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The Effects of Average Revenue Regulation on Electricity Transmission Investment and Pricing

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Abstract

This paper investigates the long-run effects of average revenue regulation on an electricity transmission monopolist who applies a two-part tariff comprising a variable congestion price and a non-negative fixed access fee. A binding constraint on the monopolist's expected average revenue lowers the access fee, promotes transmission investment, and improves consumer surplus. In a case of any linear or log-linear electricity demand function with a positive probability that no congestion occurs, average revenue regulation is allocatively more efficient than a Coasian two-part tariff if a positive access fee under average revenue regulation is lower than that under a Coasian two-part tariff.

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1. INTRODUCTION

Congestion pricing has been applied to bulk power markets in order to achieve efficient rationing of access to constrained electric networks. Examples include the capacity elements of Statnett's transmission tariffs in Norway and locational marginal pricing in the PJM Interconnection in the United States. Congestion pricing, which sets transmission prices equal to nodal price differences between regions sending and receiving electricity respectively, is expected to achieve short-run economic efficiency in competitive electricity markets. That is because nodal prices are consistent with marginal cost pricing of electricity and interregional differences in nodal prices reflect marginal costs of transmission (Hogan, 1992; Chao and Peck, 1996; Stoft, 2002).

Congestion pricing also leads to long-run efficiency if a congestion price reflects the marginal benefit of capacity expansion and transmission capacity is expanded to the point where the unit price of congestion is equal to the marginal cost of capacity.[1] If the transmission sector exhibits constant returns to scale technology, revenue from congestion pricing alone exactly covers expenses of capacity expansion so that a transmission company has an incentive to expand its congested networks (Vickrey, 1971; FERC, 1989, pp.96-97).

For a transmission company with increasing returns to scale technology, however, an additional source of revenue is necessary to finance the expansion of its network capacity. Cost functions of transmission investment have been found to exhibit scale economies over the relevant range of transmission capacity (Baldick and Kahn, 1993). Thus, revenue from congestion pricing is insufficient for a proper expansion of transmission capacity in the case of increasing returns to scale technology. In fact, transmission lines that have been built in anticipation of recovering their costs entirely by the revenue from congestion pricing do not appear to be profitable in Australia (Joskow and Tirole, 2003, p.7).

Based on the idea that capacity expansion is financed by a combination of the revenue from congestion pricing and that from the fixed access fee, Vogelsang (2001) investigated the price-cap regulation of access to transmission networks that exhibit increasing returns to scale. Given the number of users of transmission networks, Vogelsang (2001) examined properties of several forms of price-cap regulation with a two-part tariff, which consists of (i) a variable congestion price that is endogenously determined by a spot market of electricity, and (ii) a strictly positive fixed fee for the access to the transmission facility owned and operated by a profit-maximizing transmission monopolist subject to the price-cap regulation.

This paper investigates how average revenue regulation on the transmission monopolist affects its investment and pricing in the long run, using a static model that allows the number of generators to be determined endogenously and that allows the access fee to be zero.[2] Average revenue regulation, which has been applied to such industries as airports, gas and electricity in the United Kingdom (Cowan, 1997), has an informational advantage over Vogelsang's mechanism of the price-cap regulation that requires the regulator to obtain precise information on the weights used for the price index. The endogeneity of the number of users is crucial in the analysis of the monopolist's choice of transmission capacity because a relatively high access fee that is needed to cover a large amount of the fixed costs in transmission investment is expected to reduce the number of users of the transmission facility, thereby discouraging the expansion of transmission capacity in the long run. Zero access fees may be optimal for the transmission monopolist if a binding constraint on the transmission network results in revenue from congestion pricing that is sufficient to cover investment costs. The optimality of a zero access fee, which indicates the superiority of a uniform price over a two-part tariff, is consistent with Ordover and Panzar (1982), who argued that for the input required in a fixed proportion to the output such as electric power transmission, a two-part tariff is inferior to a uniform price from either a welfare or monopoly profit-maximizing standpoint.

This paper also makes a welfare comparison of a two-part tariff under average revenue regulation with a Coasian two-part tariff (Coase, 1946; Brown and Sibley, 1986, pp.66-67).[3] For social welfare to be maximized under a zero-profit constraint, a Coasian two-part tariff in which the unit price is set equal to marginal cost and all profits are extracted via the access fee appears to be an optimal method of regulating a transmission tariff. However, a Coasian two-part tariff may be less efficient than a two-part tariff under average revenue regulation if a relatively high access fee under the Coasian two-part tariff significantly reduces the number of users of the transmission facility in comparison to average revenue regulation. The paper shows that in case of any linear or log-linear demand function of electricity with a strictly positive probability that no congestion occurs, average revenue regulation is allocatively more efficient than a Coasian two-part tariff if a positive access fee under average revenue regulation is lower than that under a Coasian two-part tariff.

How to regulate a transmission monopolist has been an important policy issue in electricity markets. The literature investigates the regulatory mechanisms of pricing access to the transmission facility (Einhorn, 1990; Hogendorn, 2003), the proper expansion of transmission facilities (Baldick and Khan, 1993; Bushnell and Stoft, 1996, 1997; Leautier, 2000; Saphores et al., 2004), and the governance of the transmission monopolist (Kleindorfer, 1998; Boyce and Hollis, 2005). The model of this paper has several features that are also found in those of the previous literature: a stochastic demand for transmission, scale economies in transmission investment, an independent transmission company which is subject to regulation, and the presence of competitive spot markets of electricity.[4, 5] The long-run effects and welfare properties of average revenue regulation in electric power transmission are the main focus of this paper.

The paper is organized as follows. Section 2 describes a simple two-node model of electric power transmission with uncertain demand and examines properties of long-run market equilibrium in a static setting. Section 3 investigates how average revenue regulation affects transmission investment and pricing of the profit-maximizing monopolist. Section 4 compares welfare effects of average revenue regulation with those of a Coasian two-part tariff of electric power transmission. Finally, Section 5 presents brief conclusions and some policy implications of the results in the paper. The Appendix section describes the derivation of comparative-static results, the proof of Proposition 2, and a simple numerical example that illustrates the results of the paper.

2. THE MODEL

2.1 The Basic Model

The paper uses a stylized geographical setting to examine the effects of average revenue regulation in electricity transmission. In this setting, a transmission line moves power from a generation node to a consumption node, as shown by Figure 1.[6] In Figure 1, n identical firms generate y megawatts of electricity at node G and supply x megawatts to consumers at node L through a single transmission line that is owned and operated by the regulated monopolist.[7] For simplicity, no loss in transmission is assumed and the amount of transmitted electricity is assumed to be equal to the amount of generated electricity, i.e., $nx = ny$. The paper also assumes the absence of ancillary services such as voltage and frequency control.

[Figure 1 here]

The supply of electricity is characterized by the free entry and exit of identical firms operating at the minimum point of a *U*-shaped average cost curve in the long run. Integer constraints are ignored, and n is determined by the condition that generators earn zero profits in equilibrium. The second-order condition for the profit maximization of generators is assumed to hold; that is, the marginal cost of generation is an increasing function of output.

Congestion occurs when total demand for transmission, nx, exceeds the capacity of the transmission facility of the monopolist. Congestion pricing is applied to efficiently ration the excess demand for transmission access. Given congestion, firms at node G should pay r per megawatt of the transmitted electricity, which is defined as the difference between the price of electricity at node L and the marginal cost of generation at node G, to the transmission monopolist. Since electricity supply is perfectly competitive, the price of electricity, denoted by p, should be equal to the sum of r and the marginal generation cost in equilibrium. Using congestion pricing to achieve rationing is allocatively efficient because, in equilibrium, consumers who are only willing to pay less than p are rationed, as are firms that have a marginal generation cost exceeding $(p - r)$.

