MULTI-PERIOD DEA INCENTIVE REGULATION IN ELECTRICITY DISTRIBUTION

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Abstract. Multi-period multi-product regulatory schemes for electricity distributors are presented, based on cost information from a productivity analysis model and an agency theoretical decision model. The proposed schemes are operational and demonstrate considerable advantages compared to the popular CPI-X revenue cap regulation. The schemes avoid arbitrariness, too high or negative informational rents as well as ratchet effects and they promote rapid productivity catch-up by making full use of available data. More generally, the paper contributes to the theoretical unification between firm-based Data Envelopment Analysis (DEA) productivity models and micro-economic reimbursement theories.

1. Introduction

Irrespective of ownership, either investor owned or publicly owned utilities, any natural monopoly poses a risk to the society by accruing excess profits and costs at the expense of the members of the population that are dependent on its services. The problem is a principal-agent problem under asymmetric information with the society (the customers represented by a regulator) as the principal and the utility (and its manager) as the agent.

In case of perfect information, the principal would offer the agent a compensation scheme corresponding to the minimal cost for the desired level of service and the agent would accept the offer at zero profit. Sometimes, the cost function can be estimated using prior knowledge about the industry or using information acquired through a bidding procedure, such as in a public procurement setting.

Generally, however, the natural monopolies (gas, water, electricity) exhibit very varying exogenous preconditions such as customer profile and density, climate and topology. This makes the direct assessment of the cost function difficult. Under such circumstances, regulators of have often resorted to inflation adjusted revenue caps with stipulated annual productivity improvements, the CPI-X model. However, such revenue caps are associated with severe limitations on the theoretical and operational side, leaving a great deal of the regime open to arbitrariness. This paper deals with the specific conditions pertaining to regulation of the Scandinavian electricity distribution industry and suggests a regulatory framework based on efficiency benchmarking and incentive theory. The results may be applied to other regulated industries with multiple-input, multiple-output characteristics as well.

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From a theoretical viewpoint, this paper extends earlier results joining Data Envelopment Analysis (DEA) cost norms with the modern approach to regulation, based on agency theory. In particular, the models in Bogetoft (1997, 1999, 2000) and Agrell, Bogetoft and Tind (2000) are taken as a starting point for the dynamic framework. The emphasis of this paper, however, is not on the derivation of theoretical results per se. Rather, we stress the application to practical regulatory problems in a particular industry. By offering a comparison to the popular CPI-X scheme and to a more advanced DEA-based cost scheme implemented in Norway, the paper provides a fragment to a regulatory manual.

The outline of the paper is as follows. In Section 2, we introduce the most common regulatory models and in Section 3 we review the literature on the efficiency of Nordic electricity distribution. The basic DEA benchmarking model is developed in Section 4. The DEA based regulatory model is developed in the single-period single-agent case in Section 5 and in the multiple-period multiple-agent case in Section 6. An illustration with the current regulatory policy in Norway is presented in Section 7. The paper ends with some conclusions and suggestions for further work in Section 8.

2. Regulation of Electricity Distribution

Various regulation regimes have been applied to electricity distribution: nationalization, cost-plus regulation, rate-of-return regulation, CPI-X revenue caps, and yardstick competitions. The idea behind nationalization is to gain an informational advantage and use this to maximize the social welfare, e.g., by introducing marginal cost pricing. Anecdotal evidence of low cost efficiency and resulting high costs has caused the wide-spread abandonment of this option in the favor of privatization. Cost-plus regulation is likewise an early low-powered alternative with incentives for over-investment and inefficiency. Rate-of-return regulation is currently found in many countries, including the United States, as a low-powered option that regulates the profitability of the industry. Early studies by Averch and Johnson (1962) point out the incentives for overcapitalization to increase the rate base with this regime. Empirical evidence summarized below suggests that this was the case for the Scandinavian distribution industry before the recent reorganization.

CPI-X revenue cap regulation is a high-powered regime. It has been applied to power distribution, e.g., in England and Wales (cf. Pollitt, 1995). Liston (1993) shows that the fixed income induces cost efficiency by the agent's cost minimization. However, several theoretical and practical problems are associated with the CPI-X model:

- If the cap is set too low, the result may be non-participation or bankruptcy.
- If the cap is too loose, the informational rents will be excessive.
- The update of the cap encourages strategic behavior on behalf of the agents, who fear being penalized in subsequent periods for productivity improvements (the ratchet effect), cf. Freixas, Guesnerie and Tirole (1985) and Weitzman (1980)
- The cap basis lacks foundation. CPI does not necessarily have any connection to the input prices. The improvement factor X, in its turn, lacks solid specification. In setting out to combine historical performance with conjectures about future developments, it often requires bargaining with industry, further aggravating the risk of strategic behavior .

- The CPI-X model does not accommodate changes in the output profile. Hereby, the revenue cap regulation gives disincentives to technological investments and quality development.

The yardstick competition regime (Shleifer, 1985) is a recent addition to the regulatory arsenal. The idea is to set an individual cost target for each distributor that equals the realized cost by the other (comparable) agents. If the residual profit is retained by the distributor, the yardstick competition provides an optimal incentive scheme in solving the first two of the CPI-X problems stated above. Its endogenous determination of the cost norm solves the arbitrariness problem. The main problems of the basic yardstick model are the lack of dynamics, the single-dimensional production description, its inability to accommodate changes in the output profile, the comparability between agents and the distribution of risk.

