Electricity Transmission Pricing Principles*

M. Soledad Arellano
Universidad de Chile
sarellano@dii.uchile.cl
Mailing Address: República 701
Santiago, Chile

Pablo Serra
Universidad de Chile
pserra@dii.uchile.cl
Mailing Address: República 701
Santiago, Chile

Abstract

This article lays down economic principles that should govern electricity transmission pricing when peak-load pricing is used to set tariffs. Transmission systems perform three different functions: to transport energy, to substitute for generation capacity, and to increase competition in the system. It is shown that the generating companies should absorb long-run marginal costs so that the proper investment signals are given, whereas fixed costs should be borne by the transmission beneficiaries. In this paper it is shown that the latter differ depending on the function performed by the transmission system.

Classification JEL: L94, L51

Key words: Electricity industry, transmission pricing

---

* This article is a substantially revised version of a paper written for HQI Transelec Chile SA. Its contents, however, are the authors' exclusive responsibility. Feedback from Juan Carlos Araneda, Eduardo Bitrán, Guillermo Espinosa, Alex Galetovic and Juan Pablo Montero is acknowledged. Arellano is thankful for Fundación Andes' funding, granted under Agreement C-13860.

1. Introduction

The purpose of this article is to lay down the economic principles that should govern electricity transmission pricing when peak-load pricing is used to set energy and capacity tariffs. These principles should be such that the resulting tariffs give the proper signals to the various stakeholders in the electric sector so that both their short-term (operational) and long-term (investment and localization) decisions lead to efficient market equilibrium. Although the problem of determining the optimal transmission pricing has been stated in the literature for some time (see, for example, Schweppe et al, 1988; Hogan, 1992; Oren et al, 1994; and Chao & Peck, 1996), the diversity of suggested approaches illustrates the fact that there is no consensus regarding the best methodology. We believe that this is due to a failure to recognize of the different functions fulfilled by transmission systems.

The transmission of electricity is a natural monopoly on account of the large economies of scale involved in its development. Although marginal cost pricing of a natural monopoly is efficient, it prevents a company from covering all of its costs. Thus, if prices are to be set at marginal cost, it is necessary to introduce a fixed charge for users in order to bridge the revenue gap. An efficient way of doing it is based on the surplus that each agent gets from consuming the good or service. This solution is efficient because it does not exclude any user that may contribute to funding the portion of the company's costs that is not covered by the variable charge.[1]

This allocation criterion has the advantage of being a general rule. However, its practical application is not devoid of difficulties since it is not easy to measure each agent's benefit. Electricity transmission features an additional difficulty: that the various services simultaneously provided by transmission might each have different beneficiaries. Indeed, the transmission system transports energy, substitutes for installed capacity, and increases competition on the electricity market. This paper illustrates through simple

[1] More generally, any allocation that fails to exclude consumers capable of paying the variable cost and contributing – even minimally – to the fixed cost is efficient.

examples that separately show the benefits and beneficiaries of transmission in its various functions, how such functions may be priced.

In estimating the dividends that a transmission line contributes to the various stakeholders in the system, the various benefits associated to the transmission system should be measured. Evidently, it is also necessary to verify that the aggregate benefits that accrue to all of the transmission system's users should be higher than the fixed cost to be prorated among these; otherwise such a facility is inefficient. The subsequent evaluation of a line should therefore take both of the above criteria into account. Thus, in order to focus on the design of pricing systems that lead to a socially efficient generating portfolio, we implicitly assume that a social evaluation is carried out beforehand to determine whether the benefit of laying each transmission line is higher than the cost thereof. [2]

The distribution of benefits among consumers and generating companies depends on the pricing system used to charge for the energy and capacity traded on the market. This analysis uses peak-load pricing, a system that provides for an optimal, decentralized solution (see Boiteux, 1960, and Joskow, 1976). When demand is inelastic, an efficient method is to charge at every moment a price for energy equivalent to the marginal cost of generating it; a charge for capacity should be added to peak-hour consumption. Such a capacity charge corresponds to the marginal cost of increasing peak-hour capacity. We also assume that the transmission system involves three types of cost: operating (or short-run marginal) cost, variable investment cost and fixed investment cost. The long-run marginal cost is equivalent to the addition of the former two.

The transportation function of a transmission system provides for meeting demand with the energy produced at the most efficient plants in the system, even though such facilities may be distant from the consumption centers. This function may be of benefit both to generating companies and consumers. In a dual-technology generation model characterized by no capacity restrictions, inelastic demand, and plants technologies that may operate with a plant factor equal to one, it is shown that the efficient way of allocating

[2] Designing optimal networks is certainly a complex task.

transmission costs is to have the long-run marginal cost of transmission be borne by the generating companies located outside consumption centers, whereas the fixed investment cost is distributed among consumers. If for some reason the capacity of the least-operating-cost technology is restricted, the generating companies located outside the consumption center and using such a technology can obtain economic profits. Therefore, the fixed investment cost should be distributed between consumers and such companies, in proportion to the benefit obtained by each group.

The use of transmission as a substitute for installed capacity is illustrated by the interconnection of two electric systems featuring peak consumption at different times of the day. In this case the transmission system provides for decreasing overall installed capacity, because both the local and the neighboring system's generation meet each system's peak. In this example there are capacity charges both for peak consumption within the system and for consumption during each locality's peak demand; the combination of both allows generating companies to finance investment in generation and in transmission. Just as in the case of the transportation function, it is shown that the long-run marginal cost of the transmission system should be borne by the generating companies, while the fixed cost should be allocated to consumers.

The use of the transmission system as a substitute for installed capacity also applies in relation to the plants that should be maintained in a system to provide reserves for supply and/or demand contingencies. In particular, the transmission system may provide for a given level of reliability (understood as the probability of failure) with lower backup capacity, or else, for a lower probability of failure keeping the size of backup capacity constant. If consumers are paying for backup capacity, they benefit on this account by making lower payments for capacity.

Finally, the transmission system increases competition on the electricity market, and can even introduce it in isolated locations. This function is no different from that of any highway that links two markets where homogeneous goods are produced and sold. In fact, the existence of a transmission line determines that any company with some degree of market power at the local level may be threatened by the entry of production from "the other side of the line". This threat restricts the amount of market power that generating companies might exercise over their respective markets. Therefore, the transmission system directly benefits consumers on this account. It follows from the above that consumers should finance the fixed cost of the lines responsible for increasing competition. In fact, the loss of market power is detrimental to generating companies; for this reason, they are not willing to finance the respective line.