The unit price of congestion is endogenously determined by the degree to which the transmission constraint is tightened in the market; that is, $r > 0$ if the transmission constraint is binding, and $r = 0$ otherwise. The profit-maximizing transmission monopolist chooses the optimal levels of a non-negative fixed access fee and the capacity of the transmission line, while the value of r is determined by the electricity market. Examples of mechanisms that determine the value of r include an electricity market in Norway where the unit price of congestion is defined as an interregional difference in market clearing prices (Bjorndal and Jornsten, 2001).

The transmission sector is assumed to have increasing returns to scale technology, which implies that the transmission sector is a natural monopoly. Total costs in the transmission sector, denoted by C_m, are assumed to be a function of the thermal capacity of the transmission line:

$$C_m = m_0 + mK \tag{1}$$

where K denotes the thermal capacity of the transmission line owned and operated by the monopolist. The parameters m_0 and m are a fixed cost and the constant marginal cost of transmission, respectively. To focus on the expansion of transmission capacity, the cost of operating the transmission line is assumed to be zero and costs in the transmission sector depend only on the thermal capacity.

The monopolist can charge firms at node G a simple two-part tariff comprising a non-negative fixed access fee, e, and a unit price, r, which corresponds to the unit price of congestion. Examples include the transmission tariff in Norway where a variable congestion price and postage stamp rate are respectively applied to the unit price and fixed access fee (Westre, 1996; Braton, 1997). If the fixed access fee is zero, the transmission tariff consists of the congestion price alone. The total revenue of the transmission monopolist is the sum of *en* and *rnx*.

The construction of an operational transmission facility takes time. Since the unit price of congestion depends on market conditions, the transmission monopolist who decides the thermal capacity of the line connecting nodes G and L is uncertain about what revenue can be earned from congestion pricing. This paper focuses on uncertainty that only affects electricity demand at node L. Causes of uncertainty in electricity demand include business cycles, population growth, and a saturation of durable goods.

The demand for electricity at node L is assumed to be a function of both electricity price at node L and the state of the world $\omega \in \Omega$, and the demand function $D(p, \omega)$ is strictly downward sloping in p for all values of ω. The set of all states of the world, Ω, can be divided into two subsets according to the necessity for rationing: $\Omega_0=\{\omega | D(p, \omega) \leq K\}$, which includes states in which no congestion occurs, and $\Omega_1=\{\omega | D(p, \omega) > K\}$, which includes states in which congestion occurs. For congestion pricing to be effective, the probability that congestion occurs is assumed to be strictly positive. The variable ω is assumed to be a continuous random variable with a compact range.

As an illustrative example, suppose that both electricity supply and demand curves are linear in electricity price as shown in Figure 2, and that the location of demand curves depends on each state of the world. When the demand curve is described by D_0, transmission capacity exceeds the amount of transmitted electricity and congestion price becomes zero in equilibrium. In contrast, the rationing of transmission demand becomes necessary and the unit price of congestion rises to r_1 in equilibrium when the demand curve is described by D_1.

[Figure 2 here]

2.2 Market Equilibrium

Equilibrium in the electricity market is determined by three conditions: (i) firms at node G earn zero profits; (ii) there is no excess demand for electricity at node L; and (iii) the capacity constraint on the transmission line is binding. These conditions are represented by the following equations, respectively:

$$(p - r)y(p, r) - C_d[y(p, r)] = e \tag{2}$$

$$n\, y(p, r) - D(p, \omega) = 0 \tag{3}$$

and

$$D(p, \omega) = K, \tag{4}$$

where $y(p, r)$ is the supply function of each firm at node G, and $C_d(y)$ is the cost function of each firm at node G. All these functions and the demand function are assumed to be twice differentiable. It is also assumed that $y_p \equiv (\partial y/\partial p) > 0$, $y_r \equiv (\partial y/\partial r) < 0$, $y_r = -y_p$, $\partial C_d/\partial y > 0$, $\partial^2 C_d/\partial y^2 > 0$, and $D' \equiv \partial D/\partial p < 0$. The assumptions that $y_p > 0$, $y_r < 0$, and $y_r = -y_p$ follow from the standard properties of competitive firms' profit functions.

The response of endogenous variables to changes in e and K depends on which subset of states occurs. While the electricity price and generators' supply are stochastic variables that depend on ω, the number of generators is not stochastic and this does not depend on ω. Some comparative-static analysis is conducted to describe the response of the long-run equilibrium values of p, r, n, y, and nx to changes in e and K. The results of the comparative-static analysis are summarized in Table 1a and Table 1b. The derivation of the partial derivatives in these tables is described in Appendix A.

[Table 1 here]

In the states in which the constraint on the transmission line capacity is binding (Table 1a), holding transmission capacity constant, an increase in the access fee reduces the congestion price. This is because the number of generators falls following a rise in the access fee. Since $\mathrm{d}y/\mathrm{d}e = y_p/y > 0$, a decrease in the number of generators in response to a rising access fee is exactly offset by an increase in y, output of each generator. Thus, total demand for transmission, nx, is not affected by a change in the access fee. Holding the access fee constant, an increase in transmission capacity lowers both the electricity price and the congestion price by the same amount, i.e., $1/D'$. Hence, the output of each generator at node G is unaffected. The equilibrium number of generators increases by $1/y$ due to the expansion of transmission capacity by one unit. The increase in capacity by one unit results in a one-unit increase in total demand for transmission.

In the states in which the capacity constraint of the transmission facility is not binding (Table 1b), the unit price of congestion is zero and the revenue of the transmission monopolist depends only on the access fee. When there is no congestion, the equilibrium is determined by two conditions: that the firms at node *G* earn zero profits and that there is no excess demand for electricity at node *L*. Thus, the equilibrium condition (4) is irrelevant for the comparative statics in states belonging to the subset Ω_0. In contrast with the states in which the transmission constraint is binding, an increase in the access fee raises the electricity price at node *L* in equilibrium, thereby lowering consumer surplus. This is because the upward shift in the total supply curve of the firms at node *G*, which is due to this rise in the access fee, raises the electricity price along the demand curve at node *L* when the transmission constraint is not binding. Although an increase in the access fee raises the supply of each generator, this additional supply is more than offset by the decrease in total supply associated with the fall in the number of generators due to the increased access fee. Thus, in equilibrium, total demand for transmission falls following an increase in the access fee when the transmission capacity constraint is not binding.

2.3 Profit Maximization of the Unregulated Transmission Monopolist

If no regulation is applied to the transmission sector, a transmission monopolist is assumed to choose the access fee and the capacity of the transmission line connecting nodes *G* and *L* so as to maximize its expected profits:

$$\underset{e,\,K}{\text{Max.}}\ \mathrm{E}(\Pi) = \mathrm{E}(rnx) + en - mK - m_0 \quad , \tag{5}$$

where *Π* denotes the profits of the transmission monopolist. The expected value of the monopolist's profits in (5) is assumed sufficiently regular for the expectations and differentiation operators to be interchangeable (Crew and Kleindorfer, 1976, p.224).

The first-order condition for maximizing the expected value of the profits in (5) with respect to the access fee is:

$$E\left(\frac{\partial \Pi}{\partial e}\right) = nP_0 + eE\left(\frac{\partial n}{\partial e}\right) = 0, \tag{6}$$

where P_0 is the probability that the capacity constraint is not binding, and

$$E\left(\frac{\partial n}{\partial e}\right) = P_0 E\left[\frac{D' - ny_p}{y^2}\middle|\Omega_0\right] + (1 - P_0)E\left[\frac{-ny_p}{y^2}\middle|\Omega_1\right] < 0. \tag{7}$$

From (6), the optimal access fee for the profit-maximizing monopolist, denoted by e_m, is:

$$e_m = \frac{nP_0}{-E\left(\frac{\partial n}{\partial e}\right)} \quad . \qquad (8)$$

The optimal access fee for the unregulated transmission monopolist is strictly positive unless the probability that the capacity constraint on the transmission line becomes binding is unity; that is, $P_0 = 0$. If the capacity constraint becomes binding in all states of the world, the optimal access fee is zero and the revenue from congestion pricing is the sole source of income for the transmission monopolist. The superiority of a uniform price over a two-part tariff for the profit-maximizing monopolist in case of $P_0 = 0$ is consistent with a finding of Ordover and Panzar (1982) for the class of production processes in which the purchased input provided by the upstream monopolist is required in fixed proportion to the output of firms operating in the competitive downstream market.

