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AUCTIONING WIND POWER SITES WHEN ENVIRONMENTAL QUALITY MATTERS

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June 2008

"MARCO FANNO" WORKING PAPER N.81

Auctioning Wind Power Sites when Environmental Quality Matters

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Abstract

In this work we frame within auction theory an index that allows to order different projects for the construction of onshore wind energy plants and that explicitly takes into account their environmental quality. Wind farm projects are defined as vectors of attributes, encompassed in four categories: the technical properties of each project; its social impact; its environmental impact and the share of earnings that proponents offer to the collectivity in compensation for the negative externalities of the wind plant. We define an absolute index that allows to order different proposals and evaluate the acceptability of each project, providing the monetary value of each point and inducing a truthful revelation of firms' private information. Moreover, we calibrate the index, on the basis of a representative project and derive the corresponding iso-scoring curves.

J.E.L. Classification: Q42; Q58; D45.

Keywords: Renewable Energy, Wind Power, Scoring Rule, Environmental Externalities.

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1 Introduction.

Wind power is one of the most important source of renewable energy.[1] It is generally widely accepted that the exploitation of onshore wind power sites can be efficiently undertaken in a market setting; however, its development implies significant market failures that justify the need of planning and regulation by the public authority. Indeed, there are relevant local negative environmental externalities that are associated with the visual and sound impact of onshore windmills and their possible negative interaction with local wildlife and other working activities.[2] From a theoretical point of view it is well known that a project is socially efficient whenever the social benefits overtake social costs. Therefore, the public body in charge of authorizing the exploitation of wind power sites should approve a specific project only after an adequate evaluation of its net benefits and then, having internalized the externalities with the proper instruments, let the market choosing the characteristics of the investment project. However, in the real world, the investment decisions about the exploitation of onshore wind power are not easy. There are asymmetries of information about the precise location of the sites and the technologies that should be adopted, preemption moves by investors, short-sighted investment problems, local resistance by local communities that bear the cost of local externalities, imprecise or unclear selection rules. All these aspects are intercorrelated. Public approvals are often constrained by some minimal requirement, among which there is, generally, obtaining a positive judgment in the Environmental Impact Assessment. Unfortunately, such a procedure can only highlight those proposals that are insufficient with respect to one or more specific aspects, but neglects to capture the interaction among all elements that characterize a specific project. A second relevant point that has to be taken into account when dealing with onshore wind power sites exploitation refers to the scarcity of resources. Indeed, even if the wind supply can be assumed to be a public good, that is not true for the land, which is a scarce and rival good. Therefore, in order to reach an efficient allocation of the investments in wind power production in a given area the public authority has to decide the highest number of wind parks

[1] In Europe at the end of 2007 there were 58,1 *Gw* of capacity installed, that covers roughly 4% of total electric demand. In the whole world, there where 94.1 *Gw*, with a growth rate of 27% (Dorn, 2008).

[2] For an analysis of visual impacts of offshore wind plants see Ladenburg and Dubgaard (2007).

that should be realized in that area. Moreover, if the number of projects that aims to be developed is higher than their desired number (for instance, the amount of investments that maximize social welfare, or the number of wind turbines that can be physically implemented in that specific place), the public body has to call on some decision making criterion that allows to order and select the various rival proposals.

In the paper we show that this problem can be tackled by a specific tool, namely, a single scoring rule that measures the net benefit associated to each project. A threshold of the scoring rule can be set in such a way to separate projects that have net positive social benefits from those whose costs exceed the benefits. Moreover, for those investment projects whose score is above the threshold, the rule allows to rank them according to their social welfare. Indeed, such a rule works as an (implicit) auction for the exploitation of onshore wind power sites. Afualo *et al.* (1998) have shown that auctions are widely used to allocate public resources since they allow to endeavour the auctioning public body with a positive revenue from the procedure and also because (if properly run) they can efficiently allocate scarce resources. The scoring rule we propose works as a multidimensional auction,[3] that takes into account the various aspects that are related to the building and running of a wind park. The crucial element of the scoring rule is the definition of the scoring function, i.e., the algorithm that allows attaching a single numerical value to the vector of the elements that describe the project. Asker *et al.* (2008) and Dini *et al.* (2006) show that the scoring function enables to translate into figures the impact that every element has on the social welfare. Therefore, for these types of auctions the score can be seen as a proxy of the net social welfare correlated to each specific project and it thus provides a (implicit) cost-benefit assessment.