The following sections address each of the functions of the transmission system independently, with special emphasis on defining which agents benefit from the line and the implications thereof in terms of pricing. The final section presents the conclusions.

2. The Transmission System as an Energy Carrier

Let us begin by discussing how transmission should be priced when its sole function is to transport energy. To do this, we begin by summarizing the traditional peak-load pricing system without transmission. This involves geographically concentrated, inelastic energy demand. We assume that there are two generation technologies, 1 and 2, whose fixed annual costs are f_1 and f_2 per MW, respectively. (These costs include annualized investment costs.) For their part, operating costs are c_1 and c_2 per MWh. Without loss of generality, we assume that $f_1 > f_2$, and $c_1 < c_2$. We use the function q(t) to denote the system load curve, where q(t) designates consumption at the t-th highest consumption hour. Finally, we assume that both technologies may operate with a plant factor of 1, that generation at the plants may vary instantly and without costs, and that no failures occur. Generating plants are dispatched by merit order, that is, they start producing from the lowest to the highest operating cost until demand is met[3]. On this set of assumptions, the problem of minimizing the total cost of the electric system is formalized as follows:

[3] In actual fact this is rather more complex, however, since the presence of indivisibilities in the operation of the plants can alter the natural order of the entry thereof, thus giving rise to what the literature has called Unit Commitment Problem (see Fischer & Serra, 2003)

$$\underset{k_1,k_2}{Min}\left\{f_1k_1 + f_2k_2 + c_2\int_0^{t(k_1)}(q(t)-k_1)dt + c_1k_1t(k_1) + c_1\int_{t(k_1)}^{T}q(t)dt\right\}$$

$$s.a.: \quad k_1 + k_2 \geq q^M$$

where q^M designates peak demand, k_1 y k_2 the installed capacity of plants type 1 and 2, respectively, and T the number of hours in the year. The statement of the problem assumes optimal use of installed capacity. In fact, between $t(k_1)$ and T hours, demand is met by type-1 plant generation, since installed capacity renders it feasible and it is cheaper than using type-2 plant generation. Between 0 and $t(k_1)$ hours, type-2 plants generate the demand unmet type-1 plants (see Figure 1). From the consumer's point of view, the relevant variable is $t(k_1)$, since it shows the number of hours during which they must pay a higher price for energy.

The Kuhn-Tucker conditions for the above problem are:

$$f_1 - t(k_1)\Delta c - \boldsymbol{l} \geq 0 \qquad k_1(f_1 - t(k_1)\Delta c - \boldsymbol{l}) = 0$$

$$f_2 - \boldsymbol{l} \geq 0 \qquad k_2(f_2 - \boldsymbol{l}) = 0$$

where $Df = f_1 - f_2$ and $Dc = c_2 - c_1$, with Dc and Df positive, given the assumptions. The objective function is convex, thus the optimal solution is:

$$t^* = Min\left(\frac{\Delta f}{\Delta c}, T\right)$$

The solution that minimizes the overall cost of the system is $k_1^* = q(t^*)$, and $k_2^* = q^M - k_1^*$. When $t^* = T$ only type-2 plants are set up.

A pricing system in line with the optimal solution is an energy charge equal to the operating marginal cost of the most expensive plant in operation (type-1 or type-2 plant, depending on the hour) and a capacity charge for peak consumption equal to the investment cost of type-2 plants. This is the traditional peak-load pricing system[4]. The Kuhn-Tucker conditions show that if the composition of the generation installed capacity is optimal, neither type of plant obtains rents. This pricing system leads a decentralized system to the optimal solution. Type-2 plants never have economic gains. Assuming free entry to the generation industry, type-1 plants will enter up to the point when they have no profits either; this happens when type-2 plants operate during t^* hours.

The above analysis omitted any spatial consideration. Let us imagine now that type-2 plants are located in the demand center, but type-1 plants are located elsewhere[5]. Let us assume that the investment cost of the transmission line that links both locations has a fixed component, p_0, and a variable component, p_1. Therefore, the investment cost of a transmission system with capacity K is p_0+p_1K. Additionally, transporting energy involves a variable operating cost c_t, which for the sake of simplicity is assumed to be constant. We also assume that $c_1+c_t < c_2$, because otherwise only type-2 plants would be set up. The problem of minimizing the cost of the integrated system is:

$$\underset{k_1,k_2}{Min}\left\{f_1k_1 + f_2k_2 + c_2\int_0^{t(k_1)}(q(t)-k_1)dt + (c_1+c_t)k_1t(k_1) + (c_1+c_t)\int_{t(k1)}^{T}q(t)dt + p_0 + p_1k_1\right\}$$

$$s.a.: \quad k_1 + k_2 \geq q^M$$

Note that, without losing generality, transmission capacity has been assumed to match the demand $(K = k_1)$. The Kuhn-Tucker conditions are:

$$f_1 + p_1 - (\Delta c - c_t)t(k_1) - \lambda \geq 0 \qquad k_1(f_1 + p_1 - (\Delta c - c_t)t(k_1) - \lambda) = 0$$

[4] At the peak demand hour, the price is higher than at the remaining hours. This is possible because each hour's demand has been assumed to be inelastic. Electricity demand, however, is elastic. In fact, there is evidence that users respond to price signals by shifting consumption from one hour to another. In practice, in countries using peak-load pricing, capacity payments correspond to the highest readings in, e.g., 10% of the hours with the highest consumption in the system; this figure is subsequently corrected by a coincidence factor. Balasko (2001) performs a theoretical general equilibrium analysis of pricing with elastic demand.

[5] This location may respond to the geographical location of fuels or hydrological resources, or to the existence of environmental restrictions that hinder the construction of type-1 plants near the consumption zones.

$f_2 - \lambda \geq 0 \qquad\qquad k_2(f_2 - \lambda) = 0$

Therefore the optimal solution is (see Figure 2):

$$\hat{t} = Min\left(\frac{\Delta f + p_1}{\Delta c - c_t}, T\right)$$

To reach the optimal solution, the pricing scheme for energy and capacity is similar to the case that involves no transmission, except that when only type-1 plants are operating, the marginal cost is $c_1 + c_t$. In other words, the price of energy when only type-1 plants are in operation includes transmission operating costs. For their part, these plants must pay both the marginal investment cost (p_1) and the operating cost (c_t) of transmission. Note that type-2 plants are in operation for a longer time than when no transmission is involved ($\hat{t} > t^*$), thus allowing type-1 plants to obtain higher energy sales revenues per unit of installed capacity. Such revenues, in turn, allow them to absorb the variable investment cost of transmission[6] (see Figure 2).