With respect to the capacity of the transmission line, the first-order condition for maximizing the expected profits is $E(\partial \Pi / \partial K) = 0$, which indicates

$$(1-P_0)\left[E\left(r \mid \Omega_1\right) + \frac{e}{\bar{y}} + KE\left(\frac{1}{D'}\middle|\Omega_0\right)\right] = m \qquad (9)$$

where $\bar{y}$ indicates the value of y for $\omega \in \Omega_1$. The left-hand side of (9) implies the expected marginal revenue associated with transmission capacity. For the profit-maximizing monopolist, the optimal capacity and access fee satisfy both (8) and (9). The second-order conditions, which indicate the strict concavity of the profit function of the monopolist, are assumed to hold for the expected profits of the transmission monopolist to be maximized; that is, $E(\partial^2 \Pi/\partial e^2) < 0$, $E(\partial^2 \Pi/\partial K^2) < 0$, and $E(\partial^2 \Pi/\partial e^2)E(\partial^2 \Pi/\partial K^2) > [E(\partial^2 \Pi/\partial e \partial K)]^2$.

3. Effects of Average Revenue Regulation

We investigate the effects of average revenue regulation based on the comparative-static analysis in Section 2.2. The transmission monopolist is assumed to maximize its expected profits subject to a constraint on its expected average revenue.[8] The profit-maximizing transmission monopolist subject to average revenue regulation faces a trade-off between the revenue from the access fee and that from the congestion price. Under average revenue regulation, the regulator imposes a constraint on average charges of the transmission monopolist, which are defined as total revenue divided by total output. Average revenue regulation has an informational advantage over the price-cap regulation of Vogelsang (2001) in which the regulator needs to find weights that best approximate idealized price-cap weights.

The following Lagrange function is defined:

$$L = (1 - \lambda_a)[E(rnx) + en] - mK - m_0 + \lambda_a R E(nx), \qquad (10)$$

where λ_a is a Lagrange multiplier with respect to a constraint on the expected average revenue of the transmission monopolist.[9] The constraint is:

$$\mathrm{E}(rnx) + en \le R\mathrm{E}(nx) \qquad (11)$$

where R is a cap on the expected average revenue of the transmission monopolist. It is assumed that $0 < \lambda_a < 1$ for the second-order condition of profit maximization to hold under the binding constraint on average revenue (Cowan, 1997, p.78). For the expected profits of the transmission monopolist to be non-negative, the cap on the expected average revenue should at least exceed the marginal capacity cost. Thus, it is assumed that $R > m$.

The first-order condition for maximizing the expected profits of the regulated transmission monopolist with respect to the access fee is:

$$E\left(\frac{\partial L}{\partial e}\right) = nP_0 + eE\left(\frac{\partial n}{\partial e}\right) + \Lambda RP_0 E\left(\left.\frac{D'}{y}\right|\Omega_0\right) \le 0;\ e \ge 0,\ eE\left(\frac{\partial L}{\partial e}\right) = 0\,. \qquad (12)$$

where $\Lambda \equiv \lambda_a/(1-\lambda_a) \ge 0$. From (12), the optimal access fee under the binding constraint on the expected average revenue, denoted by e_a, is:

$$e_a = \left[\frac{P_0}{-E(\partial n / \partial e)} \right] \left[n - \Lambda RE\left(\frac{-D'}{y} \middle| \Omega_0 \right) \right] \quad if\ n > \Lambda RE\left(\frac{-D'}{y} \middle| \Omega_0 \right) \ ,$$

$e_a = 0$, otherwise. (13)

Except for the case where $P_0 = 0$, the optimal access fee for the monopolist under the binding constraint on the expected average revenue is lower than that for the unregulated monopolist; that is, $e_a < e_m$. If $P_0 = 0$, the optimal access fee becomes zero for both the unregulated and regulated monopolist in the transmission sector. These results are summarized by the following proposition associated with the effects of average revenue regulation on the access fee:

PROPOSITION 1. *Unless the probability that transmission congestion occurs becomes unity, in equilibrium, the binding constraint on the expected average revenue of the profit maximizing transmission monopolist lowers the access fee. If the probability that transmission congestion occurs becomes unity, in equilibrium, the access fee is not affected by the binding constraint on the expected average revenue of the profit maximizing transmission monopolist.*

PROOF. If $P_0 > 0$, the access fee chosen by the profit-maximizing transmission monopolist subject to no regulation is given by (8), which exceeds the optimal access fee subject to average revenue regulation in (9), because $\Lambda R\mathrm{E}(-D'/y|\Omega_0) > 0$. If $P_0 = 0$, the optimal access fee becomes zero for both the case of no regulation and the case of average revenue regulation.

Q.E.D.

The intuition behind Proposition 1 is straightforward. Uncertainty about electricity demand at node *L* leads to the possibility that the capacity constraint is not binding and no revenue is earned from congestion pricing. To cover this loss in revenue, the access fee must be strictly positive if the expected value of the transmission monopolist's profits is maximized. Average revenue regulation, if binding, forces the transmission monopolist to lower the access fee. If the capacity constraint is binding in all states of the world (i.e., $P_0=0$), however, congestion pricing alone is sufficient and an access fee is not necessary for the transmission monopolist.

With respect to the capacity of the transmission facility, the necessary condition for maximizing the expected profits is $\mathrm{E}(\partial L/\partial K) = 0$, which indicates

$$(1-P_0)\left[E(r \mid \Omega_1) + \frac{e}{y} + KE\left(\frac{1}{D'}\middle|\Omega_1\right)\right] = m - \Lambda[(1-P_0)R - m] \ . \tag{14}$$

Equation (14) implies that the monopolist's expected marginal revenue with respect to transmission capacity must deviate from its marginal cost at the optimum as long as the constraint on its expected average revenue is binding. The term on the left-hand side of (14) implies the expectation of the monopolist's marginal revenue with respect to transmission capacity under no binding constraint on its expected average revenue, which corresponds to the left-hand side of (9).

The right-hand side of (14) implies the *effective* marginal cost of capacity for the transmission monopolist subject to average revenue regulation. Equation (14) implies that whether the binding constraint on average revenue raises or lowers transmission capacity depends on the sign of the term $(1-P_0)R - m$. Because of the assumption that $E(\partial^2 \Pi / \partial K^2) < 0$, the expected marginal revenue curve with respect to capacity is downward sloping, as in the standard model of monopoly profit maximization. Thus, the binding constraint on the expected average revenue reduces the *effective* marginal cost of capacity, thereby raising the optimal capacity of the transmission line, if and only if the term $(1-P_0)R - m$ is strictly positive.

The effect of average revenue regulation on transmission capacity, which is indicated by the second term on the right-hand side of (14), is summarized in the following proposition:

PROPOSITION 2. *The binding constraint on the expected average revenue of the monopolist raises the capacity of its transmission line.*

PROOF. See Appendix B.

Proposition 2 immediately leads to the following condition associated with the choice of a cap on the expected average revenue:

$$(1-P_0)R - m > 0. \tag{15}$$

The increase in transmission capacity promotes electricity trade between the generators' node and the consumers' node. As a result, one expects the electricity price to fall. Indeed, the following corollary indicates that average revenue regulation, if binding, contributes to the improvement of the expected consumer surplus through the lower access fee and the higher transmission capacity:

COROLLARY 1. *The binding constraint on the expected average revenue of the transmission monopolist increases the expected consumer surplus.*

PROOF. Differentiating the expected consumer surplus with respect to the access fee and the transmission capacity respectively, and substituting $\partial p/\partial e$ and $\partial p/\partial K$ in Tables 1a and 1b yields

$$E[\frac{\partial}{\partial e}\int_p D(q,\omega)dq] = P_0 E\left[\frac{-D(p)}{y}\middle|\Omega_0\right] < 0$$

$$E[\frac{\partial}{\partial K}\int_p D(q,\omega)dq] = (1-P_0)E\left[\frac{-D(p)}{D'}\middle|\Omega_1\right] > 0 \ .$$

From Propositions 1 and 2, the above inequalities indicate that the binding constraint on the expected average revenue of the transmission monopolist raises the expected consumer surplus.