The paper proceeds as follows: in the next section we show the proposed scoring rule, analyzing it in the mark of the multidimensional auction theory; in the subsequent section we calibrate the index, showing an example of its possible implementation. References follow. The mathematics of the scoring rule is reported in the appendix.

[3] Che (1993), is the seminal paper on multidimensional auctions. See also Che (forthcoming) for a review of recent theoretical developments.

2 The Scoring Rule for Selection of Wind Power Projects.

Generally, when the public authority[4] runs a multidimensional auction it applies the "best economic offer" as the decisive decision criterion, attaching a score to each proposal according to the following summation:

$$\sum_i \theta_i v_{ij}(x_{i1}, ..., x_{iN}) \tag{1}$$

where θ_i is the weight attached to the element i, $v_{ij}(x_{i1}, ..., x_{iN})$ is a number (between 0 and 1) that refers to the evaluation of the ith element in the proposal j, and x_i is the figure that is proposed by the proponent about element i. There are two main ways to score the different proposals: a discretionary way, or a quantitatively pre-defined one. The formers requires the intervention of a specific committee that, given some subjective technical evaluation, decides how many points each offer is worth for that specific element of the proposal. The latter is based on some specific pre-defined algorithm, which can be absolute or relative. Under absolute scoring rule, the score received by the proposal j depends only on its own proposed figure, and it is thus completely independent from the amount proposed by the other $N - j$ proposals, as it is for relative scoring rule. Thus for absolute scoring we have that:

$$v_{ij} = v_{ij}(x_{ij}) \tag{2}$$

Discretionary procedure are generally applied whenever there are some aspects that are too difficult to be evaluated on the basis of quantitative judgments only, as it happens, for instance, for judgments about the aesthetic quality of a masterpiece, or the trust about some proponent. Obviously, these aspects undermine the transparency of any scoring rule, and thus they should not be the pivotals element of a multidimensional scoring rule. For

[4] In this paper, we generically denote as "public authority" the subject who has the right to authorize the exploitation of wind power in specific sites and need to apply a selection rule for it. For what it matters, it could well be a private firm who owns the lands and want to select sub-contractors.

this reason, in our scoring rule we adopt the discretionary method just for the assessment of a single parameter, namely, the local environmental impact of wind parks.

Automatic methods are generally implemented through relative scoring formulas. Indeed, even if they allow to calibrate the point received by each proposal as compared to the others, they may be inefficient since do not provide the correct incentives to proponents (Dini *et al.* 2006). Indeed, with relative scoring formulas, firms cannot infer the preferences of the public authority and thus need to make inferences about them, which might lead to inefficient proposals. Moreover, relative methods cannot allow evaluating the quality of the single proposal; this, in our case, would undermine the possibility of assessing the net social welfare of a proposed wind park in absolute terms. For these reasons, we adopt an absolute procedure in our scoring rule to attach points to the various elements considered. However, the adoption of absolute scoring rules requires an important caveat. Indeed, whenever the public body specifies the points attached to the proposal it (implicitly) declares its willingness to pay (i.e., not to receive) in order to obtain an increase in the score, i.e., in the quality of the proposal (see Dini *et al.* 2006). In other words, preferences of the public authority can be inferred by calculating the Economic Value of a Point (EVP).