This pricing system does not allow for financing the fixed cost p_0 of the transmission line. Who should pay for it? In the solution that maximizes social welfare, generating companies have no economic gains; therefore, if the transmission line is socially profitable, the fixed cost of transmission should necessarily be borne by the consumers. In this regard, it should be borne in mind that the transmission line is justified only if the cost thereof is lower than the social benefit it generates. In this case, such social benefit is determined by the benefit to be obtained by consumers since part of their supply comes from type-1 plants (because producers get no economic gains). This benefit is given by:

[6] Strictly speaking, there is also the case in which the optimal solution without transmission involves the operation of only type-2 plants; in this case, however, there are no type-1 plants, hence no transmission is required.

$$W = (\Delta c - c_t)\int_{\hat{t}}^{T} q(t)dt$$

If type-1 generating companies were under the obligation to pay the fixed cost of transmission (p_0), their installed capacity would decrease up to the point where financing the fixed investment cost of transmission becomes feasible (see Figure 3). The solution, if any, would meet the following condition:

$$\tilde{t} = Min\left(\frac{\Delta f + p}{\Delta c - c_t} + \frac{P_0}{(\Delta c - c_t)q(\tilde{t})}, T \right)$$

Note that if $\hat{t} < T$, then $\hat{t} < \tilde{t}$. Hence when generating companies pay for the fixed cost of transmission there is a reduction in consumers' welfare, which is given by:

$$\Delta W = P_0 - (\Delta c - c_t)\int_{\hat{t}}^{\tilde{t}} q(t)dt \quad \leq \quad P_0 - (\tilde{t} - \hat{t})(\Delta c - c_t)\, q(\tilde{t}) = 0$$

There is an immediate insight to be gained from the above result. The composition of the generating portfolio is not the optimal one because the plants with the highest operating costs should generate for longer time to allow type-1 plants to finance their investment. Therefore consumers pay a higher price for energy. The situation of generating companies, in turn, does not change because their economic gains continue to be zero. Therefore social welfare drops. Consequently, in this model it is efficient for consumers to absorb the fixed investment cost of transmission. Given that demand is assumed to be inelastic, the method of charging the fixed investment cost to consumers is irrelevant. Under different conditions, however, differentiated fixed charges would have to be introduced and they should be such that could not exceed the benefit that each consumer obtains from the transmission line.

So far, we have implicitly assumed that there are no restrictions on plant size. To illustrate the impact of capacity restrictions on the results, let us assume that the maximum capacity of type-1 plants is limited to $k^w < k_1^*$[7]. Therefore, assuming that a transmission line is built, type-1 plants' economic gains are equal to:

$$\boldsymbol{p} = (t(k^w) - \hat{t})k^w(\Delta c - c_t) > 0$$

and consumers' benefits (net of line costs), as against the benefits obtained from a scenario without transmission, are equal to:

$$\Delta W = (\Delta c - c_t) \int_{t(k^w)}^{T} q(t)dt$$

The construction of the line is justified as long as the aggregate benefits that accrue both to generating companies and to consumers exceed the annual fixed cost of the line, with toll fees being distributed on the basis of the respective benefits. Therefore, the fraction of the line cost that should be paid by those generating companies located outside the consumption zone is:

$$\frac{\boldsymbol{p}}{\Delta W + \boldsymbol{p}} = \frac{\left(t^w - \hat{t}\right)k^w}{(t^w - \hat{t})k^w + \int_{t(k^w)}^{T} q(t)dt}$$

Note that the fraction of the fixed investment cost of transmission that would correspond to type-1 generating companies depends basically on how far below the optimal level their installed capacity is.

Finally, let us discuss a third case where type-1 plants are those located near the consumption center, and that type-2 plants are distant from it. We also assume that $f_2 + p_1 < f_1$, because otherwise in the efficient solution there would only be type-1 plants. Under these conditions, the problem of minimizing the cost of the system is:

[7] Restrictions may refer to the availability of fuel or hydro resources, or to legal regulations (zones saturated

$$\underset{k_1,k_2}{Min}\left\{f_1 k_1 + f_2 k_2 + (c_2 + c_t)\int_0^{t(k_1)} (q(t) - k_1)dt + c_1 k_1 t(k_1) + c_1 \int_{t(k_1)}^{T} q(t)dt + p_0 + p_1 k_2\right\}$$

$$s.a.: \quad k_1 + k_2 \geq q^M$$

Note that, without losing generality, transmission capacity has been assumed to match demand *(K = k2)*. The Kuhn-Tucker conditions are:

$$f_1 - t(k_1)(\Delta c + c_t) - \lambda \geq 0 \qquad\qquad k_1(f_1 - t(k_1)(\Delta c + c_t) - \lambda) = 0$$

$$f_2 + p_1 - \lambda \geq 0 \qquad\qquad k_2(f_2 + p_1 - \lambda) = 0$$

Therefore the optimal solution is:

$$\breve{t} = Min\left(\frac{\Delta f - p_1}{\Delta c + c_t}, T\right)$$

To reach the optimal solution, the pricing system must stipulate a payment for energy equal to c_2+c_t when type-2 plants are in operation (between t=0 y$\breve{t}$), and a payment for capacity equal to f_2 + p_1. Such a payment for capacity is explained by the fact that in order for capacity to increase at a minimum cost, it is necessary to invest both in type-2 plants and in the transmission line. Hence type-2 plants should pay (directly) the variable investment cost (p_1) as well as the operating cost (c_t) of transmission, while consumers should take care of the fixed investment cost *(*p_0*)* of transmission. Once the optimal solution is found, it should be ascertained that the benefit obtained by consumers from the transmission line is higher than the fixed investment cost. Note that $\breve{t} < t^*$*;* that is, there is less capacity in type-2 plants and more capacity in type-1 plants when the latter are located in the demand center.

---

with a given pollutant, for example).

In this model, the generating companies located outside the demand center should pay directly for the long-run marginal cost of transmission, whereas the fixed cost of constructing the line should be borne by those users who benefit directly from the line. Note, however, that in order for this transmission-pricing scheme to lead to an efficient equilibrium, payment for capacity must incorporate the marginal investment cost of transmission (p_1). If payment for capacity were only f_2, the transmission line should be entirely financed by consumers, since type-2 technology generating companies cannot afford it, and the solution would not be optimal.