The key to effective regulation is found in the access to information. We argue that by utilizing the maximum amount of information in the regulation and by reducing the regulatory lag, five positive effects are obtained. First, by tailoring the revenue cap to the individual agent in a close sense, the total informational rent is minimized. Second, by reducing the time lag from evaluation to reimbursement and repeating the evaluation more frequently the risk and the consequences of misrepresenting an agent in a yardstick sense are minimized. Third, by excluding the evaluated unit from the basis of comparison, the ratchet effect can be effectively dealt with. Fourth, by using observed production cost rather the estimated consumer prices, the arbitrariness of the CPI may be avoided. Similarly, the need of postulating a negotiated X factor may be substituted by an actually realized productivity improvements. Fifth, by using the richer production description in DEA, changes in production profile can easily be taken into account.

3. Nordic Efficiency Studies

The Scandinavian electricity market has been undergoing a major transformation since the late 1990s, heading towards the world's largest free-competition electricity market. In the deregulation, each of the four functions of the electricity sector (production, transmission, distribution and retail) is met with a different market form. The energy production and retail markets in Norway, Sweden and Finland has constituted a free market since the end of the millennium, whereas the liberalization process in Denmark is likely to be delayed for a few more years. The transmission industry in Sweden and Norway is allotted to a state monopoly, analogously to the road and railway systems in these countries. The distribution market, as a natural monopoly, will be subject to various regulation regimes in the four countries and it thus provides an excellent showcase for the potential strengths and weaknesses of the applied theory.

The appropriateness of a particular regulatory policy foremost depends on the prevailing conditions in the industry and the societal demands that the policy sets out to protect. The efficiency of the Nordic electricity distribution market has attracted a considerable attention from industry research organizations as the liberalization of the market was within sight.

Torgersen (1993), Kittelsen and Torgersen (1993) and Kittelsen (1994) investigate the Norwegian electricity distribution system. Kittelsen (1994) uses a data set of 172 distributors in 1989 and a model with three inputs (employee hours, transmission losses in MWh, external services bought) and three outputs (length of power lines, total power deliveries, number of customers). The models in Kittelsen and Torgersen (1993) and Kittelsen (1993) are similar, differing in some additional outputs and inputs and variables to account for background factors. The findings point out the presence of significant technical inefficiency for the distributors, an estimated waste of around 25% of the resources consumed, valued up to 1,8 billion NOK. Their natural monopoly status has in this case lead to a disguised inefficiency rather than excess profits, which would have been expected. The authors conclude that there is a strong need for an efficiency-improving incentive system and make a case for maximum price regulation to replace the profit-based system. The quality dimension of the service is accounted for, either by a delivery insurance system or through delivery thresholds (e.g., minimum capacity).

Studies from the other Scandinavian countries confirm the impression of considerable inefficiencies in the industry, as given in Table 1.

Hjalmarsson and Veiderpass (1992a, 1992b) and Veiderpass (1992), reporting on a study of Swedish electricity distributors during the period from 1970 to 1986, affirm lasting labor inefficiencies and unevenly distributed information rents. Agrell and Bogetoft (2000) study the 1997 cost efficiency of 234 electricity distributors, modeling a short-term activity with fixed grid capital. The Danish electricity distribution is discussed in Hougaard (1994), reporting an average inefficiency of 20-40% of the resource consumption regardless of company size. The Danish study indicate a connection between overpricing and inefficiency, suggesting that in particular private households bear the cost of technical inefficiency. Further, public utilities are shown to be less efficient than private and cooperative companies in Denmark, as opposed to the Swedish case where Veiderpass (1992) did not find any connection between ownership and efficiency. Some details from the studies are given in Table 1.

In summary, there is substantial evidence of inefficiency in the industry, amounting to large potential cost savings. This prompts for the development and active application of effective and flexible regulatory approaches, in the long-term interest of industry and customers alike.

Table 1. Summary of frontier analyses of Nordic electricity distributors.

Country	Techn. eff.	Cost eff.	Alloc. eff.	Obs.	Year
Sweden (Veiderpass, 1992)	77%	-	-	285	1985
Sweden (Agrell-Bogetoft, 2000)	-	73%	-	234	1997
Norway (Kittelsen, 1994)	93%	72%	77%	171	1989
Denmark (Hougaard, 1994)	78%	-	-	82	1991

4. The DEA-Benchmarking Model

The idea behind the frontier benchmarking model is to take multiple inputs and outputs into account in order to compare decision making units (DMU), here distributors. The inherent difficulty with benchmarking is that all DMU have private information about their ability to transform inputs into outputs, which enables them to extract information rents. The objective of the regulator is to minimize the extraction of information rents while assuring a satisfactory service. Normal inputs for these models are staff (labor hours), productive assets (operating capital, transmission lines in km) and energy (transmission losses in MWh). It is assumed that inputs are to be minimized for each given level of outputs, with the exception of capital, which may be treated as a fixed input if the period of regulation is too short. The particular conditions that differentiate distributors are called non-controllable inputs, e.g., customer density, climate zone and other environmental factors outside of our control. Kittelsen (1993) uses a corrosion index, maximum power and customer profile as categorical variables that are eliminated through a step-wise procedure. Non-controllable inputs are not minimized, but included in the model to assure comparable technologies. E.g., it would be meaningless to compare delivered power/employee hours for a rural and a municipal distribution company, since the technology from the municipal distributor cannot be used in a rural setting. Without loss of generality, the non-controllable inputs are formulated so that a lower value signifies a more favorable condition. By means of the inputs, under influence of the non-controllable inputs, a set of outputs is produced. The outputs are found as revenue generators, i.e., an increase in outputs corresponds to a proportional increase in revenue. In addition to the amount of delivered electricity (MWh, divided into household and industrial customers) and peak power capacity (MW), the number of customers (divided into house-holds and industrial customers) is included since a fixed annual charge is debited. Note that all inputs and outputs are given in real terms, even when prices exist. This is done to separate the price-effect from pure resource allocation, enabling us to reuse past production data to construct future cost norms.