The EVP corresponds to the marginal increment of the offer that it is necessary in order to obtain one single points more. Clearly, this value is constant iff the scoring function that attaches the point figure to that element is linear. Therefore, in order to evaluate the various elements of a proposal with an absolute scoring rule a minimum and a maximum threshold has to be set. The min equals the value of that specific element that obtains a null point, while the max corresponds to the value beyond which it is not possible to increase the score by increasing the offer on that element. The product of the weight attached to each aspect with the EVP assigned to the monetary offer defines the maximum amount that the public authority is willing to spend in order to receive a proposal that equals the max.

We evaluate the proposals of installing a wind park looking at four elements of the proposals:

1. the local (negative) environmental impact of the project: N

2. the economic compensation for local communities expressed as royalties (percentage of revenues): R

3. the technical characteristics of the project: E

4. the social impact of the project: S

There are several reasons that justify the need to evaluate all these aspects. The meaning of N is rather obvious, since it aims at prizing those projects that implies lower negative local externalities. For the same reason, R expresses the amount of revenues that are given back to the local community; the idea is that this should (at least) reduce the opposition of local communities that underestimate the global benefit and overestimate the (local) damages.[5] Similarly, S aims at prizing those projects that guarantee not only financial returns but also labour ones.[6] The technical impact E captures the "quality" of the investment, i.e., it emphasizes, ceteris paribus, those projects that can guarantee higher wind power for given wind supply (an thus maximize the production of positive global externalities).

The score we propose is the following:

$$I = \theta_N v_N + \theta_R v_R + \theta_E v_E + \theta_S v_S \tag{3}$$

It is quite complex to evaluate the environmental impact of a wind production plant, and it is not clear which proxy should be employed for it. Therefore, we prefer to leave the evaluation of N to a specific committee that should judge the proposals on the basis of a pre-defined grid of aspects, each of which is to be evaluated according to a given scale and then converted in a numerical score encompassed between null and 1. Call this v_N. In order to define the total score assigned to each proposal with respect to this element, we just have to decide the weight that such an aspect has in the scoring rule, namely, θ_N.

The royalty offered is generally expressed as a percentage of the expected income. In this way, both the public body and the firm share the risk of

[5] It is the well-known NIMBY behavior. For an analysis of the factors that influence local acceptance, see Jobert and Laborgne (2006), Nadaï (2007) and references therein.

[6] Recall that the land on which a wind plant is going to be set is a rival good. Other renewable sources that are less marginal such as biomass, for instance, may be preferred by public bodies since they need a higher share of labour in their production function w.r.t. wind plants. In other words, the scoring rule captures the idea that biomasses (may) guarantee a double dividend and that wind power plants should be compared to other alternatives w.r.t. this component of the social return of the investment. If this is not the case, simply set $\theta_s = 0$.

the business, due to randomness of wind supply. However, the benefits for the local community do not depend on the expected revenue but on the (ex-post) realized ones. For this reason, in our formula v_R is proportional to the product between the proposed royalty and the forecasted revenue described in the financial and economic plan that each proponent has to submit together with the proposal. Revenues are evaluated on the basis of the forecast of the wind supply, that allows calculating the amount of full load hours (the ratio between the energy produced by the considered wind farm and the nominal power of the same wind farm):

$$v_R = \min\left[\frac{r\alpha Q - R_{\min}}{R_{\max} - R_{\min}}, 1\right] \tag{4}$$

where r is the proposed royalty (% of the yearly revenue), Q are *Mwh* forecasted, and α allows to convert the physical amount of energy in economic figures.[7] αQ is thus the cash flow that is estimated by the public authority,[8] and $r\alpha Q$ is the estimated yearly compensation, expressed in euro. $R_{\min}$ and $R_{\max}$ are the minimum and the maximum compensation that are going to be accepted by the public body. Offers lower that $R_{\min}$ receive zero points, while firms cannot gain more than the maximum amount of point they can obtain by offering a compensation higher than $R_{\max}$. Notice that $v_R \in [0, 1]$. The figure of full load hours of a given wind farm is given by: $Q = \prod_{i=1}^{m} O_i T_i$ where m is the number of wind turbines that are to be installed in the project, O_i is the amount of full load hours of each turbine that is estimated according to the wind forecast and T_i is the nominal power of each turbine that has to be installed.