3. The Transmission System as a Facilitator of Competition across Markets

The transmission system plays a fundamental role in creating competition in the electric system. In fact, the existence of a transmission line determines that any company with some degree of market power at the local level may be threatened by the entry of production from "the other side of the line". This threat imposes restrictions on the degree of market power that producers might exercise over their local markets, since any attempts to charge prices higher than the competitive level will result in higher energy imports from the neighboring market, subject to the maximum capacity of the line.

To formalize the impact of the transmission system on the degree of competition of electricity markets, the model used in Section 2 is herein expanded in order to consider two initially isolated markets (A and B) and then discuss the effect of interconnecting them. To simplify the analysis to the outmost, and focus exclusively on the "competition effect," we assume that both cities feature the same load curve $q(t)$ and that a monopolist supplies each. We assume that there is a fixed cost F for the installation of each type 1 plant that makes unprofitable setting up a second plant, and this explains monopoly power.[8] Otherwise we could assume that technology 1 corresponds to hydraulic generation, and each generator monopolizes local water rights. We further assume that the monopoly is

[8] A more general free-entry oligopoly case is discussed in Arellano and Serra (2004).

under the obligation to meet demand, but that it may choose the technology to do so[9]. Therefore the only way for producers to exercise market power is through the composition of their generating portfolio. Specifically the monopoly power is exercised by restricting type-1 generation capacity. Each monopolist solves the following optimization problem:

$$\underset{k_1}{Max}\{\Delta c k_1 t(k_1) - \Delta f k_1\}$$

The solution that maximizes each monopolist's profit is given by:

$$t^m = Min\left(\frac{\Delta f}{\Delta c}\frac{e_q^m}{1+e_q^m}, T\right) = Min\left(t^* \frac{e_q^m}{1+e_q^m}, T\right)$$

where e_q^m is the elasticity of function $q(t)$ assessed at point $q(t^m)$. In order for t^m to be well defined, it is necessary that $|e_q| > 1$ for the definition range of q. Between 0 and t^m the monopolist meets demand using both technologies, while between t^m and T it only uses technology 1. Additionally, we define $k_1^m = q(t^m)$ y $k_2^m = k^M - k_1^m$

Note that given that $dq/dt < 0$ and $t^m > t^*$, $k_1^m < k_1^*$ and $k_2^m > k_2^*$ (see Figure 4). Therefore, as regards the composition of the generating portfolio that maximizes welfare, the monopolist overinvests in the technology whose operating cost is highest and underinvests in that whose operating cost is lowest. Thus, it succeeds in making the plant with the highest operating cost set the price for a longer period of time, thereby increasing revenues.

Let us now assume that a transmission line connecting both markets is constructed, and the capacity of the line, K, is such that the line suffers no congestion (this is to be demonstrated at a later time). We also assume that both the variable investment cost and

[9] This obligation is not necessarily a legal one, since the monopolist may voluntarily choose to meet overall demand as a means of preventing the authority's, or its own consumers' reactions. Alternatively, it may be assumed that there is a monopoly with type-1 technology, but a competitive bid with type-2 technology.

the operating cost of the line are equal to zero ($p_1 = c_t = 0$), so that the only cost associated to the transmission system is its fixed investment cost p_0[10].

The (uncongested) transmission line causes both markets to become fully integrated. In other words, there is allegedly a single energy market. Hence, overall demand is given by $Q(t) = q^A(t) + q^B(t) = 2q(t)$, since we have assumed that there are no transmission losses and that the load curves of both cities are equal. Interconnecting both markets introduces competition; hence producers are forced to consider the neighbor's production at the time of making their own production decisions. We assume that the interconnection of both markets does not make room for a third generator. That is to say, the entrance of a new generator makes all of them loose money.

Just as in the previous case, we assume that plants are dispatched in merit order and that the tariff system corresponds to peak-load pricing. Then, the decision variable for generating companies is how much capacity of each type of plant (technology 1 or 2) should be installed. Note also that the type-2 technology capacity to be installed (k_2^A *y* k_2^B) is not (directly) relevant to the decision that agents should make, because they are paid at marginal cost (both as regards energy and capacity). We assume a Cournot-type behavior; that is, each generating company maximizes its profit by considering its rival's type-1 technology installed capacity as given. Therefore, the producer located in market A solves the following problem:

$$\underset{k_1^A}{Max}\left\{\Delta c\, k_1^A\, t\left(\frac{k_1^A + k_1^B}{2}\right) - \Delta f\, k_1^A\right\}$$

where k_1^i is the choice made by the generating company located in market "i" vis-à-vis the capacity of the plant that uses type-1 technology. The first-order condition is:

[10] Note that under such circumstances t* = $\hat{t}$.

$$t\left(\frac{k_1^A + k_1^B}{2}\right) = \left(\frac{\Delta f}{\Delta c} - t'\left(\frac{k_1^A + k_1^B}{2}\right) k_1^A \right)$$

On account of symmetry, the first-order condition for the producer located at B is:

$$t\left(\frac{k_1^A + k_1^B}{2}\right) = \left(\frac{\Delta f}{\Delta c} - t'\left(\frac{k_1^A + k_1^B}{2}\right) k_1^B \right)$$

Thus, we can define $k_1 = k_1^A = k_1^B$. Then, type-2 plants operate between $t=0$ y t^c, where

$$t^c = t(k_1) = Min\left(t^* \frac{2e_q^c}{1+2e_q^c}, T \right)$$

and e_q^c is the elasticity of function $q(t)$ assessed at point $q(t^c)$. Assuming that elasticity is a non-increasing function of q, it is concluded that $t^* < t^c < t^m$ and $k_1^* > k_1^c > k_1^m$ (see Figure 4). As a result of the interconnection of both systems and the ensuing duopoly, the size of the type-1 generating park chosen by producers lies in between the size of the monopolistic solution and the size that would be chosen under conditions of competition. In other words, the competition introduced by the transmission line reduces the market power that each generating company initially used to exercise at the local level.

Note also that $k_1^A = k_1^B = k_1$, as a result of which the line is not used to carry energy from one market to another. This is an important finding because it shows that the transmission line contributes to reducing the market power of producers participating in local monopolies, even without the need to transport energy. In other words, the mere presence of the line is a sufficient threat to discipline producers in their attempt to exercise market power. Any assessment of the social profitability of the transmission system based only on the use made of the line (energy flow actually transmitted) runs the risk of ignoring its role in mitigating market power.

