal choices:

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

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

$$p_t^S(q_t^S, \theta_t) = c_t + \theta_t + C'' q_t^S. \tag{9}$$

The regulator chooses the allocation across technologies in order to equate their expected marginal social costs,

$$(c_1 + C'' q_1^S)(1 + \lambda) + \lambda C'' q_1^S = (c_2 + C'' q_2^S)(1 + \lambda) + \lambda C'' q_2^S.$$

The expected marginal costs of the two technologies are equalized only when the regulator is not concerned about payments, i.e., $\lambda = 0$. Otherwise, the regulator takes into account the impact of the allocation on expected payments, as captured by the third term on both sides of the equality. A further difference as compared to (4) is that this expression does not depend on the realized cost shocks, θ_1 and θ_2.

Using $Q^S = q_1^S + q_2^S$, the equilibrium contribution of each technology to total output can be written as

$$q_1^S = \frac{Q^S + \Phi^S}{2} \tag{10}$$

$$q_2^S = \frac{Q^S - \Phi^S}{2} \tag{11}$$

where

$$\Phi^S \equiv q_1^S - q_2^S = \frac{\Delta c}{C''}\frac{1+\lambda}{1+2\lambda} \leq \Phi^N \tag{12}$$

denotes the difference in the quantity targets across technologies. This difference is decreasing in λ as the regulator is more concerned about minimizing rents. For $\lambda = 0$, $\Phi^S = \Phi^N$, while $\Phi^S < \Phi^N$ for all $\lambda > 0$.

As compared to the technology neutral case, the equilibrium prices in each auction depend exclusively on its own cost shock. Furthermore, the two prices need not coincide, which matters for total payments,

$$\begin{aligned} p_1^S(q_1^S, \theta_1) &= c_1 + \theta_1 + \frac{C''}{2}\left(Q^S + \Phi^S\right) \\ p_1^S(q_1^S, \theta_1) &= c_2 + \theta_2 + \frac{C''}{2}\left(Q^S - \Phi^S\right). \end{aligned}$$

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.

3.3 Comparison

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

Lemma 2 *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 2 above points at two important results. First, under either mechanism, the regulator 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 (5)-(6) and (10)-(11), as well as $Q^N = Q^S$,

$$q_1^S - E\left[q_1^N\right] = E\left[q_2^N\right] - q_2^S = (\Phi^S - \Phi^N)/2 < 0.$$

In words, as compared to the technology neutral design, the regulator 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.[18] Indeed, by increasing the allocation to the ex-ante less efficient technology, the regulator 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

$$E\left[T(q_1^S, q_2^S)\right] - E\left[T(q_1^N, q_2^N)\right] = \frac{C''}{2}\left(\Phi^S - \Phi^N\right)\Phi^S < 0. \tag{13}$$

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,

$$E\left[C(q_1^S, q_2^S)\right] - E[C(q_1^N, q_2^N)] = \frac{C''}{4}\left(\Phi^S - \Phi^N\right)^2 + \frac{E[(\Delta\theta)^2]}{4C''}. \tag{14}$$

The second term in (14) 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.

Expressions (13) and (14) capture the basic trade-off faced by the regulator 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 regulator should favor a technology neutral auction over technology specific auctions if and only if*

$$W_q^N - W_q^S \equiv \Delta W_q^{NS} = \frac{1}{4C''}\left[2\sigma(1-\rho) - \frac{\lambda^2}{1+2\lambda}(\Delta c)^2\right] > 0. \tag{15}$$

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 regulator should opt for the technology neutral design when the efficiency loss of not doing so - as captured by first term in brackets in (15) - is more important than the additional rents left with suppliers from not running separate auctions - as captured by the second term. Expression (15) 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

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

the regulator 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).

4 Hybrid Schemes

Since neither technology neutrality nor technology separation succeed in containing both costs and payments, one may argue in favour of hybrid approaches that allow for some partial separation between technologies. We consider two approaches currently in use: technology banding and minimum technology quotas (MTQs).

4.1 Technology Banding

A handful of countries currently rely on technology banding for setting renewable support.[19] 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.