The average value of O_i for a given wind park, namely, O, has been chosen as a proxy for the technical quality of the project. Indeed, its value depends both on the wind supply (which in turns depend on the chosen site) and on the quality of the turbine that the proposal has chosen. We set a score v_E is a monotone function of O. Thus, our scoring rule prizes project that provide a higher amount of wind energy both directly through v_E and

[7] α has to be set ex-ante and is common for all proposals. It can be set equal to the value of the green certificates for those areas where such an incentive scheme has been set, or it corresponds to the (common) energy price if no wind firm has market power.

[8] It is an estimate calculated by the public authority given the value of α which corresponds to the theoretical value of the producible energy in each year. It is needed just to express royalties in percentage terms; thus, we do not consider the financial cost of the project.

indirectly through v_R, since the higher the amount of equivalent-hours of a wind-mill the higher the revenues and thus the possible royalties on them. However, there is an important point that has to be underlined here. There is an asymmetry of information between the proponent of the wind farms and the public authorities since the information about wind supply of a specific site is a private one.[9] Therefore, there is an incentive for the enterprise to play strategically, increasing the estimate of O in order to increase the score that it can obtain. We use two tools[10] that allow us to reduce the possible distortion. The first one refers to the way the public authority calculates the compensation due. The idea is to link the amount due both to effective revenues and to those that the enterprise would have gained had the wind plan effectively worked the forecasted amount of hours. Formally:

$$R_t = \beta r \alpha Q_t^E + (1-\beta)\alpha Q \tag{5}$$

Where R_t is the amount of royalties that are to be paid in year t, Q_t^E is the amount of energy that is effectively produced in year t, z is a pre-defined percentage set by the public body and $\beta \in [0,1]$. In this way, the compensation that the enterprise will effectively pay in each year is positively correlated both to Q (estimated energy) and to Q_t^E (energy effectively produced). Therefore, there is a disincentive to strategically overestimate Q but at the same time the proponent does not bears entirely the full risk of possible mistakes in the estimates.[11] The second tool that we adopt to reduce the incentive to gaming, is the algorithm that captures the technical

[9] Generally, it depends on the point-wise samples that a proponent has to take through specific on site studies that are generally run after some pre-contractual agreement between the firms and the owners of the land.

[10] A third possible mean is a reputational one. Indeed, one could track the differences between the estimated figures reported in the proposal and those that are measured ex-post and on the basis of the differences between these one could assess a measure of trustworthiness of the proponent. Such a measure could be used to prize in future assessment those proponents that have proposed estimates that were closer to the realized ones. See Doni (2006) and Albano *et al.* (2008) for an explanation of the importance of reputational mechanism in procurement auctions. However, we prefer not to exploit this point here since we aim at defining a scoring rule whose validity is independent on the amount of times that it is used, also because exploitation of wind power site is generally not a repeated interaction setting.

[11] We are implicitly assuming that providing a good estimate of the true wind power is a public good and for this reason the public body has to share the risk of estimate with the private firm. In the appendix, we show how to calibrate β taking into account the trade-off between risk allocation and incentives for truth-telling. Consider, however, that the tool

quality of the plant. We adopt a concave function that reduces the incentive to overestimate the full load hours, since the impact of a given increase in the full load hours on the score that can be obtained is decreasing:

$$v_E = \min\left[\frac{O - O_{\min}}{O_{\max} - O_{\min}} \frac{O_{\max} - O_{\min}y}{O - O_{\min}y}, 1\right] \tag{6}$$

where O is the average amount of full load hours of the wind plant. $O_{\min}$ and $O_{\max}$ are the minimum and the maximum amount of full load hours; $y \in (-\infty, 1)$ is a parameter that expresses the concavity of the formula (the closer to 1, the more concave the formula, while for y that goes to $-\infty$ the formula becomes linear; see Appendix A.2). Again, notice that $v_E \in [0, 1]$.