The fact that the transmission line is not used does not imply that any level of transmission capacity will suffice to produce this pro-competition effect. In this regard, it should be noted that the estimations were made under the assumption that there was no congestion on the line and that consequently producers behaved as if both markets were only one. We adapt Borenstein et al.'s (2000) methodology to our model to estimate the least capacity (K*) that the line should have to force producers into behaving like a duopoly. To this end, it should be noted that for any size of line $K < K^*$, producers would prefer to reduce their production and provoke congestion on the line (or, in other words, to "passively" accept imports from the neighboring market) in order to exercise market power over residual demand (net of imports) at a later stage. Consequently, the minimum level K^* will be that in which the profit obtained by the monopolist with its "passive" strategy is equal to the profit to be obtained from a Cournot duopoly.

K^* is assessed in two stages. First, the behavior of a monopolist "restricted" by the presence of imports equivalent to $K > 0$ from a neighboring market at each point in time is examined[11]. We assume that the capacity bid is in type-1 plants (featuring least-cost operation). Note that an eventual bid for capacity in type-2 plants does not affect the monopolist in A. Later, the minimum K^* will be estimated such that the profits obtained by the restricted monopolist are equal to those to be obtained if the market were structured as a duopoly (with Cournot-type behavior).

A monopolist restricted by the introduction of imports faces a residual demand $\overline{q}(t)$ given by the difference between market demand $q(t)$ and imports K; that is, $\overline{q}(t) = q(t) - K$. Also, $\bar{t}(q)$ is defined as the inverse function of $\overline{q}(t)$. (See Figure 5.)

The problem faced by this monopolist is given by:

$$\underset{k_{1_1}}{Max}\left\{\Delta c k_1\, \bar{t}(k_1) - \Delta f k_1\right\}$$

[11] It may be demonstrated that the most restrictive scenario for the monopolist is that in which the line is congested throughout the period.

Therefore the optimal solution is:

$$\bar{t} = Min\left(t^* \frac{\bar{e}_q}{1+\bar{e}_q}, T \right)$$

where $\bar{e}_q$ is the elasticity of function $\bar{q}(t)$ assessed at point $\bar{q}(\bar{t})$. Given that $\bar{q}(t) = q(t) - K$, $|\bar{e}_q(t)| > |e_q(t)|$ for all K > 0. This, together with the assumption that elasticity is a non-increasing function of q, results in that $t^c < \bar{t} < t^m$ and $k_1^c > \bar{k}_1 > k_1^m$. The "restricted" monopolist overinvests in the highest-operating-cost technology vis-à-vis the socially efficient solution; however, the distortion is lower than that resulting from a "pure" monopolist, and higher than that stemming from a duopoly. The foregoing implies that the presence of the transmission line limits generating companies' behavior even if the line is congested[12].

We still need to verify that the city B producer will bid on market A for *K** capacity in the lowest-operating-cost plants. Given that the capacity of the transmission line is *K**, and that the plants with the highest variable cost (type 2) in market A will operate for $\bar{t}$ hours, which is longer than t^c, it is attractive for the city B monopolist to install K* capacity in type-1 plants to serve city A.

The results obtained may be used to estimate which is the least capacity of the line so that the "restricted" (p^{mr}) monopolist's profits may be equal to those to be obtained in a Cournot duopoly (p^c).

$$p^{mr} = -\Delta f\,(q(\bar{t}) - k) + \Delta c\,(q(\bar{t}) - k^*)\bar{t}$$

$$p^c = -\Delta f\, q(t^c) + \Delta c\, q(t^c)\, t^c$$

[12] In a wider context than this model allows, it should be borne in mind that, even if the line is congested, the residual demand the generating companies face in the presence of imports is necessarily lower and more elastic than the market's, thus contributing to limiting the market power that may be exercised.

The condition $\pi^{mr} = \pi^{c}$ implies that:

$$k^* = q(\bar{t}^*) - q(t^c)\frac{t^c - t^*}{\bar{t} - t^*} > 0$$

The impact of the transmission line among market agents is uneven. In fact, as a result of the interconnection each producer's profits are reduced by:

$$\pi^c - \pi^m = -\Delta f\,(k_1^c - k_1^m) \quad + \quad \Delta c\,(k_1^c t^c - k_1^m t^m) < 0$$

The above expression is negative because, by definition, t^m is the point where the expression $\Delta c k_1 t(k_1) - \Delta f k_1$ is highest.

On the other hand, the consumers at each locality are at an advantage because the overall expense for energy they have to incur decreases by

$$\Delta c \int_{t^c}^{t^m} q(t)dt$$

On the aggregate, the change in welfare is given by:

$$\Delta W = \Delta c\left[(k_1^c - k_1^m)(t^c - t^*) + \int_{t^c}^{t^m} (q(t) - k_1^m)dt \right] > 0$$

The line will be socially profitable if and only if the benefit to consumers is higher than the fixed cost of the line, i.e., $\Delta W > \pi_o$. Note that, should the line be socially profitable, it would only benefit consumers and it is therefore these agents who would have to assume the fixed cost of the line.

At first sight the construction of a line that will not be used might seem socially wasteful. It might be thought that it is more efficient to appropriately regulate the two local monopolies and thus avoid constructing the line. However, it is widely acknowledged that regulation is a poor substitute for competition. Moreover, in this case regulation would take a step further than usual, because it would not only include tariffs and the obligation to provide the service, but would also stipulate the type of technology to be used. Also, it should be borne in mind that in both localities the construction of the transmission line would decrease the need for backup plants; hence the line would be used to carry energy when generation in one locality is insufficient to meet demand on account of failures in the generating plants. Finally, the fact that no transmission takes place is exclusively due to our assumption that the markets are completely symmetrical, both from the supply- and the demand-side standpoint. As long as asymmetries are introduced in the markets, energy would flow from one city to another, and the function of "facilitating competition" would intermingle with the transportation and backup functions.

4. Transmission as a Substitute for Installed Capacity

Transmission lines also serve as a substitute for installed capacity. In other words, the interconnection of two electric systems makes it possible, in some cases, to reduce (or put off) generation investment plans and thus to decrease the generation installed capacity. This holds especially true in the case of asymmetrical electric systems, such as, for example, the case of two electric systems where peak consumption occurs at different times of day[13]. An analysis of the social welfare associated to the construction of the line should compare the benefit to be derived from this concept to the cost of constructing and operating the line.

