Economics Bulletin

Volume 45, Issue 4

Signalling for electricity demand response: When is truth telling optimal?

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Abstract

Electricity providers as well as transmission system operators (TSO) around the world implement demand response programs for reducing electricity consumption by sending information on the state of balance between supply demand to end-use consumers. We construct a Bayesian persuasion model to analyse such demand response programs. Using a simple model consisting of two time steps for contract signing and invoking, we analyse the relation between the pricing of electricity and the incentives of an energy provider to garble information about the true state of the generation. We show that if the electricity is priced at its marginal cost of production, the energy provider has no incentive to lie and always tells the truth. On the other hand, we provide conditions where overpricing of electricity leads the energy provider to send no information to the consumer. As a result, in case of electricity mispricing, information provision gives to energy providers a new way to exert market power.

Research supported by the Chair EDF-CA CIB of Finance and Sustainable Development, the Finance for Energy Markets Research Initiative and the ANR project EcoREES ANR-19-CE05-0042 and the ANR PEPR Math-Vives project MIRTE ANR-23-EXMA-0011. Research supported under grant 6301-2 from the Indo-French Centre for the Promotion of Advanced Research. Ankur's work was also supported by the grant CRG-2019-002975 of the Science and Engineering Research Board, Department of Science and Technology, India.
Citation: Rene Aid and Anupama Kowli and Ankur A. Kulkarni, (2025) "Signalling for electricity demand response: When is truth telling optimal?", *Economics Bulletin*, Volume 45, Issue 4, pages 1850-1859
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Submitted: May 24, 2025. **Published:** December 30, 2025.

As we we look for the connections between pricing and information provision, our approach is in a sense *dual* to this: in our case the energy provider acts as a sender who *provides* information (possibly garbled) to the consumer who acts as a receiver. In this sender-receiver interaction game (see Myerson (1997) for a seminal paper on this design), we chose the framework known as *Bayesian persuasion* introduced by Kamenica and Gentzkow (2011) and Kamenica (2018). The persuasion setting falls in the area of *information design*. In this setting, the sender shapes the posterior probability distribution of the receiver by sending suitable signals on the state of the world. The sender could use randomization for information provision. It would lead to the receiver getting 'mixed signals'. This deliberate, strategic ambiguity is a hallmark of such settings, see Kamenica and Gentzkow (2011), Forges (2020) and Forges and Koessler (2008). Nevertheless, we limit our study to the case of pure strategies.

Main contributions In our framework, an energy provider and a representative consumer have signed an energy provision contract at a pre-agreed pricing formula. This contract takes the force of a given pricing formula for energy consumption but it also involves an information mechanism under which the energy provider sends information on a potential variation of prices induced by variation of production (i.e. availability of renewable energy for instance). The pricing formula considered is either the spot price of electricity or a deviation for this reference price. In our model, the representative consumer is large enough so that variation of its consumption induces variations of the spot price. Thus, the energy provider may want to take advantage of the realised value of production by sending an information that is best for its own benefit. While the pricing contract is assumed to be given and not endogeneous to the equilibrium between the energy provider and its representative consumer, we explore the possibility for the energy provider to influence the consumer's action by sending signals to persuade the consumer to act accordingly. The design of such signals and their truthfulness is the subject of this paper.

We assume that the energy provider and the consumer share a common prior distribution on the level of future generation. However, high quality information on level of generation is accessible only the energy provider while the consumer has to rely on the information sent by the energy provider to take its consumption decision. The energy provider must decide how it may use this fresh information to influence the consumer. Decision-theoretically speaking, the consumer is the only player that can act in our setting: the amount of consumption chosen by the consumer determines the payoff of both players. Thus the energy provider's decisions are limited to only influencing this choice of the consumer by reshaping the latter's information by sending suitable signals.

Formally we model our setting as a Bayesian persuasion game with the energy provider acting as the sender and the consumer as the receiver of information about a state. In such a setting, the sender sends signals and the receiver updates its belief about the unknown state using Bayes rule. The problem for the energy provider is to design signals such that the energy provider obtains the maximum payoff under the optimal action chosen by the consumer under the posterior distribution.