Social impact is evaluated through an automatic method, where the proxy is the number of new employees hired in each wind farm for its use and maintenance:

$$v_S = \min\left[\frac{s}{s_{\max}}, 1\right] \tag{7}$$

where s is the number of full time employee and $s_{\max}$ is the upper bound of s. Therefore, every new employee hired allows the proponent to increase her score by $\frac{\theta_s}{s_{\max}}$. Clearly this parameter has to be calibrated in order to make it coherent with the EVP, that can be easily calculated by just deriving the increase in the expenditure that has to be paid in order to obtain an extra point. If we suppose that each new employee has a cost of δ, we can easily set the EVP associated with S, call it EVP_S, as:

$$EVP_S = \frac{\delta s_{\max}}{\theta_s} \tag{8}$$

Similarly, for the EVP associated with revenues we have that:

$$EVP_R = \frac{R_{\max} - (1 - \theta_R)R_{\min}}{\theta_R} \tag{9}$$

Obviously, the parameters have to be calibrated so that $EVP_S = EVP_R$.

Summing up, the scoring rule we propose to evaluate the different projects of wind power production farms is the following:

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proposed is a viable one that does not derive from the solution of a possible interaction game set between the public authorizing body and the proposers.

$$I = \theta_N v_N + \theta_R \min\left[\frac{r\alpha Q - R_{\min}}{R_{\max} - R_{\min}}, 1\right] + \theta_E \min\left[\frac{O - O_{\min}}{O_{\max} - O_{\min}} \frac{O_{\max} - O_{\min} y}{O - O_{\min} y}, 1\right] + \theta_S \min\left[\frac{s}{s_{\max}}, 1\right] \tag{10}$$

3 The Calibration of the Scoring Rule.

It is natural to interpret the scoring rule in equation 10 as a social welfare function whose weighs are $\theta_i, i = \{N, R, E, S\}$. The public authority should assess the weights according to its preferences and set the value of the (exploitation) of the environment, i.e. N, through an appropriate evaluation method.[12] In that case, the calibration should be performed assessing values of $R_{\max}$ and $s_{\max}$ so that $EVP_S = EVP_R$ and it assumes a plausible value (taking into account that a limited amount of workers can be hired in wind firms). However, such a first best exercise is often overridden in the practise by the effective needs of the public authority, that requires a calibration even without having carried trough any ex-ante evaluation exercise. Therefore, we calibrate the index I here taking into account a reference project, and choosing the weights and the threshold so that no single aspect is decisive, for otherwise we would undermine the possibility that the index considers the whole set of parameters that are relevant for the projects. Consider for instance R. We need to set v_R so that even if the enterprise offers the max of r it does not have the guarantee of being authorized unless it obtains positive scores in the offers about the other parameters. Moreover, the weights have to be set so that they reflect the importance that each component has in the public decision (i.e., welfare) function, were it is generally assumed that royalties is the most relevant component. For the threshold (even if the choice should be left to the public authority), it should be graduated according to the environmental quality of the land over which the investment projects are planned. For instance, in the new regulation for development of wind power set by the Italian Region Basilicata (GSE-Regione Basilicata, 2008), the whole surface of the region has been classified in four categories depending on the different environmental quality of the areas, and each of it

[12] The literature about environmental evaluation is too vast to be reported here. For a review, see Mäler and Vincent (2005).

has a different threshold associated.[13] From now onward, we will neglect this point and assume that there is a single threshold, set at 80% of the maximum possible score (100).