In order to illustrate how the transmission line can contribute to decreasing the installed capacity required to meet demand, we will use a simplified version of the model described in the previous section. In particular, we assume that there are two demand centers, each one characterized by a load curve $q_i(t)$, $i=A,B$. At each center, peak demand occurs at a different point in time. Both centers are supplied by a similar type of plant (i.e.

with similar technology), the investment cost of which is f and the operating cost is c. In the non-integrated solution, that is, in the absence of a transmission line, each center's installed capacity matches its peak demand. Under an optimal pricing scheme, consumers pay c for each unit of energy consumed, and those who consume at peak times must also pay a charge for capacity amounting to f per unit consumed.

In what follows we will describe the optimal integrated solution, where a transmission line whose capacity is K links both centers. For the sake of simplicity we will assume that in the transportation of energy only investment costs are involved, that is, we will assume that there are no transmission-related operating costs. The problem can therefore be written as:

$$\underset{k_A, k_B}{Min}\left\{ fk_A + fk_B + p_0 + p_1 K \right\}$$

$$s.a.: \quad k_A + k_B \geq q^M$$

$$k_i + K \geq q^i \qquad i = A, B$$

where k_i is the installed generating capacity of city i, q^i is the peak demand at center i, and q^M is the peak demand of the integrated system. By labeling λ the Lagrange multiplier of the first constraint and μ_i the multipliers of the second set of constraints, the Kuhn-Tucker conditions are as follows:

$$f \geq \lambda + \mu_i \qquad k_i\left(f - \lambda - \mu_i\right) = 0, \qquad i = A, B$$

$$p_1 \geq \mu_1 + \mu_2 \qquad K\left(p_1 - \mu_1 + \mu_2\right) = 0$$

$$k_1 + k_2 \geq q^M \qquad \lambda\left(k_1 + k_2 - q^M\right) = 0$$

$$k_1 + K \geq q^i \qquad \mu_i\left(k_i + K - q^i\right) \qquad i = A, B$$

[13] Another example might be the interconnection of two systems with different degrees of adjustment in

Let us assume that the solution is interior and that all constraints are active[14]. The optimal solution then is:

$$K = \frac{q^A + q^B - q^M}{2}$$

$$k_i = q^i - K$$

And the Lagrange multipliers are:

$$\lambda = f - \frac{p_1}{2} \qquad \mu_i = \frac{p_1}{2}$$

Therefore, a necessary and sufficient condition for achieving an interior solution where both constraints are active is for the investment cost per investment unit to be lower than half of the investment cost per generation unit ($f > p_1/2$).[15]

The equations clearly illustrate the role of the transmission system as a substitute for installed capacity. In this regard, note that the increases in a city's peak demand without increasing the demand of the integrated system are met by using the other city's installed capacity. Additionally, to reduce transmission costs, generation capacity is transferred from one center to the other by an amount equivalent to half of the increase in demand. On the other hand, when demand increases at the integrated system's peak time without peak demand increasing in the cities, the increase in each system's capacity (and consequently in the integrated system) makes it possible to decrease transmission capacity by the equivalent to half of such an increase in demand.

This solution is consistent with a pricing system where consumption at the system's peak demand hour pays a capacity charge of $f - p_1/2$, and consumption at each center's

supply and demand.

[14] This is feasible because we assumed that peak demand occurs at different times in both markets.

[15] The condition is rather more complex if transmission-related operating costs are included.

peak demand hour pays a capacity charge of $p_1/2$. These capacity charges provide for financing the installed generation capacity and the variable part of transmission investment. The long-run marginal cost of transmission is paid directly by generating companies; to do this, however, they use the revenues obtained from the payments for capacity that consumers have made. Note, too, that the variable transmission cost is borne by those consumers that demand energy when the line capacity is used to the fullest. The above charges do not finance the fixed investment cost of transmission, which should be charged to consumers since generating companies obtain no economic profits there from.

Constructing the line increases social welfare provided that the benefit associated to a decrease in installed generation capacity is lower than the cost of constructing the line, that is, the following condition must be met:[16]

$$\left(f - \frac{p_1}{2}\right)(q_A + q_B - q^M) > p_0 .$$

The interconnection of two systems also makes it possible to reduce the backup capacity of an electric system, or to increase the system's degree of operational security keeping backup capacity constant. This effect is discussed in the Appendix.

5. Final Comments

Assessing the expansion or construction of a transmission line must take into account all the benefits and costs that originate from it. Otherwise the decision made is likely to be incorrect. This determines the need to fully understand the various functions played by the transmission system in an electric system. The first, and most obvious, function is to transport energy from one point in the system to another, thus allowing demand to be met with the energy produced at the least-operating-cost plants in the system, even though they may be distant from the consumption centers. Secondly, and as a direct

[16] Those users whose consumption is high during the system's peak time might be at a disadvantage by the transmission line. We are implicitly assuming that monetary benefits have the same weight for all consumers, or that they have a similar load curve.

consequence of the transportation function, the transmission system also acts as a substitute for installed capacity (including backup capacity). Finally, the transmission system facilitates competition across markets. A transmission line connecting two markets restricts the market power that producers might exercise over their local markets because any attempt to charge prices above the competitive level will result in larger energy imports from the neighboring market, subject to the capacity of the line.

This article discusses in detail the three functions of the transmission system in an electric system, as well as the way in which the use of the line should be priced, provided that the comparison of cost and benefits of the line indicates that the construction thereof is socially profitable. In each case, the simplest possible model - and the one that isolates the function to be analyzed - has been used.

The pricing scheme applied to transmission should be related to the pricing system used to pay for energy and capacity. This paper assumes that electricity is priced under the peak-load pricing, which was expanded to take into account the spatial variable. For this reason, the specific form pricing takes herein is more complex. As a consequence of this collection scheme, generating companies located outside the consumption center must pay directly for the long-run marginal cost of the transmission system (which includes the system's variable investment and operating costs), although in the last instance it is the consumers who bear the cost of this charge through the energy and capacity payments they make.

As to the fixed charge for investment in transmission, this article argues that those users who benefit directly from it should finance it, and in proportion to the benefits they receive. In a competitive scenario, with free entry to the generation segment and with no capacity restrictions, generating companies do not obtain economic profits thus the fixed cost should be entirely paid for by consumers. In a wider scenario in which the transmission system allows generating companies to obtain positive economic gains, the fixed charge should be distributed among consumers and generating companies in proportion to the benefit obtained by each. This occurs, for example, in the case of restrictions on installed capacity at the plants located outside the consumption center, since both the generating companies in question and consumers benefit from the line.