Q.E.D.

On the *K*-*e* plane, the slope of the iso-average revenue contour corresponds to the marginal rate of substitution of *K* for *e* under the constant expected average revenue if $P_0 > 0$. Totally differentiating (11) with equality and substituting the first-order conditions (13) and (14) yields the marginal rate of substitution of *K* for *e* at the optimum of the regulated monopolist:

$$\frac{de_a}{dK_a} = \frac{(1-P_0)R - m}{-P_0 RE\left(\frac{D'}{y}\middle|\Omega_0\right)} \ . \qquad (16)$$

where K_a is the optimal capacity of the transmission facility for the monopolist under the binding constraint on its expected average revenue. From (15), the nominator on the right-hand side of (16) is strictly positive. Thus, if $P_0 > 0$, the marginal rate of substitution of K for e becomes strictly positive at the optimum for the transmission monopolist subject to average revenue regulation.

4. WELFARE COMPARISON BETWEEN AVERAGE REVENUE REGULATION AND A COASIAN TWO-PART TARIFF

As an alternative form of regulating transmission pricing, the regulator is supposed to choose the access fee and the transmission capacity that result in zero profits of the transmission monopolist. This form of regulation shares a feature of zero profits of the transmission monopolist with cost-of-service regulation that has been traditionally applied to a transmission sector.[10] A policy question of interest is whether social welfare under average revenue regulation is higher than that under cost-of-service regulation when R is set equal to the expected average revenue earned by the monopolist under cost-of-service regulation. Assuming a Coasian two-part tariff as an efficient form of regulating transmission investment and pricing on a cost-of-service basis, this section examines welfare properties of average revenue regulation with a cap equal to the expected average revenue earned by the monopolist under the Coasian two-part tariff.[11]

A measure for social welfare is defined as the sum of consumer surplus and profits of the transmission monopolist in the long run:

$$W = \int_{p} D(q, \omega)dq + rnx + en - mK - m_0 \quad . \tag{17}$$

where W is a measure for social welfare. Note that, by assumption, since generators at node G earn zero profits, their profits are excluded from the right-hand side of (17).

4.1 Case 1: $P_0 = 0$

If $P_0 = 0$, the optimal access fee must be zero in both the case of unregulated monopolist's profit maximization and the case of regulated monopolist's profit maximization.[12] As a Coasian two-part tariff, the regulator is supposed to set the access fee equal to the fixed cost per firm and determines the capacity of the transmission line so as to make the expected total revenue from congestion pricing equal to mK:

$$\mathrm{E}(nx)R_0 = m_0 + mK_0 , \tag{18}$$

$$e_0 = m_0/n, \tag{19}$$

and

$$K_0 = \mathrm{E}(rnx)/m , \tag{20}$$

where R_0 is the expected average revenue, e_0 is the access fee, and K_0 is the transmission capacity under a Coasian two-part tariff, respectively.[13] In the case where $P_0 = 0$, (20) indicates the first-order condition with respect to transmission capacity for maximizing the expected value of social welfare in (17), because $\mathrm{E}(rnx) = \mathrm{E}(r|\Omega_1)K_0$. The expected price of congestion is equal to the marginal capacity cost of the transmission line in (20). Thus, the Coasian two-part tariff defined in (19) and (20) satisfies both the first-order condition for welfare maximization with respect to capacity ($(1 - P_0)\mathrm{E}(r|\Omega_1) = m$) and a zero-profit constraint on the transmission monopolist.

The Coasian two-part tariff comprising e_0 and K_0 results in a higher transmission capacity than average revenue regulation with $R = R_0$. This is because $\mathrm{E}(r|\Omega_1) = R > m$ under average revenue regulation. In comparison to the Coasian two-part tariff, average revenue regulation with $R = R_0$ reduces consumer surplus through a lower capacity, in spite of a lower access fee, which does not affect consumer surplus as long as congestion occurs.

The expected profits of the transmission monopolist become negative under average revenue regulation with $R = R_0$, because from (18)

$$\begin{aligned} R_0\mathrm{E}(nx) - m_0 - mK_a &= [(mK_0 + m_0)/K_0]K_a - m_0 - mK_a \\ &= m_0(K_a - K_0)/K_0 < 0. \end{aligned}$$

Thus, if $P_0 = 0$, the expected social welfare under the Coasian two-part tariff satisfying (19) and (20) is larger than that under average revenue regulation with $R = R_0$, which is not feasible in terms of the viability of the transmission sector.

4.2 Case 2: $P_0 > 0$

If $P_0 > 0$, the optimal access fee becomes either zero or positive under average revenue regulation. For a welfare comparison, suppose that R is set equal to the expected average revenue R_0 in (18). If $P_0 > 0$, a welfare comparison depends on whether the number of generators at node G is larger than the term $\Lambda R\mathrm{E}[-D'/\mathrm{y}|\Omega_0]$ in (13).

From (13), $e_a = 0$ if $P_0 > 0$ and $n < \Lambda R\mathrm{E}[-D'/\mathrm{y}|\Omega_0]$. Thus, an iso-average revenue contour intersects an iso-profit contour on the K axis at the optimum, as shown by point A in Figure 3.[14] At A, the iso-profit contour Π_1 that is centered around the unregulated monopoly optimum intersects the iso-average revenue contour with $R = R_0$, which is shown by the dotted line in the figure. The iso-welfare contour that passes through A is denoted by W_1 in the figure. For all iso-welfare contours that are centered around the welfare optimum, the following equation applies:

$$\lim_{e\to 0}\frac{de}{dK}\bigg|_{const.welfare} = \lim_{e\to 0}\frac{-E(\partial W/\partial K)}{E(\partial W/\partial e)} = \lim_{e\to 0}\frac{m-(1-P_0)\left\lfloor E(r|\Omega_1)+e/\overline{y}\right\rfloor}{eE(\partial n/\partial e)} = \infty . \tag{21}$$

Note that the access fee is zero at the optimum of welfare maximization. At A, the slope of the iso-average revenue contour with $R = R_0$ is less steep than that of the iso-profit contour Π_1, because otherwise $e_a > 0$. Point C represents the combination of K_0 and e_0, and C is to the right of A. The iso-profit contour Π_0, which is the locus of K and e that require profits equal to zero, intersects the iso-average revenue contour with $R = R_0$ at C. Since Π_1 is located closer to the unregulated monopoly optimum than Π_0, the expected profits of the monopolist under average revenue regulation with $R = R_0$ are strictly positive and higher than the expected profits under the Coasian two-part tariff, which become zero.

[Figure 3 here]

From (15),

$$(1 - P_0)R_0 \quad = \quad (1 - P_0)[(1 - P_0)\mathrm{E}(r|\Omega_1)K_a/\mathrm{E}(nx)] \quad > \quad m\,. \tag{22}$$

Rearranging terms in (22) yields

$$(1 - P_0)\mathrm{E}(r|\Omega_1) \quad > \quad m\mathrm{E}(nx)/[K_a\,(1 - P_0)] \quad = \quad m\{1 + [P_0/(1 - P_0)][\mathrm{E}(nx|\Omega_0)/K_a]\} \quad > m. \tag{23}$$

Inequality (23) implies that the expected price of congestion under average revenue regulation with $R = R_0$ exceeds the marginal capacity cost, while the expected price of congestion is equal to the marginal capacity cost under the Coasian two-part tariff satisfying (19) and (20). Thus, in comparison to the Coasian two-part tariff, average revenue regulation with $R = R_0$ results in the lower capacity of the transmission facility. Average revenue regulation leads to a decrease (an increase) in expected consumer surplus if the reduction of consumer surplus caused by a lower capacity is more (less) than the rise in consumer surplus caused by a lower access fee.