Our quest is to illuminate the role of truthtelling on the part of the energy provider. More specifically, when do the signals sent by the energy provider constitute truth, and nothing but the truth? Our main finding is that there is a close link between the nature of the contract and truthtelling – if the contract is such that the price equals the marginal cost of generation, truthtelling is optimal. In other words, if the contract is "priced to perfection" in the sense that it has accurately estimated the probability distribution of the future generation, there are no additional benefits to be drawn from reshaping the truth. Similar results hold even in the case where there are multiple consumers interacting *à la* Cournot.

Fascinatingly mispriced contracts may also induce truthtelling – for instance, this happens when the contract price is lower than the marginal cost of electricity production. But, when the contract is sufficently larger than the marginal cost of production, then it is beneficial to the energy provider to stop sending information to its consumer. In that case, because the consumer does not know the true state of the world, it consumes too much when there is not much energy and pays a high price that largely exceeds the energy production cost.

Our contribution in this paper lies in relating truth-telling to the energy provision pricing contract, and, in particular, to estimation of future uncertainties. To the best of our knowledge this connection has not been established before, more so in the context of demand response. This connection should drive the attention of energy regulators on the possiblity for energy providers to exert market power in a new way compared to the well-known mechanism that consists in strategically reducing generation. Energy providers with large enough consumers portfolio may simply use information signals sent to their consumers to influence the spot price and thus, their profit.

The paper is organised as follow. Section 2 describes the model. Section 3 gives the main results and their proofs while Section 4 concludes.

2 Model

We consider an electricity market where the generation is served by enough producers so that the market can be considered competitive. We assume that an energy provider has a perfect forecast of the renewable generation denoted q, but this level is not known to the consumers. Indeed, even though forecasting renewable energy generation at a daily-time scale is yet an imprecise exercise, the knowlegde of the consumers is significantly lower compared to energy provider's. In this section we consider the interaction between the energy provider and a single representative consumers whose current consumption is denoted y_0.

The consumer can take an action $a \in \mathbb{R}$ to modify its consumption. To focus on the effects of the information known to the energy provider, we assume that there is no noise in the action of the consumer whereby the consumption after action is given as $y_0 - a$. Thus, by observing the consumption, the energy provider knows the action of the consumer and is not facing an observation problem as in the moral hazard demand-response model in Aïd et al. (2022). The consumer's decision a has to be taken prior to the knowledge of the true level of renewable generation $q \in \mathbb{R}$. The consumer and the energy provider have agreed on a price contract where the per unit price charged for consumption is a function $p(y, q)$ of the consumption y and the generation q. We assume this function takes the following form $p(y_0 - a, q) = p(y - a - q)$, whereby the unit price is a function of the difference between the consumption and the generation. In the sequel, the price function p is either the spot price of electricty or a deviation for this reference case. Note that, though the generation q is not known to the consumer, the above pricing rule is fixed and known. After defining the utility of the consumer by $U(q,a) := \hat{u}(y_0 - a) - c(a) - p(y_0 - q - a)(y_0 - a)$, where $\hat{u}(y_0)$ is the indirect utility of consuming electricity y_0, $c(a)$ is the cost of making undesired modification of consumption a. For sake of simplicity and to get closed-form expressions, we take the instanciation $\hat{u}(y_0 - a) := uy_0 - ua$, where $c(a) := \frac{1}{2}ca^2$, and $u, c > 0$.

The energy provider is assumed to know the utility function of the representative consumer. In practice, this assumption can be translated in the knowledge of the usual level of consumption of consumers. Levels below the usual observed level of consumption is assumed to enduce disutility to consumers.

We assume that both the energy provider and the consumer share the same prior on q denoted by $\mathbb{P}^0$, and under this prior q has bounded support and finite variance. This prior can be thought as the known statistical distribution of wind during the year. The energy provider observes the generation q and sends a message to the consumer.

The *signalling policy* of the energy provider specifies a probability distribution on the messages for each value of q. The policy is denoted $\pi(\tilde{q}|q)$, where $\tilde{q}$ is the message sent and q the observed renewable energy generation. We assume that the signal and the renewable generation share the same bounded support. Telling the truth, all the truth and nothing but the truth consists in setting $\pi(\tilde{q}|q) = 1$ iff $\tilde{q} = q$.