To formalize the above, we assume that each of n DMUs, say DMU^i, transform m_x controllable inputs x^i and m_z non-controllable categorical inputs z^i into m_y outputs y^i. The prices, if existing, on the controllable inputs and outputs are $w^i \in \mathbb{R}_+^{m_x}$ and $p^i \in \mathbb{R}_+^{m_y}$.

We assume that the technological possibilities are the same for all DMUs' (except for the differences captured by the non-controllable) variables. Specifically, these possibilities may be thought of as the set T of feasible input -output combinations

$$T = \{(x, z, y) | (x, z) \text{ can produce } y\}$$

We shall generally assume that T satisfy

Condition 1. *Free disposability:* $(x, z, y) \in T, x' \geq x, z' \geq z, 0 \leq y' \leq y \Longrightarrow (x', z', y') \in T$.

Condition 2. *Convexity: T is convex.*

Condition 3. *r returns to scale,* $(x, z, y) \in T \Longrightarrow (qx, z, qy) \in T, \forall q \in K(r)$ *,where* $k = "crs", "drs," $ *or* $"vrs"$*, and* $K(crs) = \Re_0, K(drs) = [0, 1]$ *and* $K(vrs) = \{1\}$*, respectively.*

The associated underlying cost model for a DMU is given by

$$C(y|z, w) = \min_x \{wx | (x, z, y) \in T\}$$

Given n observations of feasible production plans (x^i, z^i, y^i) the *DEA based cost norm* for a DMU facing input costs w and non-controllable inputs z is $C^{DEA}(.|., .)$:

$\mathbb{R}_0^{m_y} \times \mathbb{R}_0^{m_z} \times \mathbb{R}_0^{m_x} \to \mathbb{R}$ defined as

$$\begin{array}{rll} C^{DEA}(y|z,w) = & \min & wx \\ & x,\lambda & \\ & s.t. & x \geq \sum_{i=1}^{n} \lambda^i x^i \\ & & z\lambda^i \geq z^i \lambda^i \\ & & y \leq \sum_{i=1}^{n} \lambda^i y^i \\ & & \lambda \in \Gamma(r) \end{array}$$

where $\Gamma(crs) = \Re_0^n, \Gamma(drs) = \left\{\lambda \in \Re_0^n | \sum_i \lambda^i \leq 1\right\}, \Gamma(vrs) = \left\{\lambda \in \Re_0^n | \sum_i \lambda^i = 1\right\}$. The second constraint effectively sorts the observations using the categoric variable z, cf. Agrell and Tind (2000). The DEA based cost function gives the minimal cost of producing the output for any output vector given the local factor prices and the local non-controllable conditions.

To develop the setting into a full regulatory model we shall make some behavioral assumptions as well.

Assume that the DMU's actual cost in the planning period is the minimal cost $C(y|z,w)$ plus whatever slack $s \in \mathbb{R}_0$ is introduced in the production process, i.e.

$$c(y) = C(y|z,w) + s$$

Note that production slack is summarized here as an additional cost, i.e., it is one-dimensional. The DMU (agent) knows $C(y|z,w)$ but the regulator (principal) does not. He does, however, know the input and outputs in n feasible (historical or inferred) production plans, i.e.

$$(x^i, z^i, y^i) \in \mathbb{R}_0^{m_x+m_y+m_z} \qquad i = 1,..,n$$

Drawing on the information from the n production plans, the regulator can infer from the minimal extrapolation property of the DEA model that

$$C(y|z,w) \leq C^{DEA}(y|z,w) \quad \forall y,z,w$$

The regulator has no more certain information about the cost structure. Formally, we let the regulator's belief about the likelihood of the different cost functions be given by the probability distribution

$$p(.) : \mathcal{C} \to \mathbb{R}_0$$

on the class $\mathcal{C}$ of increasing convex r return to scale functions satisfying the above inequalities. The belief distribution represents whatever additional information the regulator has and it is used to close the model as a Bayesian Game.

The objective of the regulator is to minimize the costs of inducing the DMU to accept a contract to produce y. The output y is assumed exogenously given and known, as the demand for the produced good is fairly inelastic and stable.

The DMU maximizes the weighted sum of profit and slack, the utility function

$$U_A = (b - wx) + \rho(wx - c(y))$$

where $b \in \mathbb{R}$ is the revenue cap, wx is the actual cost and y is the implemented production plan. The parameter $\rho \in [0,1]$ is the relative value of slack versus profits for the DMU. The DMU's reservation utility is assumed to be 0, without loss of generality.

From a social point of view it is important which production plans are selected under which conditions. For a given cost function $C = C(.|z,w)$ let $c[C]$ be the input costs chosen by the DMU and let $y[C]$ be the production plan that is implemented. We shall then say that the outcome is *cost efficient* if and only if

$$c[C] = C(y[C]|z, w) \quad \forall C \in \mathcal{C}$$

such that outputs are produced without cost slack, i.e. at minimal cost.