Whether the expected social welfare under average revenue regulation with $R = R_0$ is larger than that under the Coasian tariff satisfying (19) and (20) is not unambiguous for the case where $P_0 > 0$ and $n < \Lambda R\mathrm{E}[-D'/\mathrm{y}|\Omega_0]$. Figure 3 illustrates a case where the expected welfare under average revenue regulation with $R = R_0$ is higher than that under the Coasian two-part tariff. In this figure, the welfare optimum is closer to the iso-welfare contour W_1, which passes through A, than the iso-welfare contour W_2, which passes through C.

If $P_0 > 0$ and $n \geq \Lambda R\mathrm{E}[-D'/\mathrm{y}|\Omega_0]$, an iso-average revenue contour is tangent to an iso-profit contour at the optimum. Point A in Figure 4 indicates the optimum under average revenue regulation with $R = R_0$. The iso-profit contour that passes through A, denoted by Π_1, is located closer to the unregulated monopoly optimum than the zero-profit contour Π_0, and the expected profits of the monopolist under average revenue regulation with $R = R_0$ are strictly positive and higher than the expected profits under the Coasian two-part tariff, which become zero. Point C, where the iso-average revenue contour with $R = R_0$ intersects the zero-profit contour, is either to the right or to the left of point A. Figure 4 illustrates a case where C is to the right of A, and the slope of the iso-welfare contour W_1 at A is less steep than the slope of the iso-average revenue contour with $R = R_0$ at A. If C is to the right of A, $K_0 > K_a$ and $e_0 > e_a$.

[Figure 4 here]

The slope of the iso-welfare contour at A is derived by substituting the first-order conditions in (13) and (14) into $de/dK|_{\text{const.welfare}}$ in (21):

$$\left.\frac{de}{dK}\right|_{const.welfare} = \frac{(1-P_0)KE(1/D'|\Omega_1)+\Lambda[(1-P_0)R_0-m]}{-P_0\left[n+\Lambda R_0E(D'/y|\Omega_0)\right]} \quad . \tag{24}$$

From (16) and (24), the following equation holds at A:

$$\frac{de_a}{dK_a}-\left.\frac{de}{dK}\right|_{const.welfare} = \frac{-n[(1-P_0)R_0-m]+(1-P_0)R_0KE(D'/y\,|\,\Omega_0)E(1/D'\,|\,\Omega_1)}{P_0R_0E(D'/y\,|\,\Omega_0)[n-\Lambda R_0E(-D'/y\,|\,\Omega_0)]} \tag{25}$$

In the case where $P_0 > 0$ and $n \geq \Lambda R\mathrm{E}[-D'/y|\Omega_0]$, the denominator on the right-hand side of (25) is strictly negative. Thus, if the nominator on the right-hand side of (25) is strictly negative at A, $de_a/dK_a > de/dK|_{\text{const.welfare}}$, and the expected social welfare under average revenue regulation with $R = R_0$ is larger than that under the Coasian two-part tariff in the case where $0 < e_a < e_0$. The negative nominator on the right-hand side of (21) indicates

$$(1-P_0)R_0 > \frac{m}{1-E\left(\frac{D'}{y}\middle|\Omega_0\right)E\left(\frac{\bar{y}}{D'}\middle|\Omega_1\right)} \quad . \qquad (26)$$

Since $\bar{y} > y$, the denominator on the right-hand side of (26) is strictly negative for any linear demand function, which exhibits the constant value of D' in all states of the world. Inequality (26) also holds if the demand function in question has a constant price elasticity.[15] Thus, if $0 < e_a < e_0$, the expected social welfare under average revenue regulation with $R = R_0$ is larger than that under the Coasian two-part tariff satisfying (19) and (20) for any linear or log-linear demand function.[16]

Appendix C presents a numerical example in which a two-part tariff for transmission demand under average revenue regulation with $R = R_0$ leads to a higher social welfare than the Coasian two-part tariff satisfying (19) and (20) for a relevant rage of fixed costs of the transmission line connecting nodes G and L. In this example, if $R = R_0 = 2.95$, which corresponds to $m_0 = 20$, the optimal access fee is zero under average revenue regulation and both transmission capacity and expected consumer surplus are lower than those under the Coasian two-part tariff. Average revenue regulation with $R = 2.95$, however, results in the expected profits of the monopolist and social welfare that are higher than those under the Coasian two-part tariff with $R_0 = 2.95$. If $R = R_0 = 6.35$, which corresponds to $m_0 = 45$, the optimal access fee under average revenue regulation is positive and smaller than that under the Coasian two-part tariff. Thus, average revenue regulation with $R = 6.35$ results in a larger social welfare in comparison to the Coasian two-part tariff with $R_0 = 6.35$.

5. CONCLUSION AND POLICY IMPLICATIONS

Assuming that an independent electricity transmission monopolist applies a two-part tariff comprising a variable congestion price and a fixed non-negative access fee, this paper examines the long-run effects of constraining the expected average revenue of the profit maximizing transmission monopolist on its choice of transmission investment and pricing. In comparison to unregulated monopoly profit maximization, average revenue regulation lowers the access fee unless the probability that congestion occurs becomes unity. Average revenue regulation raises transmission capacity and improves expected consumer surplus in comparison to unregulated monopoly profit maximization. This finding excludes the possibility, from a welfare viewpoint, that average revenue regulation is worse than no regulation, which has been a concern about average revenue regulation (Cowan, 1997).

The superiority of a two-part tariff over a uniform price may hold under average revenue regulation if the probability that congestion occurs becomes less than unity. This finding contrasts with that of Ordover and Panzar (1982), who argue that for the input required in fixed proportion to output such as electric power transmission, a two-part tariff is inferior to a uniform price in the presence of increasing returns to scale technology from either a welfare or monopoly profit-maximizing standpoint. They also argue that a two-part tariff cannot be justified in transmission pricing. On the contrary, this paper shows that a two-part tariff can be more desirable than a uniform price and that the policy of applying a two-part tariff to transmission pricing, which has been implemented in many countries, is justified with average revenue regulation .

The finding that average revenue regulation can achieve higher welfare than a Coasian two-part tariff indicates that the application of average revenue regulation to transmission pricing may lead to a substantial improvement in economic efficiency. A Coasian two-part tariff, in which the unit price is set equal to marginal cost and all profits are extracted via the access fee, is the most efficient form of cost-of-service regulation. However, even in comparison to this 'best' form of cost-of-service regulation, average revenue regulation can achieve a higher welfare and be more allocatively efficient. Thus, average revenue regulation is expected to achieve a significant gain of allocative efficiency in comparison to traditional cost-of-service regulation, which has been applied to the transmission sector in many countries. Since average revenue regulation, which provides a transmission monopolist with an incentive to reduce costs, is more efficient in production than cost-of-service regulation, average revenue regulation can be a promising policy alternative that results in a substantial improvement of economic efficiency.

For average revenue regulation to be allocatively efficient, however, the regulator must consider the probability that congestion occurs, the level of the access fee, and the demand structure of electricity. The occurrence of congestion in transmission networks is crucial, because if transmission congestion frequently occurs, the fixed fee may not be necessary for the transmission monopolist who can completely cover investment costs through the revenue from congestion pricing alone. In the case where a transmission line in question is always constrained, average revenue regulation may result in an efficiency loss in comparison to cost-of-service regulation.

From a welfare viewpoint, the superiority of average revenue regulation over cost-of-service regulation may not hold when the high access fee discourages the entry of generators, thereby raising electricity prices and reducing consumer surplus. Average revenue regulation can be allocatively more efficient than cost-of-service regulation in the case where average revenue regulation results in a lower access fee and capacity level than cost-of-service regulation. Average revenue regulation with a low access fee is also appropriate from the viewpoint of competition policy because a lower access fee induces more competition in electricity markets.

