Pricing the connection to an electricity distribution network

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Abstract

This paper provides an economic view on how the connection to a distribution network should be priced when the operator consider the spatial distribution of consumers. It highlights the impact of public service constraints on the investment in service quality, the size of the network and the connection fee. The model is based on the geographical dispersion of agents in the distribution area and on the costs linked to this dispersion as opposed to those common to all connected customers. We first determine the first-best results and so the optimal size of the network. This leads to a situation undesirable from two points of view: i) the net profit of the operator is negative, ii) the price payed proportionally to distance is seen as discriminatory by politicians who favor 'postage stamp" principle. We successively study these two drawbacks, i.e. the budget constraint and the intra-zone price adjustment. Finally, we show that we can implement first best thanks to two-part tariff.

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1 Introduction

There exists an important economic literature on electricity wholesale markets (e.g. Borenstein, Bushnell and Wolak [2002]; Fabra, von der Fehr and Harbord [2006]), on capacity markets (e.g. Creti and Fabra [2007]), on the ownership and management of the transmission grid (e.g. Joskow and Tirole [2005]), on transport pricing (e.g. Crampes and Laffont [2001]) and on retail supply (e.g. Joskow and Tirole [2007]). By contrast, there is little economic research on electricity distribution. The existing literature can essentially be separated into two branches. The first one concerns the design of concession contracts for this natural monopoly activity (see for instance Saplacan [2008]). The second group deals with benchmarking applied on this sector in order to fix tariffs, and to control the quality of service (e.g. Jamasb and Pollitt [2007, 2008]). In both types of literature, the design of the network, especially its spatial characteristics, is considered as exogenous, and, in the case of contract theory, a secondary concern. However, before contracting with local authorities on tariffs and on the expected profit, operators must negotiate on how many people should be connected to the network, their locations, as well as on the topological features of the network.[1]

Electricity distribution is a natural monopoly activity.[2] Indeed, distribution requires a huge investment in infrastructure but, once installed, the marginal cost of distributing electricity to consumers is close to zero. Absent any security concern the duplication of the infrastructure would be suboptimal. On top of this horizontal view electricity distribution entails vertical effects. The distribution network is an infrastructure that no retailer can by-pass but controlled by only one agent. Therefore it is an essential facility for the provision of electricity. If the network is vertically integrated with energy retail, the owner has some interests in proposing discriminatory access conditions to its competitors. Therefore, it is an industry where a high level of regulation is required. For example, the European Commission encourages governments of the Member States to unbundle the activities considered as essential facilities from the ones in which competition is implementable.[3] Nevertheless, in several Member States, distributors are still patrimonially bundled with the historical incumbents who are competing in the retail market against non integrated suppliers. The essential facility question is not addressed in this paper.

In many developed countries, the distribution network is owned by local authorities and the management of the network is conceded to a third party. The public decision-maker has to choose the network builder or developer and the operator. It must also design the delegation contract. These tasks are the core of the theory of Public Private Partnership. Thanks to competition for the right to serve as a monopolist supplier, municipalities may change their distributor even though they lack information about the network they own.[4] Actually, incumbents, thanks to their experience, have a better knowledge on the network condition and then have a comparative advantage with respect

[1] Note that in most developed countries, almost all consumers are already connected to the grid.

[2] However, as shown in Saplacan [2008], a more detailed analysis allows to identify some possibility of competition.

[3] See Directive 2009/72/EC, article 26.

[4] Franchise bidding also allows to collect a fraction of the surplus that the monopolist will extract from consumers.

to other distribution companies.[5]

The electricity distribution activity is tightly linked to the geographical characteristics of the region under consideration. The cost to install and maintain a line is very different in mountain regions and in plain regions. In spite of that, public service obligations can oblige the operator to provide the same service, that is to deliver electricity to a specified number of consumers. Clearly, the economic modeling of such activity has to include spatial and physical requirements.

As in all distribution networks, electricity distribution brings about losses. The quantity injected at the head of the network is larger than the quantity consumed. This difference is due to thermal losses created by "Joule effect". Thermal losses increase with respect to the distance between the head of the network and electricity takers and with respect to the quantity injected in the network. In order to compensate thermal losses, the operator of the network may be obliged to purchase energy blocks. This essential feature of the distribution activity is not addressed in our paper.

The model is aimed at computing the optimal size of a network and determining the connection fee. The critical number of individuals connected to the network results from the consumers' decision upon either to be connected or to consume electricity produced locally. We analyze how the network should be managed at first best and we contrast the results to the choices of an independent private operator. We show that the independent operator charges each consumer more than at first best. Moreover, we study different cases where the operator must comply with public service constraints aimed at allocating the distortion due to second-best pricing.