Let $\alpha > 1$ be the handicap received by the ex-ante inefficient technology (technology 2). 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.[20]

The regulator'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,

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

[19]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, installations were entitled to receive 1.8 ROCs per MWh of offshore wind, 0.9 ROCs for onshore wind installations, and 1.4 ROCs for building mounted solar photovoltaics (UK Government, 2013).

[20]This price adjustment is also often used whenever the two goods are considered to be of different qualities; e.g. liquidity auctions, backed by strong or weak collateral. In this case, the high quality good is given a handicap, or a supplement on top of the market price. In the product-mix auction (Klemperer, 2010), the handicap is endogenously determined, together with the fraction of high-quality goods, according to the regulator's demand schedule.

one can obtain the equilibrium contribution of each technology,

$$q_1^B(Q^B, \alpha^B, \theta_1, \theta_2) = \frac{Q^B}{1+\alpha^B} + \frac{c_2 + \theta_2 - \alpha^B (c_1 + \theta_1)}{(1+\alpha^B) C''} \tag{16}$$

and

$$q_2^B(Q^B, \alpha^B, \theta_1, \theta_2) = \frac{\alpha^B Q^B}{1+\alpha^B} - \frac{c_2 + \theta_2 - \alpha^B (c_1 + \theta_1)}{(1+\alpha^B) C''}. \tag{17}$$

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

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

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 3 *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. ■

In the absence of uncertainty, the regulator 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 (15) in Proposition 1 does not hold.

Building from Lemma 3, 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 (16) and (17) to obtain expressions for these two components as follows

$$E\left[C^B(Q^B, \alpha^B)\right] = E\left[C^S(q_1^S, q_2^S)\right] + \frac{\sigma[\rho(1+(\alpha^B)^2) - 2\alpha^B]}{C''\left(1+\alpha^B\right)^2}, \tag{19}$$

and

$$E\left[T^B(Q^B, \alpha^B)\right] = E\left[T^S(q_1^S, q_2^S)\right] + \frac{\sigma\left(1+\rho\right)\left(\alpha^B - 1\right)^2}{C''\left(1+\alpha^B\right)^2}, \tag{20}$$

where $Q^B = q_1^S + q_2^S$. Consistent with Lemma 3, 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 (19) and (20), 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 (18) becomes certain (just like the market-clearing price under separation), thereby making the regulator'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 (16) and (17) 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.[21]

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 regulator indifferent between technology separation and banding. Using the regulator's indifference condition, $W_q^S = W_q^B$, this cutoff is given by[22]

$$\bar{\rho} = \frac{2\alpha^B - \lambda(\alpha^B - 1)^2}{1 + (\alpha^B)^2 + \lambda(\alpha^B - 1)^2} < 1. \tag{21}$$

For $\rho > \bar{\rho}$, separation dominates banding, and vice-versa.

One key component in the cutoff expression (21) is the cost of public funds, λ. A lower value of λ pushes $\bar{\rho}$ further up, making banding more attractive. The reason is that the regulator's payments do not weigh as much, thereby mitigating the advantage of separation in reducing rents. The other key component in (21) 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[23]

$$\alpha^B(\sigma \to 0) = 1 + \frac{2\lambda\Delta c}{\Delta c\,(1+\lambda) + C''Q^B\,(1+2\lambda)} < \frac{5}{3}, \tag{22}$$

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

[21] 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 component 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.

[22] 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.

[23] Note from (6), 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.

the regulator'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.

4.2 Minimum Technology Quotas

Instead of relying on technology banding, Spain has introduced minimum technology quotas (MTQs) into its latest renewable auction. In our setting, a MTQ auction is a single uniform-price auction which ensures that each technology gets a minimum quota. When these MTQs are not binding, the auction reduces to a standard technology neutral auction with all technologies receiving the exact same price. As soon as one of the MTQs is binding, the binding technology receives a higher price as compared to that of the other technologies.