The demand structure of electricity also affects the welfare advantage of average revenue regulation over cost-of-service regulation. The finding that for any linear or log-linear demand function the expected social welfare under average revenue regulation can be larger than that under the Coasian two-part tariff implies the necessity of investigating the demand structure of electricity prior to the choice of a regulatory scheme for transmission pricing. A demand function of electricity is often approximated by either a linear or a log-linear form in the policy analysis of electricity markets.[17] If electricity demand is well described by either a linear or a log-linear function of electricity price, average revenue regulation has the potential to improve allocative efficiency in comparison to cost-of-service regulation.

NOTES

1. For simplicity, this paper assumes that transmission capacity can be continuously expanded. In practice, however, transmission investments are lumpy and the equality of the marginal benefit with the marginal cost of transmission does not necessarily hold (Leautier, 2000).

2. The paper assumes an independent transmission company that does transmission investment, maintains the system, bears the costs, and collects the revenues, which is refereed to as a ‘Transco’ model (Vogelsang, 2001; Joskow and Tirole, 2003). An alternative to the Transco model, which is referred to as a ‘merchant transmission’ model, is based on decentralized property rights for the merchant investors, and relies on competitive,

market-driven transmission investment.

3. An alternative to a two-part tariff is Ramsey pricing, which can be inferior to a two-part tariff in the presence of significant economies of scale (Vogelsang, 2001, p.144). A two-part tariff has been often applied to transmission pricing in practice. For the practice of transmission pricing in various countries, see Green (1997), for instance. Deng and Oren (2001) investigate a complex form of non-linear pricing of transmission.

4. The paper does not consider a real options approach to transmission investment, which is investigated by Martzoukos and Teplitz-Sembitzky (1992), and Saphores et al. (2004).

5. The effects of imperfect competition on congestion pricing and the fixed access fee are investigated by Matsukawa (2005) in a more general setting.

6. An interpretation of this setting is that generation costs at node L are large enough to make the location of generation plants at L not viable over a relevant range of production. This simple model ignores loop flow, which lets power flows on one line raise or decrease the capacity of other lines.

7. To focus on the effects of regulation on both the investment and pricing of electricity

transmission, the paper does not consider generators' choice of where to site their plants, which is analyzed by Hogendorn (2003). Hogendorn (2003) does not investigate the choice of a transmission tariff, assuming that the independent transmission company and generators make investment decisions under an exogenous price of transmission.

8. An alternative form of regulating transmission pricing is to cap a monopolist's *total* revenue, which has been adopted in Norway, Australia and the United Kingdom (Makholm et al., 2000). If the expected *total* revenue is capped in the model of this paper, the optimal access fee under the total revenue constraint becomes the same as e_m in (8) and the optimal capacity becomes less than that satisfying (9). Thus, in the model of this paper, total revenue regulation is worse than no regulation from a welfare point of view. In the model of this paper, a profit-maximizing transmission monopolist subject to average revenue regulation faces a trade-off between the revenue from the access fee and that from the congestion price, while the monopolist subject to a total revenue constraint would only change its transmission capacity to maximize the expected profits.

9. This formula for average revenue regulation follows Armstrong and Vickers (1991), and Cowan (1997).

10. Rate-of-return regulation, which allows a transmission company to earn a fair return on

its investment, is a familiar form of regulating transmission pricing on a cost-of-service basis.

11. This paper does not consider the effect of regulation on productive efficiency. If the regulator cannot observe the monopolist's efforts in reducing investment costs, a Coasian two-part tariff satisfying (19) and (20) may lead to a loss of productive efficiency, because the monopolist does not have an incentive to lower cost parameters m_0 and m. Average revenue regulation is expected to achieve a higher efficiency of production than the Coasian two-part tariff, because the monopolist subject to average revenue regulation can increase its profits by reducing cost parameters m_0 and m.

12. If $P_0 = 0$, uniform pricing with a zero-profit constraint can be an alternative form of regulation for welfare comparison. This form of regulation sets the access fee equal to zero and leads to transmission capacity that results in zero profits. If R is set equal to the expected average revenue earned by the monopolist under the uniform pricing with a zero-profit constraint, the capacity of the transmission line under the average revenue regulation is the same as that under uniform pricing with a zero-profit constraint. Thus, average revenue regulation results in the same level of the expected social welfare as that under uniform pricing with a zero-profit constraint.

13. Traditional cost-of-service regulation usually sets e equal to the embedded cost of

transmission as in postage stamp rates, and transmission capacity is not directly regulated. The regulator can affect the monopolist's choice of transmission investment through a regulatory process of examining transmission investment planning. Congestion pricing is not applied to traditional cost-of-service regulation. For welfare comparison, however, congestion pricing is assumed to be applied to the transmission sector and the regulator is assumed to be able to determine both the access fee and the transmission capacity so as to make the monopolist's profits zero when a Coasian two-part tariff is applied to the transmission sector.

14. At the optimum for a profit-maximizing monopolist under a binding constraint on its expected average revenue, the iso-average revenue contour must be upward sloping because of the condition in (15). At this optimum, the iso-average revenue contour must be convex to the origin. The convexity of the iso-average revenue contour, which is proved by a positive value of the differentiation of $\mathrm{d}e/\mathrm{d}K$ for constant R with respect to K, is also found in Armstrong and Vickers (1991), and Cowan(1997).

15. The denominator on the right-hand side of (26) is $1 - \mathrm{E}(p/\varepsilon|\Omega_1)\mathrm{E}(\varepsilon/p|\Omega_0)$ where ε is the price elasticity of electricity demand. Thus, if the electricity demand function is log-linear in electricity price, the denominator on the right-hand side of (26) is strictly negative.

16. In the case where $e_a > e_0$, for the expected social welfare under average revenue regulation with $R = R_0$ to be larger than that under the Coasian two-part tariff, de_a/dK_a must be less than $de/dK|_{\text{const.welfare}}$. If $de_a/dK_a < de/dK|_{\text{const.welfare}}$, the left-hand side of (26) must be less than the right-hand side of (26). Thus, in the case where $e_a > e_0$, the expected social welfare under average revenue regulation with $R = R_0$ is smaller than that under the Coasian two-part tariff if the demand function for electricity is either linear or log-linear.

17. See, for instance, Green and Newbery (1992) who assume a linear demand function in the evaluation of alternative scenarios for deregulating the United Kingdom wholesale market of electricity.

APPENDIX A: Derivation of the Partial Derivatives in Table 1

To see the response of the electricity price to a change in the access fee when the transmission capacity constraint is binding, firstly total differentiation of (4) yields

$$\frac{\partial p}{\partial e} = 0 \ . \tag{A1}$$

Then, totally differentiating (2), and substituting (A1) and the first-order condition for generators' profit maximization yields

$$\frac{\partial r}{\partial e} = -\frac{1}{y} \ . \tag{A2}$$

Equations (A1) and (A2) lead to the response of firm supply to the access fee:

$$\frac{\partial y}{\partial e} = \frac{y_p}{y} \quad , \tag{A3}$$

where $y_p \equiv \partial y/\partial p$. Note that $\partial y/\partial r = -(\partial y/\partial p)$ for perfectly competitive supply if transmission demand is equal to the supply of electricity, i.e., $nx = ny$. Finally, totally differentiating (3), and substituting (A1) and (A2) yields

$$\frac{\partial (nx)}{\partial e} = 0 , \tag{A4}$$

and

$$\frac{\partial n}{\partial e} = -\frac{n y_p}{y^2} . \tag{A5}$$

As for the response of the electricity price to a change in the capacity of the transmission facility, total differentiation of (4) yields