5. Single-period Single-unit DEA Regulation

In the particular application, the regulator has access to high-quality verifiable cost information $c[C]$. Extending model (P_{V1}) in Bogetoft (2000), we formulate the *single-period regulatory problem with verifiable actual costs* (P_V) as

$$\begin{array}{lllr}
\min\limits_{b,\, c(C)} & \Sigma_{c \in C}\; b[c[C]]p(C) & & \\
s.t. & b[c[C]] - c[C] + \rho(c[C] - C(y|z,w)) \geq 0 & \forall C \in \mathcal{C} & (IR) \\
 & b[c[C]] - c[C] + \rho(c[C] - C(y|z,w)) \geq & \forall C, c' : & \\
 & \qquad b[c'] - c' + \rho(c' - C(y|z,w)) & C(y|z,w)) \leq c' \leq b[c'] & (IC) \\
 & b[c'] \in \mathbb{R} & \forall c' \in \mathbb{R}_0 &
\end{array}$$

The individual rationality (IR) constraints ensure that the DMU is willing to participate and use the cost strategy $c[C]$. The incentive compatibility (IC) constraints ensure that this strategy is in fact the best possible strategy to use. The regulator tries to minimize the resulting expected payments to the DMU subject to these constraints.

Our next proposition characterizes the solution to this contracting problem with verifiable costs c. The proposition extend the result of proposition 2 in Bogetoft (2000) to the present setting.

Proposition 1. *An optimal solution* $(b^V[c], c^V[c])$ *to the single period contract design problem with verifiable actual costs* (P_V) *is given by*
$c^V[C] = C(y|z,w)$ *(cost efficiency)*
$b^V[c] = c + \rho[C^{DEA}(y|z,w) - c]$ *(DEA-yardstick)*

Proof. The proof of Proposition 1 can be developed using the same ideas as used in Bogetoft (2000). We leave out the details here ∎

Proposition 1 gives that the regulatory scheme using full cost reimbursement and a DEA-yardstick promotes cost efficient production, i.e. no slack. The DMU has incentive to participate and the regulator minimizes the cost of asymmetric information by making full use of the available cost-information.

From a practical point of view, the advantage of this scheme is that it provides an operational yardstick evaluation. It uses that cost slack is less valuable than profit to the DMU, but equally expensive for the regulator to provide. A disadvantage of the scheme is of course that the relative value of slack ρ may not be easy to assess. An opportunistic DMU will try to signal a high value of ρ in order to increase his informational rents. However, as long as we can at least find an upper bound on the value of ρ, we can use this as the basis for compensation and the IR and IC constraints will be fulfilled for all smaller values of ρ (Bogetoft, 1997).

Example 1. *Consider a slightly masked distributor (A) from the set of Norwegian distributors NVE (1997), with data for model* $C^{DEA}(y|z,w)$ *as in Table 2 below.*

Using the entire data set as reference, the DEA cost norm of the distributor is determined to 72.2 MNOK compared to the actual cost 81.98 MNOK. This estimate is based only on distributors that have a climate zoning equal or worse than A and an inverted customer density not less than that of A. The contract offered in Table 2, using a slack value $\rho = 0.25$*, gives A a bonus amounting to a fourth of the difference between the attained costs and the DEA cost norm. Since the DEA norm is an upper bound to the true cost function* $C(y|z,w)$*, it is feasible for A to attain cost efficiency. With the current value of slack,* $\rho = 0.25$*, A is indifferent between* $C(y|z,w) = 72,200$ *kNOK and further improvements of the operational cost. In case A does not lower the costs for an unchanged output* y*, the revenue cap* $b(81,980) = 81,980 + \rho(72,200 - 81,980) = 79,535$ *kNOK will effectively discourage the consumption of slack,* $81,980 - 72,200 = 9,780$ *kNOK since the cash loss, valued at* $2,445$ *kNOK, amounts to the utility value of the slack.*

Table 2. Data for electricity distributor A.

Category	Name	Amount	Unit	Price, w	Unit
Output, y	Clients	29,114			
	Delivered energy	848,070	MWh		
Input, x	Labor	97	fte	285,215	NOK/fte
	Losses	57,989	MWh	149	NOK/MWh
	Capital	547,410	kNOK	10.1	%
Non-controllable inputs	Climate zone	5			
	Customer space	0.535	km^2		

Table 3. Reimbursement for electricity distributor A.

Category	Amount	Unit
Historical cost, wx	81,980	kNOK
$C^{DEA}(y\|z,w)$	72,200	kNOK
Slack value, ρ	25	%
Revenue cap, $b(c)$	$c + 0.25(72,200 - c)$	kNOK
Revenue cap, $b(72,200)$	72,200	kNOK
Revenue cap, $b(70,000)$	70,550	kNOK

6. Multi-period Multi-unit DEA Regulation

The relevance of a multiple period regulatory regime is quite obvious. Specific investments are not likely to be undertaken at the optimal level unless the regulatory principles are settled for at least some years. Thus, it is natural to think of the historical data as referring to a prior review period and to assume that the regulator commits to a regulatory system for periods $1, ..., T$. This is depicted in Figure 1 below.

We will now extend our single-period regulatory scheme to an operational multi-period model. Let $y_1^i, ...y_T^i$ be the desired production plans, $w_1^i, .., w_T^i$ the input prices and $z_1^i, .., z_T^i$ the non-controllable categoric variables over the planning period $t = 1, ..., T$.