The paper is organized as follows. In Section 2, we set up the model. We present the hypotheses on consumers' behavior, and we determine the optimal level of investment and the optimal tariff of access. This provides a benchmark to see how decentralization and public service constraints may distort the operator's decisions away from the first best solution.

Section 3 takes a budget balancing constraint into consideration. Indeed, because of the public opinion and/or for legal reasons, the first best solution that incurs huge financial losses is not viable. We first determine the second-best linear price that balance the operator's budget and then the second-best investment in quality.

Section 4 deals with two-part pricing. We first show that two-part tariffs allow to implement first best and we analyze the distributive effects of this type of tariff.

In section 5 we conclude and suggest further developments.

[5] Actually, the European Commission wants to oblige local authorities to organize competition for the field, in order to increase competition in public service.

2 Optimal design of a distribution network

Since electricity is not storable, consumers need to have either a local generation plant or a wired connection to remote plants.

The spatial dispersion of consumers is key in the electricity distribution activity. Each consumer is defined by θ which stands for the distance between the consumption point and the entry point of energy in the distribution network. The density of agents located at distance θ is denoted $f(\theta)$ and the cumulative distribution by $F(\theta)$. The general form of consumers spatial dispersion can be illustrated by the density:

$$f(\theta) = a + b\theta \tag{1}$$

The linear form of the density function allows to capture the main characteristics of the region and to simplify computations. This distribution function depends on the region where consumers live. One can distinguish different types of regions depending on where consumers are concentrated with respect to the head of the network.

In some regions, the population is concentrated far from the high voltage line where energy is taken. The farther from the head of the distribution network, the larger the number of consumers. It requires that $b > 0$.

The opposite is a region where consumers are concentrated close to the head of the network ($b < 0$). The features of this region are those of a valley, for instance in France the valley of Grenoble. There is a high concentration of population along the first kilometers of line and then the population is increasingly scattered.

The simplest type of region is a suburb. In this kind of area, the population is uniformly distributed, which means $b = 0$.

This region characterization allows to compare connection and tariff solutions and to address the question of perequation among heterogeneous distribution zones. Nevertheless, in this paper, we only analyze the simplest configuration, that is the uniform distribution case. In section 2.1, we expose the hypothesis concerning the behavior of consumers. In section 2.2, we then determine the optimal size of the network and the optimal investment in service quality.

2.1 Consumer behavior

We assume that consumers are free to choose between two sources of electricity. The first source is the electricity coming from the network which conveys energy from the transformer located at the border between the high-voltage transport grid and the distribution grid. The alternative is local self-production. In other words, consumers choose between being connected or not.

We assume that all consumers within a region are identical, except for their location. A consumer who chooses to be connected to the network has a gross utility defined by:

$$U(q,s)$$

where q is the quantity of electricity consumed and s the quality of the service. It is an increasing and concave function in each argument. The quality of service is an increasing function of the equipment installed in the network (transformers, type of lines, ...). The higher the equipment denoted by K, the higher the quality of the service provided by the distributor. For connected consumers, K is a public good. The utility function $U(.,.)$ increases according to the quantity consumed and the quality of service, therefore $U(.,.)$ is increasing with the level of common equipment K installed in the network. Once connected, a consumer buys from his retailer the quantity:

$$q(p_e,K) = arg\max_q U(q,s(K)) - p_e q$$

where p_e is the unit price of electricity. This function is decreasing with p_e and increasing with K. We define the indirect net utility of a consumer when he/she is connected by[6]:

$$v(p_e,K) \stackrel{def}{=} U(q(p_e,K),s(K)) - p_e q(p_e,K) \tag{2}$$

It is easy to check that $\partial v/\partial p_e < 0$ and $\partial v/\partial K > 0$.

An agent not connected to the network has an indirect net utility $v(p_a)$, where p_a is the cost of the self-produced electricity or the price of electricity from an independent source. This electricity may come from wind turbines, solar-plants, water mills, etc. We assume that this independent electricity provides the same service to consumers wherever they are located. If we are in a situation such as $p_a << p_e$, for instance because agents are in a windy area or a very sunny one, then we can have $v(p_a) > v(p_e,K)$ even though K is very large. If so, connection to a distribution network is not economically profitable. In what follows, we assume that $p_a > p_e$ and thus it is *a priori* profitable to install a network, with geographical characteristics that remain to be determined.