Remarks:

(i) Information cost: In our setting, we choose to consider that there is no information cost for the energy provider, i.e. it has a perfect knowledge of the future level of renewable energy generation without having to bear any kind of forecasting cost. This assumption can be considered as a limiting case where forecasting cost can be considered to be negligeable compared to generation and energy value. The introduction of a cost function for information acquisation for the energy provider would simply add a new term in its objective function and the result would involve also the marginal cost of information acquisition.

(ii) Committment: Since we are using the model of Bayesian persuasion, we assume that the energy provider commits to a signalling policy. This act of commitment should be interpreted in the following way: the energy provider's has set a forecasting method of renewable generation and sticks to it. An alternative setting would be to consider a *cheap talk* equilibrium model *à la* Crawford and Sobel (1982). This setting consists in removing the commitment assumption of the sender and defining the information equilibrium in mutual best-response, i.e. making the consumer also a strategic player.

(iii) Pricing rule: We assumed that the pricing rule was defined prior to the design of information provision. We leave for further research the case where the pricing rule is endogeneous to the market design and takes into account the provision of information by the energy provider.

For a given signalling policy π and for a given signal $\tilde{q}$, the consumer's problem is to solve:

$$\sup_a J(a;\tilde{q},\pi) := \mathbb{E}\big[U(q,a)|\tilde{q}\big]. \tag{1}$$

Assuming this problem admits a unique solution, we denote the best response of the consumer by $\hat{a}^\pi(\tilde{q})$.

Knowing the best-responses $\hat{a}^\pi$ of the consumer to a given signalling policy π, the energy provider (the Sender) chooses the signalling policy to solve,

$$\inf_\pi J^{\mathrm{S}}(\pi) := \mathbb{E}\big[f(y_0 - \hat{a}^\pi(\tilde{q}) - q) - p(y_0 - \hat{a}^\pi(\tilde{q}) - q)\big(y_0 - \hat{a}^\pi(\tilde{q})\big)\big],$$

where the expectation is taken under $\pi \otimes \mathbb{P}^0$ for the realisation of the pair $(\tilde{q}, q)$ and $f(x)$ is the cost that the energy provider has to bear due to the imbalance $x := y_0 - \hat{a}^\pi(\tilde{q}) - q$ between the renewable generation and the consumption. The program of the energy provider consists in minimising the procurement cost of energy imbalance and maximising the revenue for energy sales. Note that it is possible that $x < 0$, in which case the energy provider makes a profit on the imbalance procurement as it turns into a sale. We assume a linear quadratic imbalance cost function, i.e.,

$$f(x) := kx + \frac{1}{2}\beta x^2, \quad 0 < k, \quad 0 < \beta, \tag{2}$$

so that the marginal cost curve is affine in production. Although in real life, the marginal cost of electricity production exhibits a steeper curvature, the assumption we make is common in the economic literature of electricity market regulation as it allows closed-form expressions for comparative static studies (see examples in Crampes and Léautier (2015)).

The pricing rule is defined as the marginal cost of production of electricity, namely

$$p_\beta(x) = f'(x) = k + \beta x. \tag{3}$$

The significance and implications of this assumption will be discussed in the following section. We consider also deviations from this pricing rule. But note that taking the pricing rule as the marginal cost of production induces an effort reduction of the consumer that precisely corresponds to social welfare maximisation in the case of full information on the renewable generation as shown in Boiteux's marginal cost pricing of electricity theory (Boiteux (1960)).

We now reflect on how the consumer approaches this problem. To solve its problem (1), the consumer computes the posterior probability that the true generation is q, upon receiving the message $\tilde{q}$:

$$\mathbb{P}(q|\tilde{q}) = \frac{\pi(\tilde{q}|q)\mathbb{P}^0(q)}{\mathbb{E}^{\mathbb{P}^0}\big[\pi(\tilde{q}|q)\big]}, \quad \text{with} \quad \mathbb{E}^{\mathbb{P}^0}\big[\pi(\tilde{q}|q)\big] = \int \pi(\tilde{q}|q)\mathrm{d}\mathbb{P}^0(q).$$

assuming that the denominator above is nonzero. Thus the expectation in (1) is taken with respect to the posterior distribution above defined by $\mathbb{P}(q|\tilde{q})$.