The regulator now faces two fundamental problems. The first problem is a simple control problem of inducing small cost in any given period given the available information. The second problem is a simple learning problem of taking into account the progressively revealed information about the costs.

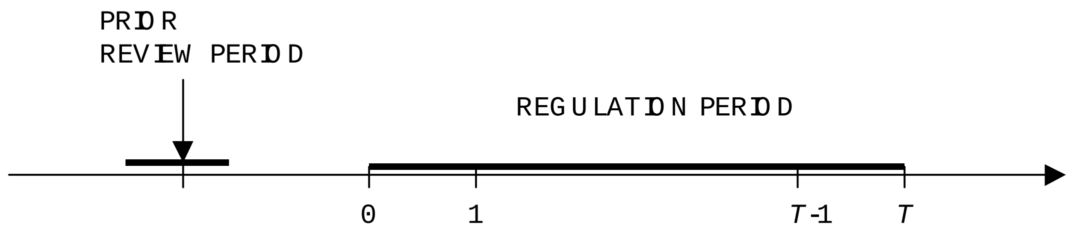

FIGURE 1. Timeline for the multi-period regulatory review period.

The first planning mode is usually referred to as the *here-and-now planning* or *blueprint planning*. It implies committing to a conditional revenue cap

$$b_t^i = c_t^i + \rho\left[C^{DEA}(y_t^i|z_t^i, w_t^i) - c_t^i\right] \qquad t = 1, .., T$$

at the outset of the planning period and to stick to these levels for the full planning period. This is relatively simple approach. The regulator develops the cost model at the outset of the planning period and uses it to determine revenue caps throughout the period. The DMU is willing to accept such a contract.

Instead of fixing the standards in the base year 0, it may be advantageous to re-estimate the cost structure every year as more an more information accumulate. This can be done without adversely affecting the DMUs behavior, i.e. without the drawback of rachet effect, as long as no DMU affects its own norm. This is the so-called *sequential planning* with revenue caps

$$b_t^i = c_t^i + \rho\left[C_t^{DEA-i}(y_t^i|z_t^i, w_t^i) - c_t^i\right] \qquad t = 1, .., T \tag{6.1}$$

where C_t^{DEA-i} is the DEA cost model using the historical information from all but the evaluated unit plus the base period information about the evaluated unit,

$$\begin{array}{rll} C_t^{DEA-i}(y|z,w) = & \min & wx \\ & x, \lambda & \\ & s.t. & x \geq \sum_{j\neq i}\sum_{s=0}^{t-1}\lambda^{js}x^{js} + \lambda^{i0}x^{i0} \\ & & z\lambda^i \geq z^{js}\lambda^{js} \qquad j \neq i, s = 0, ..., t-1 \\ & & y \leq \sum_{j\neq i}\sum_{s=0}^{t-1}\lambda^{js}y^{js} + \lambda^{i0}y^{i0} \\ & & \lambda \in \Gamma(r) \end{array}$$

This scheme has numerous advantages, in comparison to the CPI-X regulation. The main advantage of this planning mode is that it utilizes information as it becomes available. It hereby eliminates the problem of excessive rents, cf. proposition 1, as well as the risk of bankruptcy due to overestimated productivity improvement potentials. The resulting cost norm, as well as any derived productivity improvement rate X, are endogenously determined by the actual performance of the operators. Moreover, the scheme explicitly addresses the ratchet effect. In a repeated relationship, if the regulator can set up a target based on the DMU's previous performance, the DMU will anticipate the inflation of targets and he will then disguise his potentials by reducing output in earlier periods to earn more long term profits. To handle this drawback, we use $C_t^{DEA-i}(y|z,w)$ instead of an all-encompassing reference technology, based on all information for all DMUs. This may not be the least expensive way to cope with the ratchet effect, but certainly pragmatic and feasible. Based on the DEA multi-output technology, the model copes elegantly with the problem concerning changes in input and/or output profile. Finally, price changes are accommodated by using an updated price vector on the underlying physical production opportunity set.

In practice, additional considerations may matter in the design of the regulatory system. It may be unrealistic to assume that a DMU, who is severely inefficient at the outset, is able to eliminate this entirely over-night before the start of the planning period. To take into account the possible time lag in eliminating initial

inefficiency we may proceed as follows.

First, we determine the cost efficiency E_0 of the unit in question on the historical data set. Thus, if we plan for DMU^i we first calculate its historical cost efficiency as

$$E_0^i = \frac{C^{DEA}\left(y_0^i | z_0^i, w_0^i\right)}{w_0^i x_0^i}$$

Next, we introduce the fraction δ of the DMU's initial efficiency deficit that it is able to eliminate per year. Using this, the cost norm in period t becomes

$$(1 - \delta(1 - E_0^i))^t \frac{C_t^{DEA-i}(y_t^i | z_t^i, w_t^i)}{E_0^i} \tag{6.2}$$

where the last fraction is cost norm in period t, assuming no individual productivity catch-up by DMU^i and the first factor accounts for the cumulative impact of the limited δ-catch up per period. The factor δ is set such that the total required catch-up never exceeds the initial inefficiency during the regulatory period

$$\frac{(1 - \delta(1 - E_0^i))^T}{E_0^i} \geq 1$$

E.g., if the initial efficiency is $E_0^i = 0.75$ and the annual catch-up $\delta = 12\%$, we initially allow the cost norm to be inflated by $\frac{1}{E_o^i} = \frac{1}{0.75} = 1.33$ and the annual postulated catch-up factor is $1 - \delta\left(1 - E_0^i\right) = 1 - 0.12 \cdot 0.25 = 0.97$, resulting in a net extension of cost norm of $1.33 \cdot 0.97 = 1.29$ in period 1, 1.25 in period 2, etc. Hence, a DMU with an excess cost of 33% at the outset of the regulatory period is only required to reduce its inefficiency down to 25% excess cost after two years.