The only difference between consumers is their location identified by θ of density $f(\theta)$. The installation and maintenance cost is equal to $c\theta$ for a group of consumers located at θ, so the per-consumer maintenance cost is equal to $c\theta/f(\theta)$. We assume that the size of the network, i.e. the number of potential customers, is normalized to 1.[7]

The type of network we are analyzing follows a hub-and-spoke pattern, that is consumers at the same distance are connected through the same line but there is no common line for those people who are at different distances. We do not consider networks where consumers at different distances are linked by (partially) common lines. In the latter, a consumer who wants to be connected generates both costs which are specific and others that are common to all the

[6]This expression is different from the indirect net utility of being connected which is $v(p_e,K) - T(\theta)$.

[7]This assumption should be relaxed in a extension of the model because real distribution costs also depend on the number of consumption sites connected.

consumers connected upstream his location.[8] Actual electricity distribution networks are a mix of these two types of network.

2.2 First best connection and investment

We determine the number of connected consumers and the optimal level of capital K installed by a well-informed and benevolent social planner. We first identify the consumers who shall be connected to the network. Knowing the connection and maintenance costs, the consumers for whom connection is socially beneficial are such that:

$$v(p_e,K) - \frac{\theta c}{f(\theta)} \geqslant v(p_a)$$

Hence, the marginal consumer (or group of consumers) may indifferently be connected to the public network or supplied by the alternative source of electricity. It results that the maximal distance of connection is defined by:

$$\widetilde{\theta}(c,K) = \frac{[v(p_e,K) - v(p_a)]f(\widetilde{\theta})}{c} \tag{3}$$

This distance is an increasing function of the quality of service, therefore of K, as well as of the energy price difference $p_a - p_e$. It is obvious that the higher the quality of service, the greater the distance of the marginal consumer since connected consumers have an increased gross surplus. Concerning the difference in prices, if the alternative source of electricity is more and more costly compared to the energy delivered by the network, it is more socially beneficial to be connected to the public network.

The social welfare created by the connection of consumers with θ no larger than $\widetilde{\theta}$ to the public network is:

$$S(c,K) = \int_0^{\widetilde{\theta}} \left[v(p_e,K) - v(p_a) - \frac{\theta c}{f(\theta)} \right] dF(\theta) - rK$$

where r represents the unit cost of the common equipment which enables to maintain the network quality. Hence, we have two types of costs: rK is common to all connected consumers; the other cost θc is due to connection of consumers at distance θ. We assume that it is independent of the number of people connected. In order to have explicit results, we focus on the case where consumers are uniformly distributed between 0 and $\bar{\theta}$ in the zone of electricity distribution.[9] With this specification social welfare is:

$$S(c,K) = \frac{\left[v(p_e,K) - v(p_a) \right]^2}{2c\bar{\theta}^2} - rK$$

[8] It means that the lines are partially common and partially individual. Here, we assume that all the common costs are captured by variable K.

[9] This type of statistical distribution is rather good for populations in suburbs. It allows to simplify computation while giving good intuitions. By contrast, it is misleading as regards other geographical features of the network.

This function is decreasing w.r.t. $\bar{\theta}$. Indeed, keeping all other variables equal, if the dispersion of the population increases (or equivalently if the population density decreases), there are fewer spots of consumption for which the connection is socially profitable.

The social planner's problem is to determine the size of common equipments influencing the service quality for connected consumers:

$$\max_{K} S(c,K)$$

The first order condition is given by:

$$\frac{v(p_e,K^*)-v(p_a)}{c\bar{\theta}^2}\frac{\partial v(p_e,K^*)}{\partial K} \leqslant r$$

The left hand side of the previous inequality can be strictly lower than r for any value of K, so that no distribution network shall be installed and it is optimal to provide everybody with local energy. It is the case when $v(p_e,0) < v(p_a)$ and $S(.)$ is concave in K. The problem has a positive interior solution only if the net-utility function, $v(p_e,K)$, is strongly concave in K.[10] If not, all consumers must be connected, $\widetilde{\theta}(c,K) = \bar{\theta}$, and the installed equipment is derived from equation (3), that is $\widehat{K} = \arg_K\{v(p_e,K) = c\bar{\theta}^2 + v(p_a)\}$. In the next paragraph, we rather explore the interior solution defined by:

$$\frac{v(p_e,K^*)-v(p_a)}{c\bar{\theta}^2}\frac{\partial v(p_e,K^*)}{\partial K} = r \tag{4}$$

Under the assumption of strong concavity of the net-utility function in K, the optimal capital to be installed is decreasing in r, $\bar{\theta}$ and c and is increasing in $p_a - p_e$, the price differential between electricity coming from the alternative source and electricity delivered by the network.