The proposed criterion for allocating the fixed cost is efficient since it does not alter the decision as to the use of the line, nor does it exclude any users that may contribute to financing that portion of the costs that is not covered by the variable charge. Allocating the fixed cost by means of a different criterion, such as charging it to generating companies although these obtain no economic profits from the use of the transmission system, introduces distortions that decrease social welfare. The loss in social welfare materializes through the creation of a generating portfolio whose composition is inefficient. In particular, the need to collect higher revenues to cover the fixed cost may force generating companies to overinvest in the highest-operating-cost technology and to underinvest in the least-operating-cost technology. Thus these companies succeed in making the former plants profitable – and therefore set the price – for a longer period of time.

In our analysis there is no risk of constructing transmission lines that are not socially profitable because it has been assumed that prior to constructing a line the associated costs and benefits have been compared. In this regard, the discussion focuses on designing the pricing system that provides for the socially optimal composition and capacity of the generating capacity in a decentralized solution. The analysis goes a step further, however, since the appropriate pricing design makes it possible for the transmission system to have the capacity and to be used efficiently.

The methodology used in this article was based on a general model that was adapted in each case to isolate the various functions of the transmission system. This was done in order to illustrate each of the functions fulfilled by the transmission system. Two pending tasks, however, are: to integrate these three functions into a single model, and to weaken some assumptions regarding transmission costs, demand inelasticity, and the use of monopolies to analyze market power.

References

- Balasko, I. (2001): “Theoretical perspectives on three issues of electricity economics,” www.balasko.com
- Boiteux, M. (1960): "Peak load-pricing." Journal of Business 33: 157-179.
- Borenstein, S., Bushnell, J., Stoft, S (2000): "The competitive effects of Transmission Capacity in a Deregulated Electricity Industry." *The RAND Journal of Economics* 31 (2), 294-325.
- Chao, H.-P & Peck, S. (1996): "A market mechanism for electric power transmission." *Journal of Regulatory Economics* 10, 25-59.
- Fischer, R. & P. Serra (2002). "Energy prices in the presence of plant indivisibilities." *Energy Economics* 25, 303-314.
- Green, R. (1997): "Electricity Transmission Pricing. An International Comparison." *Utilities Policy* 6 (3), 77-184.
- Hogan, W. (1992): "Contract Networks for electric power transmission." *Journal of Regulatory Economics* 4, 211-242.
- Joskow, P. (1976): "Contributions in the theory of marginal pricing.” *Journal of Regulatory Economics* 7, 1907-206.
- Schweppe, F.C., M.C. Caramaris, R.D. Tabors & R.E. Bohn (1988): Spot Pricing of Electricity. Kluwer, Boston.

Appendix
The Transmission System as a Backup Supplier

The interconnection of two systems makes it possible to reduce backup capacity in an electric system[17] or, alternatively, to increase the system's degree of operational security keeping backup capacity constant.

To illustrate this effect it should be borne in mind that electric systems may feature two types of generation-related failures: capacity failures, caused by sudden plant outages, and energy (or long-lasting) failures, such as those stemming from draught conditions in systems with a high proportion of hydraulic generation. The optimal response to these potential problems varies. In the case of energy or long-lasting failures, the system needs to have backup plants capable of replacing the energy shortfall caused by the draught; to this end traditional thermal (mainly coal-fired) plants are used, even though their cost is higher than that of gas combined-cycle plants. When a sudden failure occurs, on the other hand, spinning reserves are required, for which reason hydraulic dam-based plants are often the best alternative.

The role of the transmission system in relation to backup capacity can materialize in various ways. Thus, for example, if capacity failures occur, the transmission system – by fulfilling a role comparable to a substitute for installed capacity, as discussed in the text – may reduce installed capacity for backup purposes.

On the other hand, its impact on security and backup can also be analyzed in terms of the probability of failure of an electric system. To that end, let us imagine two cities, A and B, whose peak demand for capacity is similar, and which are also identical. A generation technology that features economies of scale is available; hence it is efficient to set up n plants in each city. Let us assume there is a probability π that a plant may fail. What is involved are very short-lived failures with no impact on aggregate consumption but with a high cost. If no backup is available, therefore, there is a probability $1 - (1-\pi)^n$ that there will be an outage at a given moment. If m backup plants are set up, the probability of the system failing at every moment falls to

$$\sum_{i=m+1}^{n+m}\binom{n+m}{i}p^i(1-p)^{n+m-i}=1-\sum_{i=0}^{m}\binom{n+m}{i}p^i(1-p)^{n+m-i}\ ^{18}.$$

This is a decreasing probability vis-à-vis the number of *m* backup plants. The interconnection of two electric systems with *n* generation plants and *m* backup plants each reduces the system's probability of failure. Alternatively, it would be possible to maintain the same initial probability of failure, but decreasing the number of backup plants. To better illustrate this effect, consider an electric system with 10 generation plants and 2 backup plants, where each plant's probability of instant failure stands at 5%. Under such circumstances, the system's probability of failure is approximately 2%. If two of both systems are interconnected, the probability of failure of the integrated system is cut down to 0.6%. Alternatively, let us assume that the supply quality standard stipulates a maximum probability of failure of 2% for the system. In this case, in the absence of a transmission line this means that each system should assign 2 plants for backup purposes, while the integrated system would only require 3 plants. (See Figure A1.1)

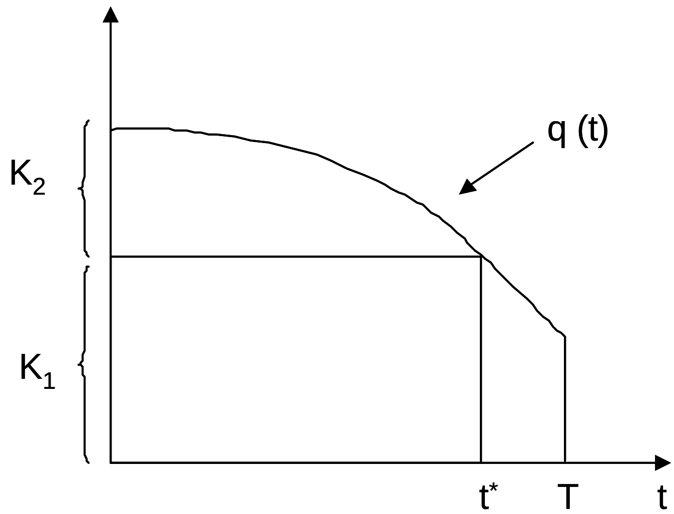
The benefit of backup substitution is even more significant when the transmission system links systems with different characteristics (composition of the generating portfolio, load curve, etc.), such as a mainly hydroelectric system with a thermal one. In the former, major failures are energy failures because severe draughts decrease generating capacity. On the other hand, in thermal systems the main failures are capacity failures, which do not occur in hydraulic systems given that hydraulic plants can respond quickly to contingencies. Therefore, during draughts the backup capacity of the thermal system can produce energy for the hydraulic system, whereas hydraulic plants respond to the short-lived failures of thermal plants.