3 Results

We consider the pricing function p_b for values b not necessarily equal to β defined by $p_b(x) = k + bx$, and the following constants $a_{0,b} := (k + 2by_0 - u)/(c + 2b)$, and $\lambda_b := b/(c + 2b)$. Define also

$$\beta < \bar{b} := \frac{1}{2}\Big(\frac{3}{2}\beta - c\Big) + \sqrt{\frac{1}{4}\Big(\frac{3}{2}\beta - c\Big)^2 + \beta c}.$$

Proposition 3.1. *Assume that the pricing formula is given by p_b. Then, it holds that*

(i) *The best-response function of the consumer $\hat{a}^\pi$ for a given signalling policy π is given by $\hat{a}^\pi = a_{0,b} - \lambda_b \hat{q}$, where $\hat{q} := \mathbb{E}\big[q|\tilde{q}\big]$. As a result, $\mathbb{E}\big[\hat{a}^\pi\big] = a_{0,b} - \lambda_b \mathbb{E}\big[q\big]$ does not depend on π.*

(ii) *The energy provider has no incentive to deviate from telling the truth as long as $b \leq \bar{b}$. As a result, it is optimal to tell the truth when the price is given by the marginal cost of production.*

(iii) *When $\bar{b} < b$, it is optimal for the energy provider to provide no information.*

Proof. (i) For a given signal π, consider the optimisation problem of the consumer given by (1). We have $J(a, \tilde{q}) = \mathbb{E}^{\mathbb{P}}\big[U(q, a)\big]$. Taking derivative inside the expectation and writing first-order condition provides

$$\mathbb{E}^{\mathbb{P}}\big[(c + 2b)a - (c + 2b)a_0 + bq\big] = 0.$$

Thus the optimal response of the consumer is given by $\hat{a}^\pi = a_{0,b} - \lambda_b \mathbb{E}^{\mathbb{P}}[q]$ and $\mathbb{E}^{\mathbb{P}}[q] = \mathbb{E}[q|\tilde{q}]$, which gives the result. Besides, by the law of iterated expectations, we get $\mathbb{E}\big[\hat{a}^\pi\big] = a_{0,b} - \lambda_b \mathbb{E}\big[q\big]$.
(ii) and (iii) First assume that $b = \beta$. The criterion of the energy provider can be written as

$$J^{\mathrm{T}}(\pi) = \mathbb{E}\big[F(q)\big] + \beta y_0 \mathbb{E}\big[\hat{a}^\pi\big] - \frac{1}{2}\beta \mathbb{E}\big[(\hat{a}^\pi)^2\big],$$

with $F(q) := \frac{1}{2}\beta(y_0 - q)^2 - kq - \beta(y_0 - q)y_0$. The two first terms are independent of π. Besides, because of (i), it holds that $\hat{a}^\pi = a_{0,\beta} - \lambda_\beta \hat{q}$ and thus, $\mathbb{E}[(\hat{a}^\pi)^2] = a_{0,\beta}^2 - 2a_{0,\beta}\lambda_\beta \mathbb{E}[\hat{q}] + \lambda_\beta^2 \mathbb{E}[\hat{q}^2]$. Because $\mathbb{E}[\hat{q}] = \mathbb{E}^{\mathbb{P}^0}[q]$, the only term that depends on π in the criteria of the energy provider is $-\frac{1}{2}\beta\lambda_\beta^2 \mathbb{E}\big[\hat{q}^2\big]$. Thus, minimizing $J^{\mathrm{S}}(\pi)$ is equivalent to maximizing $\mathbb{E}[\hat{q}^2]$. Now, for any random variable m correlated with q, the following inequalities hold from Jensen's inequality:

$$\mathbb{E}[q]^2 = \mathbb{E}[\mathbb{E}[q|m]]^2 \leq \mathbb{E}[\mathbb{E}[q|m]^2] \leq \mathbb{E}[\mathbb{E}[q^2|m]] = \mathbb{E}[q^2]. \tag{4}$$

When m is independent of q (i.e. no information is revealed and thus $\hat{q} = \mathbb{E}[q]$), $\mathbb{E}[\hat{q}^2] = \mathbb{E}[q]^2$ which is the minimum (first term of the sequence of inequalities), whereas if $m = q$ (full information revelation), $\mathbb{E}[\hat{q}^2] = \mathbb{E}[q^2]$ which the maximum (last term of the inequalities). Thus, the energy provider's criteria is minimized when $b = \beta$ and the energy provider tells the truth.