Let $\underline{q}_t$ be the MTQ for technology $t = 1, 2$ and Q the total number of units to be auctioned off, with $\underline{q}_1 + \underline{q}_2 \leq Q$. When $\underline{q}_t$ is binding, $q_t = \underline{q}_t$ and $q_{-t} = Q - \underline{q}_t$, leading to a price wedge, $p_t = c_t + \theta_t + C''\underline{q}_t > p_{-t} = c_{-t} + \theta_{-t} + C''(Q - \underline{q}_t)$. Unlike technology banding, MTQ can replicate the outcome of technology neutral auctions, by setting $\underline{q}_1 = \underline{q}_2 = 0$ and $Q = Q^N$, and technology specific auctions, by setting $\underline{q}_1 = q_1^S$ and $\underline{q}_2 = q_2^S$ and $Q = \underline{q}_1 + \underline{q}_2 = Q^S$. Since technology banding fails to replicate the latter (see Proposition 2), one may be tempted to conclude that MTQ is always superior to technology banding. We next show this is not necessarily the case.

For a given MTQ design, i.e., a triplet $\{\underline{q}_1^M, \underline{q}_2^M, Q^M\}$, the outcome may fall into three different regions depending on the realizations of θ_1 and θ_2: (i) the region where $\underline{q}_1$ is binding, that is, when $C_1'(\underline{q}_1; \theta_1) \geq C_2'(Q - \underline{q}_1; \theta_2)$ or

$$\theta_1 - \theta_2 \geq \Delta c + C''(Q - 2\underline{q}_1) \equiv \ell_1;$$

(ii) the region where $\underline{q}_2$ is binding, that is, when $C_2'(\underline{q}_2; \theta_1) \geq C_1'(Q - \underline{q}_2; \theta_1)$ or

$$\theta_1 - \theta_2 \leq \Delta c + C''(2\underline{q}_2 - Q) \equiv \ell_2,$$

and (iii) the neutrality region, that is, when

$$\ell_2 \leq \theta_1 - \theta_2 \leq \ell_1.$$

Therefore, the optimal MTQ design can be found as the solution of the following problem:

$$\max_{\underline{q}_1, \underline{q}_2, Q} \sum_{t=1,2} \int_{\underline{\theta}_{-t}}^{\bar{\theta}_{-t}} \int_{\ell_t + \theta_{-t}}^{\bar{\theta}_t} W(\underline{q}_t, Q - \underline{q}_t; \theta_t, \theta_{-t}) g(\theta_t, \theta_{-t}) d\theta_t d\theta_{-t} +$$
$$+ \int_{\underline{\theta}_2}^{\bar{\theta}_2} \int_{\ell_2 + \theta_2}^{\ell_1 + \theta_2} W(q_1^N(Q, \theta_1, \theta_2), q_2^N(Q, \theta_1, \theta_2); \theta_1, \theta_2) g(\theta_1, \theta_2) d\theta_1 d\theta_2$$

where $W(\cdot)$ is the relevant welfare function for each region and $q_1^N(Q, \theta_1, \theta_2)$ and $q_2^N(Q, \theta_1, \theta_2)$ are given by the quantity expressions under technology neutrality, (5) and (6), respectively.

Without solving this maximization problem, it is not difficult to see that the optimal MTQ design may involve a single region, i.e., the region where the MTQ for the ex-ante less efficient technology is binding (region (ii) in our case), or the three regions described above. The neutrality region only exists as a transition between regions (i) and (ii). This transition only exists when shocks are sufficiently large relative to Δc so that one technology becomes more efficient than the other for some realizations of θ_1 and θ_2, but not for others. This insight leads to the following result.

Proposition 3 *Technology banding can be superior to MTQ.*

Proof. By means of an example, suppose that cost shocks are such that $\Delta c > \bar{\theta}_1 - \underline{\theta}_2$. Since technology 1 is more efficient than technology 2 for any realization of θ_1 and θ_2, the optimal MTQ design reduces to technology specific auctions; it only includes region (ii). And we know from Proposition 2 that in this case there exists a correlation cut-off, $\bar{\rho} < 1$, below which technology banding dominates technology specific auctions. ■

Proposition 3 serves to illustrate that technology banding may be the right choice when one technology is clearly more efficient than the other, both from an ex-ante as well as from an ex-post perspective. In contrast, MTQ is more flexible for handling the regulator's uncertainty when it is hard to tell ex-ante which technology will end up being more efficient, i.e., when cost shocks are large relative to Δc. In this case, MTQs are better at handling very different outcomes; namely, the fact that one technology may be more efficient than the other (regions (i) and (ii)) or that the two technologies may turn to be equally efficient (the neutrality region (iii)).