Under the assumption that consumers finance overall installed capacity, including backup capacity, the benefit of "backup" then accrues directly to them. The fixed cost of the transmission line should therefore also accrue to consumers.

[17] Plants that need to be kept to provide spinning reserves.
[18] It has been implicitly assumed that all plants have the same capacity.

Figures

FIGURE 1



Optimal Composition of the Generating Portfolio

FIGURE 2
Optimal Composition of the Generating Portfolio
(including a Transmission Line)

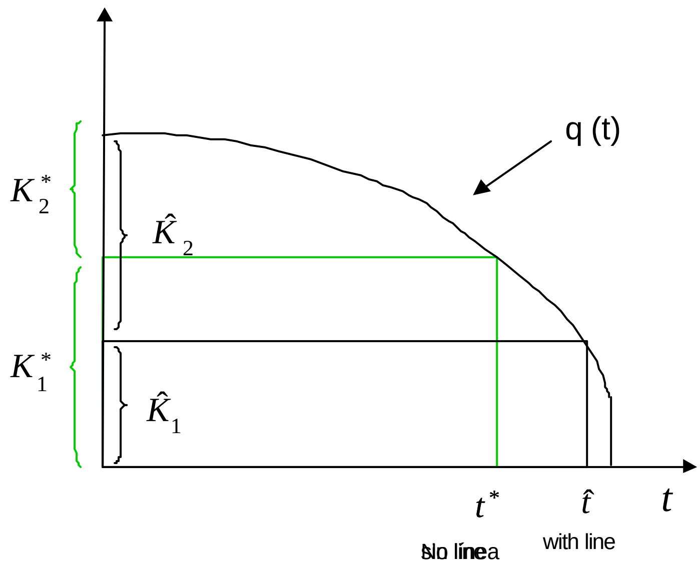


FIGURE 3
Composition of the Generating Portfolio according to Fixed Transmission Cost Allocation

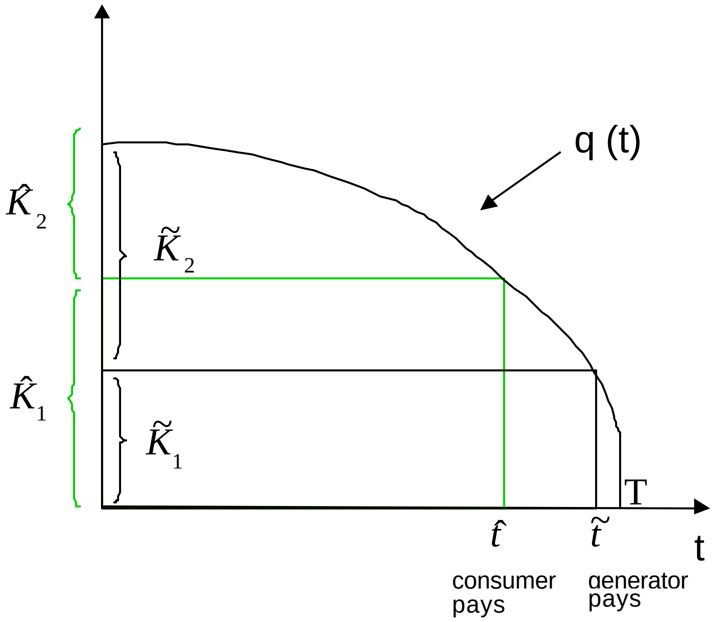


FIGURE 4
Composition of the Generating Portfolio Under Different Assumptions of Competitive Behavior

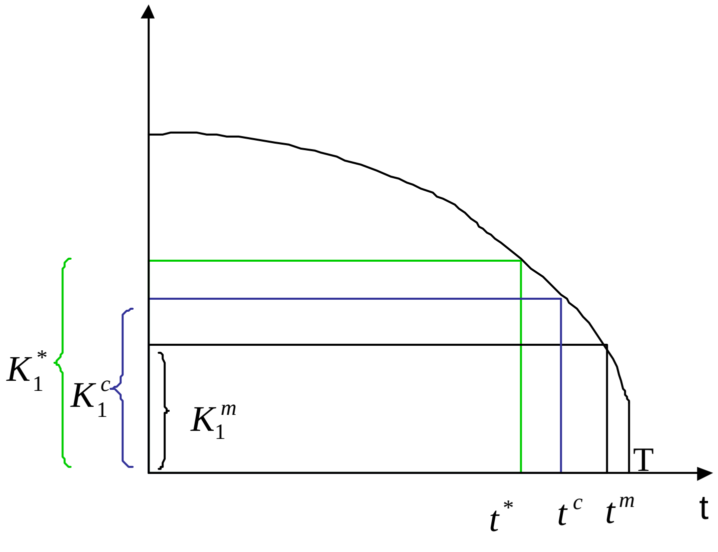


FIGURE 5

Load Curve with/without Imports

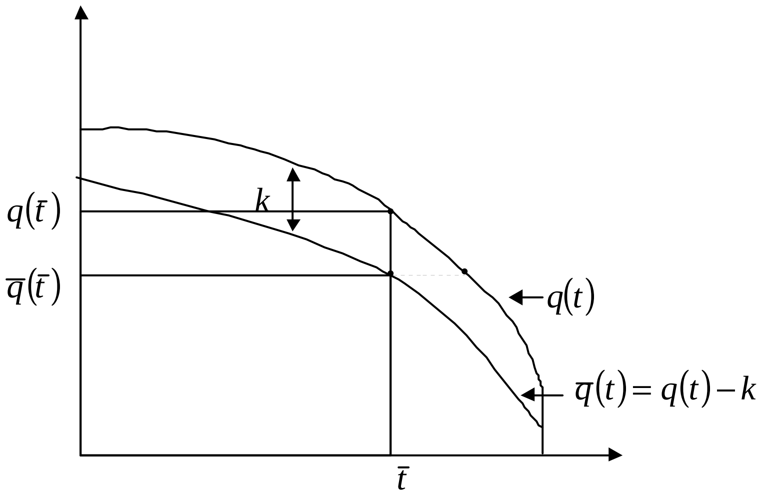


Figure A1