The following is a possible calibration:

- $\theta_N = 30$
- $\theta_R = 40$
- $\theta_E = 20$
- $\theta_S = 10$
- $R_{\min} = 0$
- $R_{\max} = 600,000$ euro
- $s_{\max} = 5$
- $O_{\min} = 1700$ full load hours
- $O_{\max} = 2400$ full load hours
- $y = 0.6$
- $\alpha = 180$ euro per *Mwh*.
- $N \in [0, 1]$

Consider the following investment project, made of 15 wind turbines of $2Mw$ each, in a site whose full load hours are 2100. With a price of green energy set at 180 euro per *Mwh*, the project has a yearly cash-flow of $11,340,000$ euro. From equations 8, 9, we can see that the EVP equals $15,000$ euro. Recall that the offer is made of four components: S, N, R and O. Suppose

[13] At the top, there are those sites (natural parks, historical landmarks, etc.) whose environmental quality is so high that no wind farm can be installed. In other words, for those sites the threshold is set at a level that cannot be reached by any project. Then there are three different categories, each of which is characterized by a decreasing level of the threshold: 80 for the "constrained areas" (high-quality areas whose environmental character is so high that no more than 20% of the whole area can be used for wind power exploitation), 75 for the "critical areas" (less qualified areas whose maximum exploitable surface amount to 40%), 60 for all remaining areas.

that there is no strategic behavior, i.e., O is truthfully reported.[14] It is easy to calculate the points that the project obtains from the technical parameter: $\theta_E v_E = 15$. By fixing one of the other parameter, we can show the trade off between the other two. From now onward, we will fix the offer on S and show the correlation between R and the score that has to be obtained in the environmental component N in order to be authorized, i.e., to get a score higher than 80. Assume that the proponents are wiling to hire four workers. We have that $\theta_S v_S = 8$. Therefore, the proposal has to obtain 57 points from N and R. If it obtains 25 points on N, it must obtain 32 points on R, which corresponds to an offer of $480,000$ euro, i.e., a share of $4,23\%$ of the revenues. Clearly, r is negatively correlated to $\theta_N v_N$, for given $\theta_S v_S$. If $\theta_N v_N = 17$, it must offer an $r = 5.29\%$ (that equals $R_{\max}$) to obtain 40 points. Obviously, the need to obtain points and thus increase offers on R or on N is reduced if it obtains more points on S. Notice, however, that the highest score it can obtain from offers on S is 10, and thus, even if it acquires 40 points on R it still has to obtain a score of 15 from the environmental evaluation in order to be authorized, which confirms that the scoring rule proposed can induce a higher quality preservation of the local environment, i.e., a lower production of negative local externalities. The same is true for increases in O, which shows that the scoring rule is able to select best projects w.r.t. the quality of the site (in terms of full load hours) too.

With the figures and the limits set above it is easy to define the equation that defines the indifference curve of the scoring rule (the iso-scoring curve): $65 - 2s = \theta_N v_N + 756r$, where offers are constrained not to be bigger than the level that gives the highest score per each parameter. In figure 1 we show the plot of the five equations that correspond each one to a different level of $s = \{1, 2, 3, 4, 5\}$ that allow the proponent to obtain the threshold level of points, namely, 80 points:

[figure 1 about here]

We can see that the constraints are such that it is impossible to obtain more that 30 point from the environmental parameter and that a minimum level of 15 has still to be attained even if the proponent is willing to hire the maximum number of workers and paying the highest royalties (in our

[14] Such an assumption allows us not to specify values for z and β. For truth-telling it is sufficient, for instance, that $z = \bar{r}$ and $\beta = 1/2$ (see appendix).On the other hand, for the sake of simplicity we prefer not to modellize here the game between firms and public authority or explicitly define conjectures about $\bar{r}$.

example 5,265% is the level of royalties that gives 40 points). Similarly, a royalty equal to 347,004 euro, i,e, 3.306% of the cash flow, is the minimum level of royalty that the proponent has to offer even if it acquires 30 points form the environmental component and 10 from the social one in order to reach the threshold level. Finally, see that, as expected, both royalties and the environmental evaluation are decreasing as s rises.