Now, when $b \neq \beta$, the criterion of the energy provider becomes

$$J^{\mathrm{S}}(\pi) = \mathbb{E}\big[F(q)\big] + (2b - \beta)y_0 \mathbb{E}\big[\hat{a}^\pi\big] + (\beta - b)\mathbb{E}\big[q\hat{a}^\pi\big] + \Big(\frac{1}{2}\beta - b\Big)\mathbb{E}\big[(\hat{a}^\pi)^2\big].$$

Besides, we have $\mathbb{E}^{\pi\otimes\mathbb{P}}\big[q\hat{q}\big] = \mathbb{E}^{\pi\otimes\mathbb{P}}\big[\hat{q}^2\big]$. Thus, the energy provider's criterion is a constant term plus $\lambda_b \Lambda \mathbb{E}\big[\hat{q}^2\big]$, with $\Lambda := -(\beta - b) + \lambda_b(\frac{1}{2}\beta - b)$. And, thus depending on the sign of Λ, maximizing J^{S} consists either on telling the truth or garbling information. Solving for the threshold b above which the energy provider has incentive to provide no information yields the desired results. □

We begin our comments on Proposition 3.1 by a quick technical remark. Even if what can be considered as the baseline consumption level a_0 is positive, it might happen that $\hat{a}^{\pi}(\tilde{q}) < 0$. When c is small, the consumer is responsive to the information on the availability of cheap energy and takes these opportunities to increase his consumption. Although our model design is not intented to capture this phenomenon, it is a behaviour looked for by energy providers when there is too much renewable energy and demand could be increased. The Low Carbon London research project is an example of a large scale demand-response research program where incentives to increase consumption were proposed to consumers (see Schofield et.al. (2014)).

More importantly, Proposition 3.1 (ii) states that the marginal *cost* pricing rule ensures that the energy provider has no incentive to garble the production forecast and that the consumer's optimal response under optimal signalling is the social optimum. The most extreme case of garbling information would be if the energy provider gives an uninformative signal. In other words, the posterior probability is equal to the prior. In that case the energy provider's payoff is minimum. Thus, sending any signal is better than sending no signal at all and sending a truthful signal is the optimal policy.

It is remarkable that the only factors that enter in the determination of the threshold $\bar{b}$ are the proportional part of the pricing rule b and the cost of reduction effort of the consumer c. The function $\bar{b}(c)$ is nonincreasing and satisfies $\bar{b}(0) = \frac{3}{2}\beta$ and $\lim_{c\to\infty} \bar{b}(c) = \beta$. Hence, whatever the value of c, there is a non-empty range of values for b, namely $(\beta, \bar{b})$ where the energy provider has an incentive to use information provision to the consumer in its own profit maximisation objective. When reduction efforts are costless to the consumer, the threshold $\bar{b}$ equals $\frac{3}{2}\beta$, meaning that the energy provider starts to take advantage of the signal only when it is paid 50% more than the marginal cost. For instance, if the energy provider always predicts high renewable energy generation, the consumer's actions is $\hat{a}(\tilde{q}) = a_{0,b} - \lambda\hat{q}$, where $\hat{q}$ is anticipated to be high. Thus, the consumer anticipating low prices makes little reduction effort. The revenue term of the energy provider criteria, namely $p(y_0 - q - \hat{a})(y_0 - \hat{a})$, outweighs the production cost term $f(y_0 - q - \hat{a})$.

A consequence of this result is that when electricity pricing deviates too much from marginal cost pricing, large energy providers can use information provision contained in demand response program to exert market power on the spot market. This observation should raise the attention of regulators on the exercises of demand response programs by energy retailers as these mechanisms offer a new tool to exert market power.

4 Conclusions

The possibility of influencing end-use consumption through signaling provides a mechanism to exploit demand-side flexibility. This, in turn, allows for the matching of inherently uncontrollable renewable production with flexible demand. We expect such mechanisms to ultimately address the operational challenges that renewable generation may pose to utilities. However, our contribution demonstrates that regulatory authorities devote some attention to exercise of demand side contracts by large energy providers as these contracts give them a new device toexert market power.

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