5 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.[24] 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.[25]

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

[25]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). The extent to which our finding below (Proposition 4) – i.e, that market power favors the neutral approach over the specific one – remains in the context of non-linear

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 (4). As ω goes up, 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 4 below compares the quantity choices under technology neutral and technology specific auctions in the presence of market power.

Lemma 4 *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 regulator 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.

menus will depend, among others, on whether 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.

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 4 *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.

6 Price-Based Procurement

So far we have considered a regulator 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 so as to maximize welfare (2), all our results go through if Q is not under the regulator's control but rather exogenously given. 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 adjust to shocks; whereas under a price-based instrument prices are fixed but quantities adjust 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 regulator'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 (9), $p_t^* = E[p_t^S] \equiv c_t + C'' q_t^*$, 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 5 *Two posted prices dominate two technology specific auctions if and only if*

$$W_p^S - W_q^S \equiv \Delta W_{pq}^{SS} = \frac{\sigma(1+\rho)}{(C'')^2}\left(B'' + \frac{C''}{2}\frac{2}{1+\rho}\right) > 0. \tag{23}$$

Proof. See the Appendix. ■

When shocks θ_1 and θ_2 are perfectly correlated, $\rho = 1$, equation (23) 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}^{SS} 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.[26]

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 (23). This result does not mean, however, that price regulation should always be preferred to quantity regulation when expression (23) 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 6 *Two posted prices dominate a technology neutral auction if and only if*

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

Proof. Immediate from the proofs of Propositions 1 and 5. ■

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 (24). 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 (24).

Since $B'' + C''/2 \leq B'' + C''/(1+\rho)$, it is clear from the comparison of (23) and (24) 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.

[26] 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.

7 Simulations

In this section we use actual cost data to illustrate some of the main results of the model. Given our motivation, we focus on procurement auctions. Using 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 implications for social costs (investment efficiency and payments) of choosing between: (i) a single technology neutral auction, (ii) two separate technology specific auctions, one for solar and one for wind, (iii) a technology neutral auction combined with technology banding, and (iv) a technology neutral auction combined with MTQs.

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. This 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,[27] we have computed the expected production of each investment project over its lifetime (which we assume equal to twenty five years; the expected lifetime of most installations).[28] 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 ratio between its investment cost, denoted by $c(\theta_t, k_i)$, and q_{itl}. By ranking 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.[29] We set γ equal to 0.9 to capture mild scale economies.[30] 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.[31] Even if average costs are set at this level, heterogeneity in locations and plant sizes gives rise to variation in average costs across projects.

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

[28] If instead we assume a shorter life-time, say, of twenty years, the main conclusions of this analysis would remain unchanged as long as we apply that number to both technologies.

[29] 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.

[30] 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 (2020).

[31] 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 implies that cost shocks move average costs by 5%, upwards or downwards.[32] 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 for all auction designs. In all designs we consider $Q = 4000$ MW and three possible values for cost of public funds, $\lambda \in \{0, 0.2, 0.4\}$.