$$\frac{\partial p}{\partial K} = \frac{1}{D'} \quad . \tag{A6}$$

Then, totally differentiating (2) and substituting (A6) yields

$$\frac{\partial r}{\partial K} = \frac{1}{D'} \quad , \tag{A7}$$

Equations (A6) and (A7) lead to the response of firm supply to a change in transmission capacity:

$$\frac{\partial y}{\partial K} = 0 \quad . \tag{A8}$$

Finally, totally differentiating (3), and substituting (A6) and (A7) yields

$$\frac{\partial (nx)}{\partial K} = 1 \quad , \tag{A9}$$

and

$$\frac{\partial n}{\partial K} = \frac{1}{y} \quad . \tag{A10}$$

Since the unit price of congestion must be zero in the states in which the capacity constraint is not binding, firm supply is the function of the electricity price, and a change in the capacity of the transmission facility does not affect endogenous variables in these states. Total differentiation of (2) yields

$$\frac{\partial p}{\partial e} = \frac{1}{y} \quad , \tag{A11}$$

and

$$\frac{\partial y}{\partial e} = \frac{y_p}{y} \quad . \tag{A12}$$

Totally differentiating (3) and substituting (A11) and (A12) yields

$$\frac{\partial (nx)}{\partial e} = \frac{D'}{y} \quad , \tag{A13}$$

and

$$\frac{\partial n}{\partial e} = \frac{D' - n y_p}{y^2} \quad . \tag{A14}$$

APPENDIX B: Proof of Proposition 2

If $e_a > 0$, totally differentiating E(*Π*) in (5) and substituting the first-order conditions (13) and (14) yields

$$dE(\Pi_a) = dK_a \Lambda[-(1-P_0)R + m] - de_a \Lambda R P_0 E\left[\frac{D'}{y}\middle|\Omega_0\right] \quad , \tag{A15}$$

where E(*Π_a*) is the expected profits of the transmission monopolist subject to average revenue regulation at the optimum. Differentiating (A15) with respect to *R* and rearranging terms yields

$$\frac{dE(\Pi_a)}{dR} = (-\Lambda)\frac{dK_a}{dR}\left\{(1-P_0) + P_0 E\left[\left.\frac{D'}{y}\right|\Omega_0\right]\frac{de_a}{dK_a}\right\}, \tag{A16}$$

Substituting (16) into (A16) yields

$$\frac{dE(\Pi_a)}{dR} = (-\Lambda)\frac{dK_a}{dR}\left(\frac{m}{R}\right) \ . \tag{A17}$$

In (A17), the left-hand side must be strictly positive, because at the optimum for the transmission monopolist subject to average revenue regulation,

$$\begin{aligned}
\frac{dE(\Pi_a)}{dR} &= \frac{d}{dR}\left[E(nx)R - mK_a - m_0\right] \\
&= E(nx) + RP_0 E\left(\left.\frac{D'}{y}\right|\Omega_0\right)\frac{de_a}{dR} + [(1-P_0)R - m]\frac{dK_a}{dR} \\
&= E(nx) + RP_0 E\left(\left.\frac{D'}{y}\right|\Omega_0\right)\frac{de_a}{dK_a}\frac{dK_a}{dR} + [(1-P_0)R - m]\frac{dK_a}{dR} \\
&= E(nx) > 0
\end{aligned} \tag{A18}$$

From (A17) and (A18), dK_a/dR < 0 if $e_a > 0$ and the constraint on the expected average revenue of the transmission monopolist is binding ($\Lambda > 0$) .

If $e_a = 0$, totally differentiating E(Π) in (5) and substituting the first-order condition (12) and $e_a = 0$ yields

$$dE(\Pi_a) = dK_a \Lambda[-(1-P_0)R + m] \tag{A19}$$

Differentiating (A19) with respect to R and rearranging terms yields

$$\frac{dE(\Pi_a)}{dR} = (-\Lambda)\frac{dK_a}{dR}(1-P_0) \tag{A20}$$

From (A18) and (A20), $dK_a/dR < 0$ if $e_a = 0$ and the constraint on the expected average revenue of the transmission monopolist is binding. Thus, for $e_a \geq 0$, the binding constraint on the expected average revenue of the monopolist increases its transmission capacity in equilibrium.

Q.E.D.

APPENDIX C: A Numerical Example

Using a simple numerical example, this appendix section illustrates a case where a demand function of electricity is linear and the positive optimal access fee under average revenue regulation with $R = R_0$ is lower than that under a Coasian two-part tariff satisfying (19) and (20) so that expected social welfare under average revenue regulation is larger than that under a Coasian two-part tariff. The optimal solutions are computed and compared between average revenue regulation with $R = R_0$ and the Coasian two-part tariff. The optimal solutions are also computed for the expected welfare maximization and unregulated monopolist's profit maximization as a reference.

The demand function $D(p, \omega)$ at node L is assumed to be linear and take the following form:

$$D(p, \omega) = 20 - p + \omega \quad . \tag{A21}$$

A stochastic variable ω is assumed to be uniform and distribute on [0, 20]. Thus, the probability that each state occurs is given by 0.05. The cost function of each firm at node G is assumed to be linear and take the following form:

$$C_d = 5 + 10y^2 \quad . \tag{A22}$$

Then, the marginal cost of generation is given by $20y$ and the firm supply function becomes

$$y(p, r) = (p - r)/20 \quad . \tag{A23}$$

Finally, the cost function of the transmission sector is assumed to be

$$C_m = m_0 + 1.25K \tag{A24}$$

where the fixed cost m_0 is assumed to vary from 16 to 46. Since the fixed costs less than 16 violate a condition for effective regulation in (15), these values are not assumed in computation. The fixed costs exceeding 46 are also out of consideration, because the Coasian two-part tariff is not feasible for these values of fixed costs.

Based on these functional forms in (A21)-(A24), the optimal values for profit maximization under the binding constraint on the expected average revenue are obtained by simultaneously solving (2), (3), (4), (11) with equality, (13) and (14). The value of R_0 is obtained from the Coasian two-part tariff, which is computed by simultaneously solving (2), (3), (4), (18), (19) and (20). A Gauss-Newton method is used to solve these simultaneous-equation systems.

[Table 2 here]

Table 2 summarizes computation results of key variables for the expected profit maximization under the binding constraint on the expected average revenue. For comparison, the results of unregulated monopoly profit maximization and welfare maximization are also presented in the table. The variable *CS* is consumer surplus, and *R* is the expected average revenue. For any relevant value of the fixed costs, the probability that no congestion occurs becomes strictly positive ($P_0 > 0$) under all objective functions, and the optimal access fee under average revenue regulation is lower than that under a Coasian two-part tariff ($e_0 > e_a$).

For the identical value of the expected average revenue, both the capacity of the transmission facility and the access fee under the Coasian two-part tariff are larger than those under average revenue regulation in Table 2. Average revenue regulation leads to a higher price of congestion but a larger number of firms at node G than the Coasian two-part tariff. Average revenue regulation results in higher expected welfare than the Coasian two-part tariff. In fact, for any relevant value of the expected average revenue, the expected welfare under average revenue regulation is higher than that under the Coasian two-part tariff in this numerical example.

This numerical example shows that if the demand function of electricity is linear and a positive access fee under average revenue regulation with $R = R_0$ is lower than that under a Coasian two-part tariff satisfying (19) and (20), average revenue regulation performs better than a Coasian two-part tariff from the viewpoint of social welfare. If $e_a = 0$, from the viewpoint of consumer surplus, average revenue regulation can be worse than a Coasian two-part tariff, as shown by the case of $R = 2.95$.