Inserting (6.2) in (6.1), we obtain the *dynamic revenue cap with limited catch-up ability*

$$b_t^i = c_t^i + \rho \left[(1 - \delta(1 - E_0))^t \frac{C_t^{DEA-i}(y_t^i | z_t^i, w_t^i)}{E_0^i} - c_t^i \right] \quad t = 1, .., T \tag{6.3}$$

As a final remark, if we want to allow for system wide declines in productivity, we could also eliminate the earlier observations in the estimation. The disadvantage of using such cost norms, that are more sensitive to new information, is that idiosyncratic variations from year to year create significant payment uncertainties. This, the trade-off between capturing system wide variations and running the risk of capturing idiosyncratic variations, is the general trade-off faced when we go from fixed to more relative performance or tournament-like payment schemes.

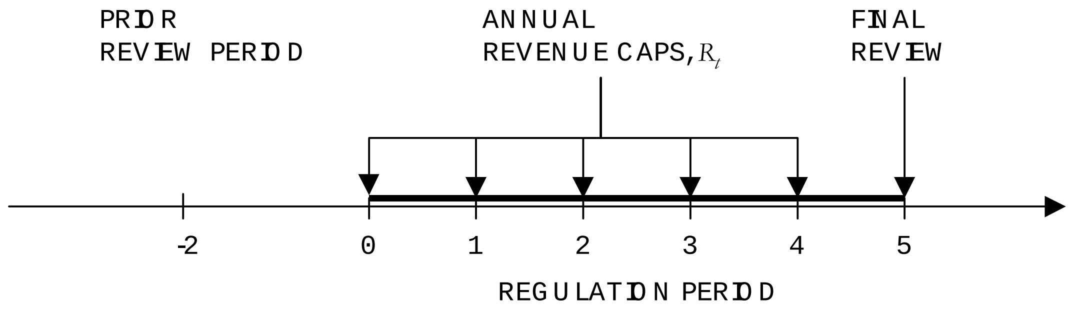

FIGURE 2. Timeline for the Norwegian electricity distribution regulation.

7. The Norwegian Scheme

In this section, we review the Norwegian Regulatory Scheme for electricity distribution and show the clear resemblance to the schemes discussed above. Based on documents from the Norwegian Water Resources and Energy Administration, NVE, such as NVE (1997) and Grasto (1997), and the independent work reported in Kittelsen (1994, 1996, 1997), the regulatory model of the Norwegian distribution market is summarized. The legal framework is based on the Norwegian Energy Act of 1991, separating production and transmission of electric power. The production and sales activities were deregulated into an open market, later pooled in a joint Scandinavian power exchange with Sweden and Denmark. The distribution remains a natural monopoly based on concession holding and delivery requirements. The distributors were subject to a rate of return regulation during 1992-1996, in January 1997 replaced by an *ex ante* revenue cap system with an efficiency incentive. The period of regulation is (initially) a five-year period, 1997-2001 and the efficiency incentive is based on reported performance in 1994-1995. The time perspective of the regulatory regime is illustrated in Figure 2. Two years before the start of the regulation period, the regulator assesses cost inefficiencies. During the period individual annual revenue caps are set by the regulator, based on previously assessed inefficiencies, reported costs and projected future demand. After a full regulatory cycle (5 years), the complete earnings of the distributor are reviewed. If the distributor cannot show the minimum rate of return in average over the period, overcharging of the customers is authorized during the following period. Analogously, if the maximum permitted rate of return has been exceeded, the excess profit will be distributed to the customers through tariff reductions. Direct violations of the revenue cap, windfall profits or -losses, are regulated with interest after a one-year delay. The interest rate is set to be the base rate of return for the industry, r_b, the riskfree rate of return with a 2% risk premium for uncertainty regarding regulatory regime.

The core of the regulation is thus an *ex ante* revenue window, which specifies the maximum, minimum and prescribed allowed revenue for the DMU. The maximum revenue is given as

$$R_t \leq \gamma^{\max} x_{cap} + c_t \qquad t = 1, .., T$$

where $\gamma^{\max}$ denotes the maximum allowed rate-of-return (15% in NVE (1997)), x_{cap} denotes the capital base of the DMU at time t and c_t is the actual cost at time t. The revenue floor is analogously given as

$$R_t \geq \gamma^{\min} x_{cap} + c_t \qquad t = 1, .., T$$

where $\gamma^{\min}$ denotes the minimum prescribed rate-of-return (2% in NVE (1997)). This constraint assures the economic survival of the distributor and may have additional effects on the cost structure of the industry. It also serves to assure the uninterrupted distribution of power to all consumers as a mean to induce regional equity. The prescribed revenue for periods $t = 1, ..., T$ is calculated as

$$R_t = k_{t,t-1} \left(\frac{y^t_{pow} + y^{t-1}_{pow}}{2y^{t-1}_{pow}} \right) \left(1 - \pi - \eta \min \left\{ \frac{1 - E_0}{1 - E_{\min}}, 1 \right\} \right) R_{t-1} \tag{7.1}$$