Acknowledgement 1 *The authors are the sole responsible for what is written in the article. In particular, Gervasio Ciaccia claims that the article does not represents the opinion of the Italian Authority for Electricity and Gas. Fulvio Fontini acknowledges the Research grant of the University of Padua n. CPDA077752/07.*

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5 Appendix

Appendix A.1

We show here that the formulation proposed in equation 5 reduces the incentive for the firm to behave strategically. Suppose that a firm has a correct estimate of the energy that equals $\bar{Q}$. Assume, moreover, that given such an estimate the enterprise is willing to pay a percentage amount of its revenues that equals $\bar{r}$. If the estimate $\bar{Q}$ is correct, the compensation becomes $\bar{K} = \bar{r}\alpha\bar{Q}$. However, the proponent has an incentive to declare a value of r and Q that maximize the points it can obtain from its offer, subject to the constraint of maintaining unchanged the effective payment. Formally, r and Q solve the following problem:

$$\underset{r,Q}{Max} \quad r\alpha Q \quad s.t. \quad \beta r\alpha Q_t^E + (1-\beta)z\alpha Q = \bar{K} \tag{A. 1}$$

If the estimate of Q is correct, we can replace Q_t^E with $\bar{Q}$; from the constraint, we have:

$$r = \frac{\bar{K} - (1-\beta)z\alpha Q}{\beta\alpha\bar{Q}} \tag{A. 2}$$

substituting it into the objective function and solving we can express the maximization problem as:

$$\underset{r,Q}{Max} \quad \frac{\bar{K}-(1-\beta)z\alpha Q}{\beta\bar{Q}}Q \tag{A. 3}$$

from the f.o.c. we obtain the following solutions:

$$Q^* = \frac{\bar{K}}{2(1-\beta)z\alpha} \quad r^* = \frac{\bar{K}}{2\beta\alpha\bar{Q}} \tag{A. 4}$$

and since $\bar{K} = \bar{r}\alpha\bar{Q}$ we can write them as

$$Q^* = \frac{\bar{r}\bar{Q}}{2(1-\beta)z} \quad r^* = \frac{\bar{r}}{2\beta}$$

See that if $\beta = 1/2$, we can induce the enterprise to truthfully reveal the percentage of revenues that it is willing to pay. This is the first best solution, since it induces the firm to offer an amount of energy that can be produced that coincide with its estimated. However, such a solution depends on the possibility of knowing ex-ante the willingness to pay of the enterprise, since $Q^* = \bar{Q}$ if $z = \bar{r}$ when $\beta = 1/2$. If the willingness to pay is ex-ante unknown, the public body has to make inferences about it. If it chose a level of z that is too low (high), the proponent has an incentive to increase (reduce) Q with respect to the true one and this implies that β should be lowered (increased). In this way the level of Q that is proposed is closer to the estimated one; this however increases (reduces) the burden of the estimation risk borne by the enterprise since the true amount that ex post the firm is going to pay depends more (less) on the estimated energy than the produced one.

Appendix. A.2

We prove here the following claim:

Claim 1 *a) The equation shown in formula 6 is concave in O for $y \in (-\infty, 1)$. b) The degree of concavity is increasing in y.*

Proof. part a): notice first that $\lim_{y\to-\infty} v_E = \frac{(O_{\min}-O)}{O_{\min}-O_{\max}}$, i.e., equation 6 becomes linear in O for $y = -\infty$, while obviously for $y \geq 1$ it equals 1. This constrains the admissible range of y. See that $\frac{\partial v_E}{\partial O} = \frac{O_{\min}}{O_{\min}-O_{\max}} \frac{O_{\max}-O_{\min}y}{(O-O_{\min}y)^2}(y-1) > 0$, $\frac{\partial^2 v_E}{\partial O^2} = -2\frac{O_{\min}}{O_{\min}-O_{\max}} \frac{O_{\max}-O_{\min}y}{(O-O_{\min}y)^3}(y-1) < 0$, $\forall y \in (-\infty, 1)$. This complete part a); for part b), recall that the degree of concavity is given by $\lambda = \frac{-v''_E}{v_E}$; here we obtain: $\lambda = \frac{2}{O-O_{\min}y}$, and we can easily see that $\frac{\partial\lambda}{\partial y} > 0$ $\forall y \in (-\infty, 1)$. This completes the proof. ■

In figure 2 we plot the value of v_E calculated according to the calibration reported in section 3, for different values of y.