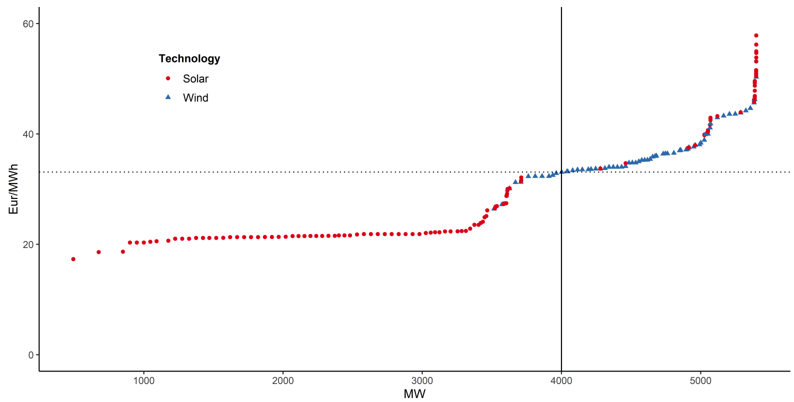
Technology neutral design Figure 1a plots the bids (i.e., average costs) and clearing price, 37 Euro/MWh, under a technology neutral auction for a given pair of cost shocks, (θ_1, θ_2). As it can be seen, the average costs of solar plants (denoted by red dots) tend to be lower than the average costs 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 $Q = 4000$ MW, it is optimal to procure both solar as well as wind projects.

Table 1 summarizes the results (expected social costs, including expected cost and payments) relative to the optimal mechanism for nine pairs of (ρ, λ) values. As can be seen in columns (1), (5) and (9), technology neutrality gives rise to lower expected costs as compared to the optimal mechanism, at the cost of increasing payments. The resulting social costs are thus higher (between a 6% and an 11% depending on the (ρ, λ) values considered). Technology neutrality performs relatively worse when the cost correlation is negative and the cost of public funds is high.

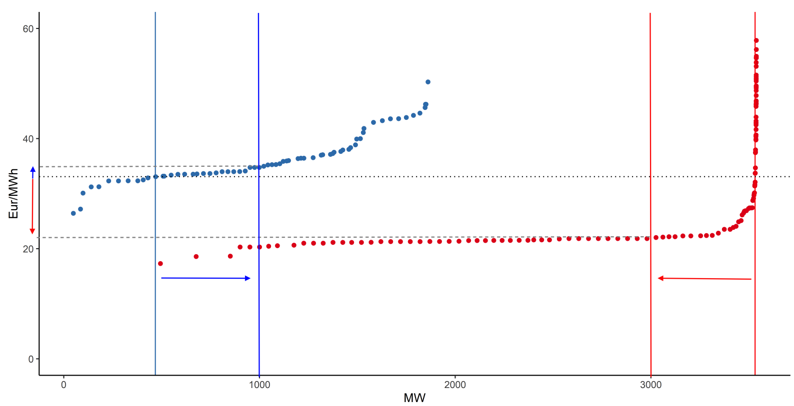
Technology specific design For given pair of ρ and λ, we first need to identify the ex-ante allocation across the two technologies $\left(q_1^S, q_2^S\right)$ that minimizes expected social costs, subject to the constraint that the two must add up to $Q = 4000$ MW. Figure 1b illustrates the effects of 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. And as explained in Section 3, these investment inefficiencies increases as we add cost shocks.

[32] These shocks may underestimate the regulator's uncertainty, but they ensure that both technologies are always procured in equilibrium. Recall that our focus here is on the relative performance of the different auction designs.

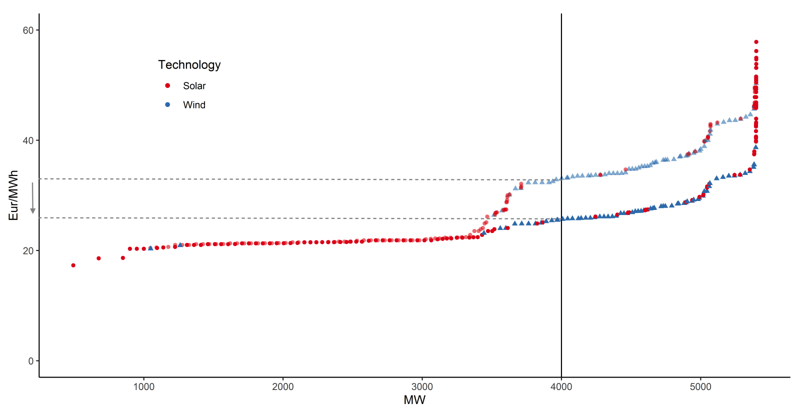
Figure 1: Bidding Results for Different Auction Designs



(a) Technology Neutral



(b) Technology Specific



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

Notes: These figures display average supply bid curves under three auction designs for a given pair of cost shocks. Red (blue) dots correspond to solar (wind) projects. Under technology neutrality (Figure 1a), all projects are ranked in increasing cost order. Under a technology specific design (Figure 1b), projects are ranked separately within each technology. The vertical lines represent how the allocation across technologies is distorted relative to technology neutrality. Under technology banding (Figure 1c), wind projects are given a handicap $\alpha = 1.3$. The solution under MTQs is represented by Figure 1a if the quotas are non-binding, or Figure 1b otherwise.