where $k_{t,t-1}$ is an inflation adjustment factor, y^t_{pow} is the gross output of power at time t, π is an imposed cost efficiency requirement (1.5% in NVE (1997)) (a proportional revenue reduction), E_0 is the historical cost efficiency at time 0 in the DEA model as above, $E_{\min}$ is a lower curbing of efficiency scores[1] (0.70 during 1999) and η is the annual efficiency catch-up factor (3% in NVE (1997)). Fundamentally, the regime is a CPI-X revenue cap with an individualized X, fixed over an horizon. The improvement factor X is composed of a general term π and an individual component η. Thus, it reflects the balance between a prevalent inefficiency among all distributors and the individual, relative inefficiency demonstrated by the DMU compared to other operators. In this sense, the regulator mounts an effort to reduce endemic inefficiency as indicated by the empirical studies above, as well as providing some incentives for frontier catch-up to individual agents.

We will now compare the implemented Norwegian regime with the proposed dynamic revenue caps with limited catch-up (6.3). In order to arrive at the Norwegian scheme, a series of additional assumptions are necessary. Assume (i) that the output is single dimensional, $m_y = 1$, (ii) that the non-controllable factors are fixed over time, $z^i_t = z^i_o$ for $t = 1, .., T$, (iii) that the cost model is characterized by constant return to scale, $r = "crs"$, (iv) that factor-prices over time are proportional, $w^i_t = k^i_t w^i_0$ $t = 1, ...T$ for some real numbers $k^i_t \in \mathbb{R}_+$, and (v) that there exits an exogenous frontier shift π. Now, by the homothetic nature of the cost function, we obtain that the optimal factor combinations are proportional as well, $x^i_t = (y^i_t / y^i_0) \cdot x^i_0$ (presuming allocative efficiency on the input side in the historical period) and (6.3) for $t = 1, ..., T$ simplifies to

$$\begin{aligned} b^i_t &= c^i_t + \rho \left[k^i_t \frac{y^i_t}{y^i_0} (1 - \pi - \delta(1 - E^i_0))^t \frac{C^{DEA}(y^i_0 | z^i_0, w^i_0)}{E^i_0} - c^i_t \right] \\ b^i_t &= c^i_t + \rho \left[k^i_t \frac{y^i_t}{y^i_0} (1 - \pi - \delta(1 - E^i_0))^t w^i x^i - c^i_t \right] \qquad (7.2) \end{aligned}$$

where k^i_t is a price index and y^i_t / y^i_0 is as quantity index. Except for the arbitrary efficiency cushion $E_{\min}$ adjustment and the profit-slack arbitrage through the ρ factor, this scheme corresponds to the Norwegian model (7.1). Indeed, in the special

[1]The curbing is introduced as an additional mean of moderating the catch-up requirements for severely inefficient units.

case (vi) where the valuation of slack and cash profit is identical, $\rho = 1$, the scheme reduces to

$$b_t^I = k_t^i \frac{y_t^i}{y_0^i}(1 - \pi - \delta(1 - E_0^i))^t w^i x^i \quad t = 1, .., T \tag{7.3}$$

To illustrate the differences and similarities between (7.2) and (7.1), consider a stylized two-period example with a normalized cost $c_0 = 100$, $\pi = 0.02, \delta = 0.10, \rho = 0.8, \eta = 0.03, \gamma_{\max} = 0.153, \gamma_{\min} = 0.02$ and $E_{\min} = 0.70$. The capital input, $x_{cap} = 473$, based on the average ratio for 180 Norwegian distributors in NVE (1997b). The effect of gradual efficiency improvements is captured by a factor k, such that $c_0 = kc_1$ with $k = 0.90, ..., 1.60$. Certainly, a distributor cannot reasonably reduce costs more than a certain fraction in any given period due to binding contracts and inputs that are not transformed by the distributor, such as transfer fees and depreciation. However, since the maximum k is unknown to the regulator, the development over the entire range is of potential interest. The NVE scheme is monotonous for efficiency scores E_0 between 0.7 and 1.0 and the Agrell-Bogetoft-Tind scheme (ABT) is monotonous for all E_0. Thus, it suffices to select the scores $E_0 = \{1.0, 0.7, 0.5\}$ to demonstrate the properties of two regulatory schemes. The resulting revenue caps b_1 (ABT) and R_1 (NVE) as functions of k are illustrated in Figure 3. Note that the positive difference between the two curves, for any E_0, indicates a one-period gain for the regulator. The ABT scheme does not provide any positive profit for underperformance, $k < 1$, whereas the NVE scheme cushions the weaker distributors by the floor $\gamma_{\min} x_{cap}$. Figure 4 illustrates the operator's gain $R_1(k) - \frac{c_0}{k}$ and $b_1(k) - \frac{c_0}{k}$, respectively. Here, the explanation for the regulator's surplus is given as a lowered informational rent to the distributor in the ABT system, thanks to the profit-slack arbitrage. However, there is always a positive incentive to reveal the true cost function, i.e., to reveal the maximum k in the one-period setting.

A closing note may be made on a particularity in the NVE scheme. For a capital base lower than the average, the NVE profit ceiling $\gamma_{\max} x_{cap}$ will form a horizontal plateau in Figure 4. An operator has subsequently no incentive to reveal any higher improvement factor k than to the beginning of this horizontal segment. The ABT scheme is unaffected by this problem.