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Table 1. Effects of the access fee and transmission capacity on key endogenous variables
(directions of changes are indicated by signs in parentheses)

a: States in which congestion occurs

$\partial p/\partial e$	$\partial r/\partial e$	$\partial y/\partial e$	$\partial n/\partial e$	$\partial (nx)/\partial e$
0	$-1/y$	y_p/y	$-n\, y_p/y^2$	0
	(−)	(+)	(−)	

(continued)

$\partial p/\partial K$	$\partial r/\partial K$	$\partial y/\partial K$	$\partial n/\partial K$	$\partial (nx)/\partial K$
$1/D'$	$1/D'$	0	$1/y$	1
(−)	(−)		(+)	(+)

b: States in which no congestion occurs

$\partial p/\partial e$	$\partial y/\partial e$	$\partial n/\partial e$	$\partial (nx)/\partial e$
$1/y$	y_p/y	$(D'-n\, y_p)/y^2$	D'/y
(+)	(+)	(−)	(−)

Table 2. Optimal values of key variables under alternative objective functions

	E(y)	E(p)	E(r)	n	K	$1-P_0$	e	E(CS)	E(W) + m_0	R
Welfare maximization	0.70	15.2	1.25	21.1	16.9	0.35	0	111.4	111.4	1.43
Profit maximization	0.86	22.2	5.06	9.1	8.1	0.71	2.4	30.4	82.8	8.01
Average revenue: $m_0 = 45$	0.77	20.3	4.91	12.5	10.0	0.70	1.0	46.9	95.7	6.35
Coasian tariff: $m_0 = 45$	0.98	20.9	1.25	9.3	10.5	0.35	4.8	42.8	87.8	6.35
Average revenue: $m_0 = 20$	0.70	16.8	2.72	18.8	14.3	0.52	0	88.6	109.6	2.95
Coasian tariff: $m_0 = 20$	0.78	16.8	1.25	17.0	15.1	0.35	1.2	89.1	109.1	2.95

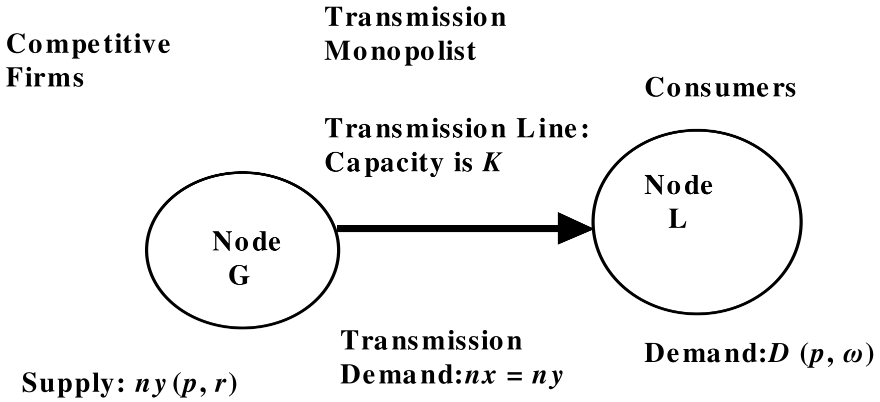

Figure 1. Two-node transmission model

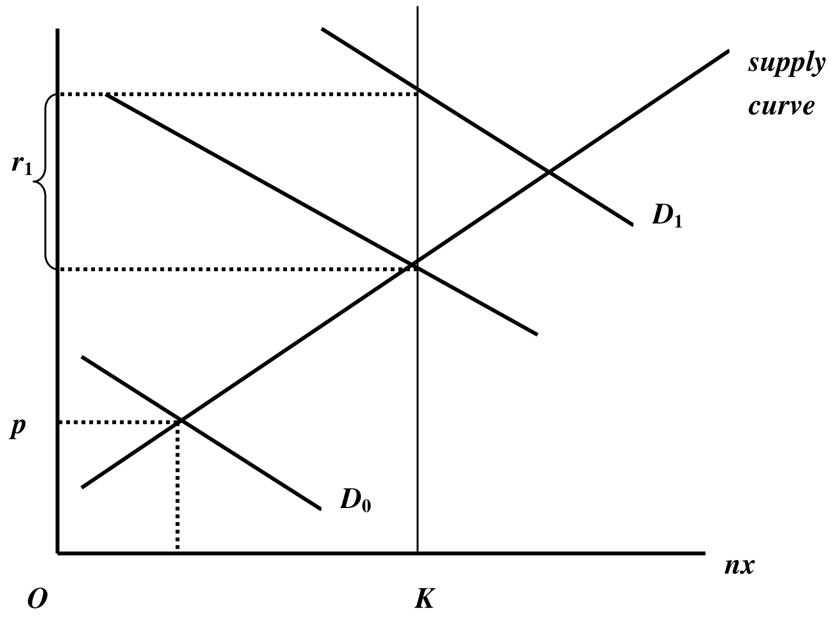

Figure 2. Congestion pricing with demand uncertainty:
an example of linear demand and supply curves

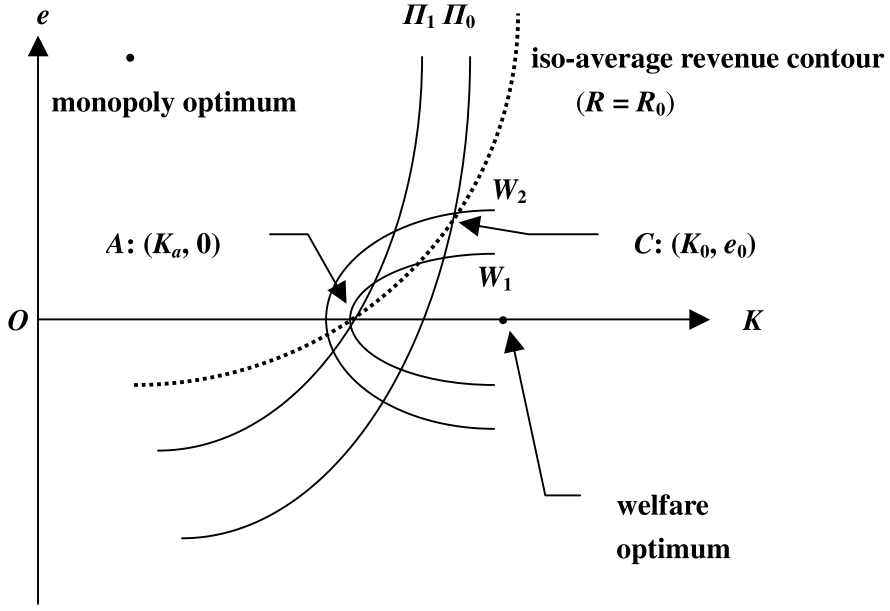

Figure 3. Welfare comparison between average revenue regulation and a Coasian two-part tariff: $e_a = 0$

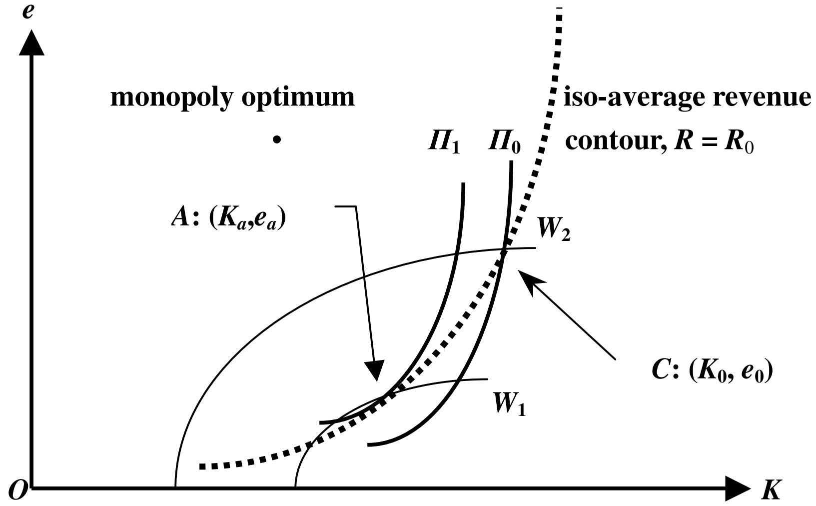

Figure 4. Welfare comparison between average revenue regulation and a Coasian two-part tariff: $e_a > 0$