Table 1: Simulation results relative to the optimal mechanism

		Social Costs				**Costs**				**Payments**			
ρ	λ	Neutral	Specific	Banding	MTQ	Neutral	Specific	Banding	MTQ	Neutral	Specific	Banding	MTQ
-0.8	0	1.0000	1.0331	1.0000	1.0000	1.0000	1.0331	1.0000	1.0000	1.0500	0.7687	1.0500	0.9881
	0.2	1.0662	1.0222	1.0423	1.0054	0.9932	1.0284	1.0036	1.0038	1.3876	0.9947	1.2130	1.0125
	0.4	1.1180	1.0188	1.0693	1.0077	0.9886	1.0274	1.0067	1.0031	1.4087	0.9996	1.2099	1.0180
0	0	1.0000	1.0167	1.0000	1.0000	1.0000	1.0167	1.0000	1.0000	1.0301	0.7730	1.0301	0.9940
	0.2	1.0591	1.0103	1.0319	1.0032	0.9919	1.0084	1.0021	1.0011	1.3574	1.0186	1.1642	1.0125
	0.4	1.1105	1.0138	1.0572	1.0082	0.9878	1.0171	1.0080	1.0006	1.3746	0.9944	1.1560	1.0135
0.8	0	1.0000	1.0009	1.0000	1.0000	1.0000	1.0009	1.0000	1.0000	1.0069	0.8896	1.0069	1.0005
	0.2	1.0530	1.0023	1.0183	1.0018	0.9910	1.0000	1.0010	1.0017	1.3288	1.0125	1.0951	1.0023
	0.4	1.0974	1.0033	1.0317	1.0033	0.9864	1.0043	0.9963	0.9970	1.3493	1.0011	1.1120	1.0178

Notes: This table reports the results of the simulations (social costs, costs and payments) under each mechanism relative to the optimal mechanism. On can see that the lowest social costs are obtained under MTQ. Technology separation results in the lowest payments but it results in higher costs. Technology neutrality results in the lowest costs but high payments. Banding does not perform as well as MTQ.

This trade-off is reflected in the simulation results reported in Table 1. Columns (2), (5) and (10) report the outcomes under the technology specific approach relative to the optimal mechanism. As compared to technology neutrality, costs under the technology specific approach are always higher and payments lower. On the one hand, the relative cost inefficiency of technology separation increases for higher values of λ, as the quantity distortion gets larger. On the other, this also enlarges the payment gap between the two approaches. 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.

Last, relative to the optimal design, the technology specific approach results on lower payments but higher inefficiency, resulting in inefficiently high social costs (between a 0.3% and an 3%). As expected, the social costs are close to optimal when the cost correlation is positive as the gains from adjusting quantities ex post are relatively small.

Hybrid designs Hybrid designs combine a technology neutral design with either technology banding or minimum technology quotas (MTQs).

Under banding, wind, the high cost technology, receives a handicap α. Figure 1c 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. The MTQs are illustrated in Figure 1a when the constraint is non-binding, or in Figure 1b otherwise.

For each set of parameters (ρ, λ), we compute the optimal handicap and the optimal minimum technology quotas, i.e., the values of α or MTQs that minimize the expected social cost. As expected, for $\lambda = 0$, the optimal banding is $\alpha = 1$, i.e., equivalent to full neutrality, and as λ goes up, so does the optimal degree of banding. For instance, it is optimal to set $\alpha = 1.3$ for $\lambda = 0.2$ and $\alpha = 1.4$ $\lambda = 0.4$. Similarly, for $\lambda = 0$, the optimal MTQ is 0, which is also equivalent to full neutrality. For higher values of λ, the MTQ goes up and reaches its maximum value, 595.5 MW, for $\lambda = 0.4$.