This modest example does not illustrate the principal difference vis-a-vis the *ex ante* revenue cap, the sequential updating of the cost norm. This feature would further accelerate the individual productivity catch-up in a regulatory application, while simultaneously lowering the informational rents of the distributor and potentially safeguarding against industry-wide shocks.

8. Conclusions

In this paper, we have examined the regulation of the electricity distribution industry and suggested a regulatory framework for the multiple-input, multiple-output, multiple-period case based on efficiency benchmarking and incentive theory. We have shown that the previously developed theory has a practical implementation and that the potential gains for the regulator are positive compared to the popular CPI-X model. In particular, the approach solves five essential problems with the

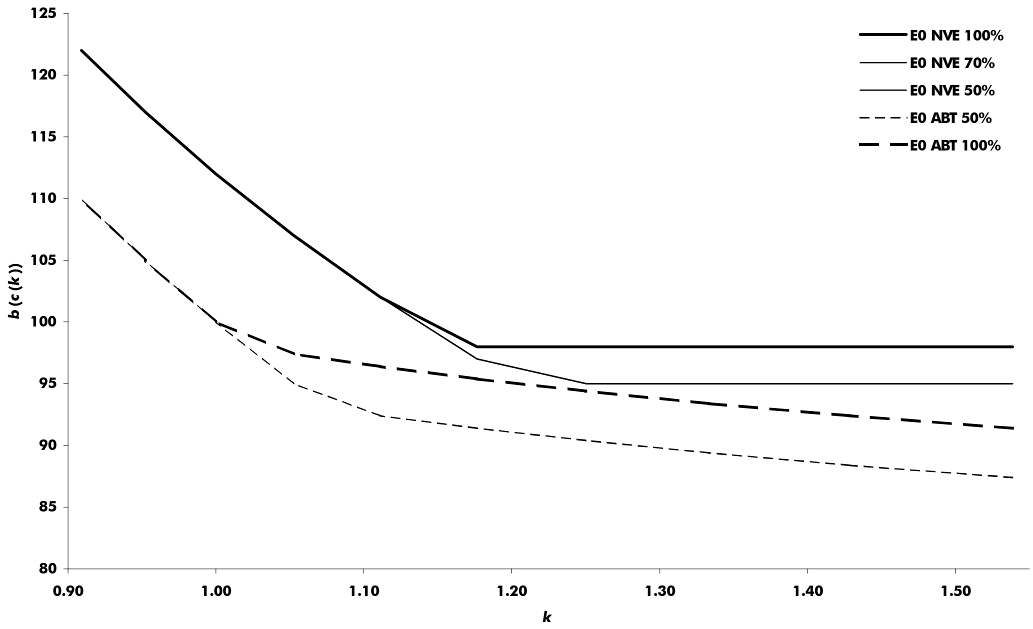

FIGURE 3. The revenue caps b_1 and R_1 for $k = c_1/c_0$ under the current (NVE) and proposed (ABT) regimes.

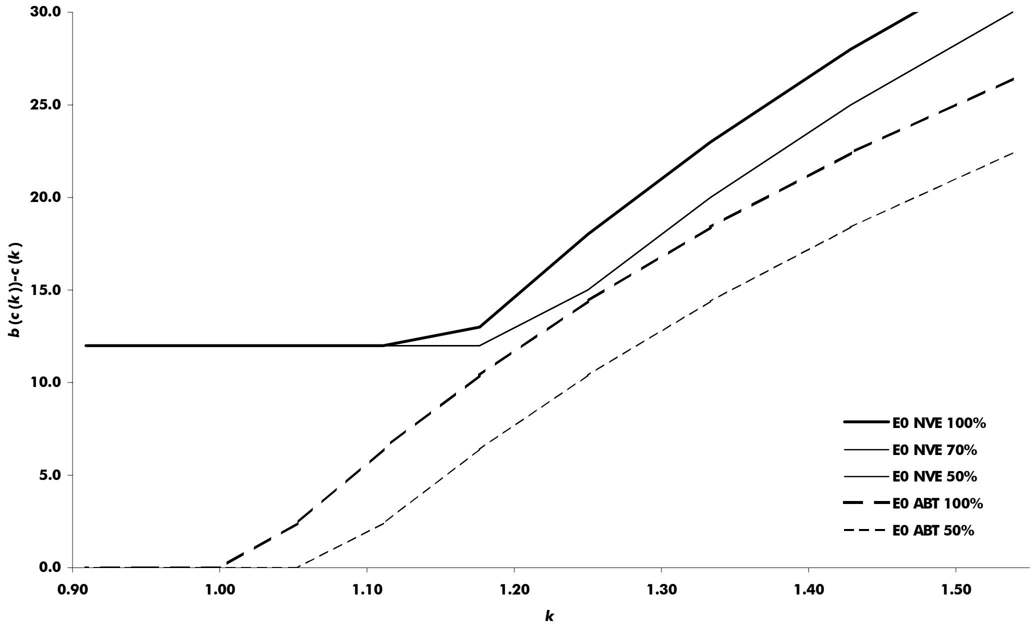

FIGURE 4. The informational rents $b_1 - c_1$ and $R_1 - c_1$ for $k = c_1/c_0$.

CPI-X model: (i) the risk of bankruptcy, (ii) risk of excessive rents, (iii) the ratchet effect, (iv) the arbitrariness of the parameters CPI and X, and (vi) the inability to accommodate changes in the output profile. The approach is illustrated with a numerical comparison against the Norwegian DEA-based regulation, which is a CPI-X model with an individualized X factor.

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