[Figure 2 about here]

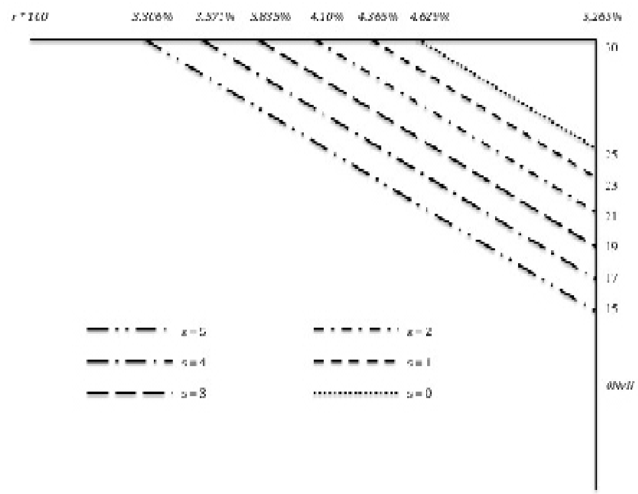

Figure 1: r *and* $\theta_N v_N$ *for different* s *that yield* 80 *points.*

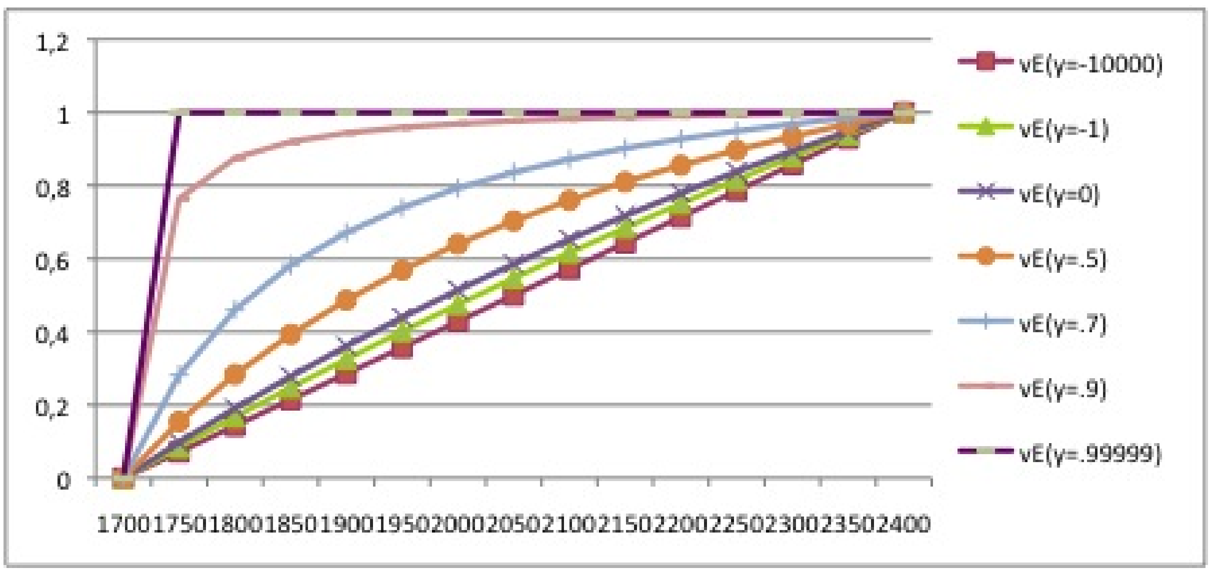

Figure 2: v_E plotted for diferent values of y.