In Table 1, columns (3)-(4), (6)-(7) and (11)-(12), one can see the results under banding and MTQs relative to the optimal mechanism. The comparison between the two shows that MTQs always lead to lower payments as compared to banding. Since the costs are nevertheless small, MTQs always outperform banding under the set of parameters considered.

Indeed, in this setting, MTQs appears to be, among all the mechanisms considered, the closest one to the optimal mechanism. The resulting social costs are only 0.3% to 0.8% above the optimal level. The reason is simple: by separating technologies for the more extreme cost realisations, it is effective in containing payments when this is most needed; while by allowing for neutrality when costs shocks make technologies more symmetric, it is effective in avoiding cost inefficiencies.

We have performed several robustness checks by choosing different values for the parameters. Overall, this conclusion remains intact. In other contexts, if technology 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.

8 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 to reduce 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.

The extremes of technology neutrality and separation can be improved by considering hybrid designs that introduce either technology banding or minimum technology quotas (MTQs). In fact, technology neutrality is always dominated by technology banding, which in turn dominates technology separation but only when cost shocks are sufficiently negatively correlated. Setting minimum technology quotas dominates both technology neutrality and separation, and might also dominate banding if the cost correlation is positive and large.

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

$$\frac{\partial B\left(Q^N\right)}{\partial Q}=E\left[\sum_{t=1,2}\frac{\partial C_t\left(q_t^N\right)}{\partial q_t}\frac{\partial q_t^N(Q)}{\partial Q}\right]+\lambda E\left[\frac{\partial p^N(Q)}{\partial Q}Q^N+p^N(Q)\sum_{t=1,2}\frac{\partial q_t^N(Q)}{\partial Q}\right]\tag{25}$$

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 (25) 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

$$\frac{\partial B\left(Q^N\right)}{\partial Q}=\frac{1}{2}(1+\lambda)(c_1+c_2)+\frac{1}{2}(1+2\lambda)C''Q^N.\tag{26}$$

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

$$\frac{\partial B\left(q_1^S+q_2^S\right)}{\partial q_t}=E\left[\frac{\partial C_t\left(q_t^S\right)}{\partial q_t^S}\right]+\lambda E\left[p_t^S(q_t^S)+\frac{\partial p_t^S(q_t^S)}{\partial q_t}q_t^S\right] \tag{27}$$

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

$$\frac{\partial B\left(q_1^S+q_2^S\right)}{\partial q_t}=\frac{1}{2}(1+\lambda)(c_1+c_2)+\frac{1}{2}(1+2\lambda)C''Q^S \tag{28}$$

where $Q^S=q_1^S+q_2^S$. Comparing (26) and (28) 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 (27) 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 (27) 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 $E\left[q_2^N\right]<q_2^S$.

Using the equilibrium choices, the comparison across formats in terms of quantities, payments and costs is given by

$$\begin{aligned}
q_1^S-E\left[q_1^N\right] &= E\left[q_2^N\right]-q_2^S=-\frac{\Delta c}{2C''}\frac{\lambda}{2\lambda+1}\\
E\left[T(q_1^S,q_2^S)\right]-E\left[T(q_1^N,q_2^N)\right] &= -\frac{(\Delta c)^2}{2C''}\frac{(1+\lambda)\lambda}{(1+2\lambda)^2}<0\\
E\left[C(q_1^S,q_2^S)\right]-E[C(q_1^N,q_2^N)] &= \frac{(\Delta c)^2}{4C''}\frac{\lambda^2}{(1+2\lambda)^2}+\frac{E[(\Delta\theta)^2]}{4C''}
\end{aligned}$$

Using the definitions of Φ^N and Φ^S in (7) and (12), these expressions simplify to the expressions given in the main text.

Proof of Proposition 2

From expressions (19) and (20) 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.,

$$\bar{W}_q^B(\alpha^B, Q^B) - \frac{\sigma[\bar{\rho}(1 + (\alpha^B)^2) - 2\alpha^B + \lambda\,(1+\bar{\rho})\left(\alpha^B - 1\right)^2]}{C''\,(1+\alpha^B)^2} = W_q^S, \tag{29}$$

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 (29), we would obtain that $\bar{W}_q^B(\alpha^B, Q^B) > W_q^S$; a contradiction.

Proof of Lemma 4

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

$$\begin{aligned}\frac{\partial B\left(Q^N\right)}{\partial Q} \quad &= \quad E\left[\sum_{i=f,d}\sum_{t=1,2}\frac{\partial C_{ti}\left(q_{ti}^N\right)}{\partial q_{ti}}\frac{\partial q_{ti}^N(Q)}{\partial Q}\right] - \\ &\quad \lambda E\left[\frac{\partial p^N(Q)}{\partial Q}Q^N + p^N(Q)\sum_{i=f,d}\sum_{t=1,2}\frac{\partial q_{ti}^N(Q)}{\partial Q}\right]\end{aligned} \tag{30}$$

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 (30) 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

$$\{q_{1d}^N, q_{2d}^N\} = \arg\max\{p^N(Q)(q_{1d}^N + q_{2d}^N) - C_{1d}\left(q_{1d}^N\right) - C_{2d}\left(q_{2d}^N\right)\}, \tag{31}$$

subject to (i) and (v).

Solving (31) we arrive at the FOC

$$q_{1d}^N(Q) + q_{1d}^N(Q) - 2(1-\omega)\left(\frac{1}{1-\omega} q_{tf}^N(Q) - \frac{1}{\omega} q_{td}^N(Q)\right) = 0, \tag{32}$$

for $t = 1, 2$. Totally differentiating (32) 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

$$q_f^N(Q) = \frac{1}{1+\omega} Q \quad and \quad q_d^N(Q) = \frac{\omega}{1+\omega} Q \tag{33}$$

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 (30) 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 (33), taking expectations, and dividing by 2, we conveniently arrive at

$$\frac{\partial B\left(Q^N\right)}{\partial Q} = \frac{1}{2}(1+\lambda)(c_1 + c_2) + \frac{1}{2} A(\omega)(1+2\lambda) C'' Q^N \tag{34}$$

where

$$A(\omega) = \frac{1 + 2\lambda(1+\omega) + \omega(1-\omega)}{(1+2\lambda)(1-\omega)(1+\omega)^2} \tag{35}$$

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 $q_2^S(\omega)$

$$\frac{\partial B\left(q_1^S + q_2^S\right)}{\partial q_t} = E\left[\sum_{i=f,d} \frac{\partial C_{ti}(q_{ti}^S)}{\partial q_{ti}} \frac{\partial q_{ti}^S(q_t^S)}{\partial q_{ti}}\right] + \lambda E\left[p_t^S(q_t^S) + \frac{\partial p_t^S(q_t^S)}{\partial q_t} q_t^S\right], \tag{36}$$

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

$$q_{tf}^S(q_t^S) = \frac{1}{1+\omega} q_t^S \quad and \quad q_{td}^S(q_t^S) = \frac{\omega}{1+\omega} q_t^S, \tag{37}$$

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 (36), one for each technology, using (37), taking expectations, and dividing by 2, yield

$$\frac{\partial B\left(q_1^S + q_2^S\right)}{\partial q_t} = \frac{1}{2}(1+\lambda)(c_1+c_2) + \frac{1}{2}A(\omega)(1+2\lambda)C'' Q^S, \tag{38}$$

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

Looking at (34) and (38), 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 (5), (6), (10) and (11) 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 (7) 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 (12) 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 4

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

Using (14) 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 (13), 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 (35). 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 5

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

$$W_p^S = E\left[bQ_p + \frac{B''}{2}(Q_p)^2 - \sum_{t=1,2}\left\{(c_t + \theta_t)\,q_t(\cdot) - \frac{C''}{2}(q_t(\cdot))^2 - \lambda p_t^* q_t(\cdot)\right\}\right] \tag{39}$$

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 (23).

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