To decentralize this optimal choice with a linear connection fee, one has to find a price which has two effects: i) all consumers located at a distance $\theta \leqslant \widetilde{\theta}(c,K^*)$ must have the incentive to be connected while the others must choose energy outside the network, and ii) at this price the distributors invests up to K^*.

The simplest solution to reach these two conditions is to charge each consumer a price per kilometer of line equal to the marginal cost of installation and maintenance, that is $p^* = c/f(\theta)$. It allows to meet the first condition: for a given K, at price p^* the marginal consumer who demands connection is $\widetilde{\theta}(c,K)$. However, there appear two majors drawbacks with this solution:

- the net profit of the operator is:

$$\int_0^{\widetilde{\theta}} p^*\theta dF(\theta) - \int_0^{\widetilde{\theta}} c\theta d\theta - rK^* = -rK^* < 0$$

[10] In words, the utility from a higher quality of service increases very quickly with K for rather small K and then it stagnates as if quality improvements were very quickly exhausted. See the proof of the second order condition in appendix A.

Therefore the operator will ask for subsidies and this may prove hardly possible (and may be illegal);

- the charge paid by each consumer depends on the distance θ and is likely to be seen as a discriminatory solution by politicians whereas, in fact, it only reflects the costs induced by the distance. Moreover, if consumers may move, it can result in a undesirable geographical location of consumers with a population highly concentrated around the source node where connection is cheaper.

Hence, under the combined pressure of public opinion and administrative authorities, first best solution is not viable. We now consider the obligation to balance the operator's budget.

3 Optimal network under budget constraint

Assume that the only constraint concerns budget equilibrium. We do not challenge the fact that the bill is proportional to distance. Under linear pricing, the second best solution is given by:

$$\begin{aligned}
&\max_{p,K} \widehat{S}(p,K) \\
&s.t. \int_0^{\widehat{\theta}(p,K)} \left(p - \frac{c}{f(\theta)}\right) \theta dF(\theta) - rK \geqslant 0
\end{aligned}$$

where the marginal consumer is located at:

$$\widehat{\theta}(p,K) = \frac{v(p_e,K) - v(p_a)}{p}$$

and the social surplus is:

$$\widehat{S}(p,K) = \int_0^{\widehat{\theta}} \left[v(p_e,K) - v(p_a) - \frac{\theta c}{f(\theta)}\right] dF(\theta) - rK$$

We successively determine the optimal linear price and the optimal level of capital to be installed under the constraint of budget balancing.

3.1 Second-best linear kilometer price

We see that social welfare, $\widehat{S}(.)$, is an increasing function of the last consumer to be connected, $\widehat{\theta}$. On the other hand, the maximal distance is a decreasing function of the price (per kilometer). Thus, the second best linear price is the smallest price compatible with the budget constraint of the operator. Consequently, the connection fee per unit of distance to charge is equal to the average cost:

$$\int_0^{\widehat{\theta}(p,K)} \left(p - \frac{c}{f(\theta)}\right) \theta dF(\theta) - rK = 0$$

Considering a uniform distribution between 0 and $\bar{\theta}$, the price per kilometer is:

$$p^{SB} = \frac{1-\sqrt{1-4\bar{\theta}Ac}}{2A} \quad (5)$$

$$with\, A = \frac{2rK\bar{\theta}}{[v(p_e,K)-v(p_a)]^2} \quad (6)$$

p^{SB} exists if and only if $A \in]0, \frac{1}{4\bar{\theta}c}]$. Under this condition,[11] the second best price belongs to the interval c and $2\bar{\theta}c$.

For a given level of capital K, the price increases with respect to c, r and $\bar{\theta}$. Indeed, when the spatial dispersion $\bar{\theta}$ increases, there are fewer spots of consumption that should be connected and the total population on which the operator can charge its common costs is reduced. Therefore, it has to charge connected consumers more.

Furthermore, p^{SB} decreases when the difference $v(p_e,K)-v(p_a)$ raises, given K. This relation is surprising at first sight only. Indeed, the operator's objective is not to make the highest profit but rather to cover its costs, rK. So, the higher the difference $v(p_e,K)-v(p_a)$ given the common cost to recoup, the larger the number of households connected to the public network and thus the price charged is closer to the first best one $p^* = c/f(\theta)$. The reason is the same as previously. If the number of consumers is higher, the operator has to charge each consumer less in order to balance its budget.

Finally, the effect of K on the second best price is ambiguous. In fact, if K is greater, the operator has to raise more and more resources (A is an increasing function of K) to cover the costs of the installed capital. On the other hand, if K increases, the interest to be connected to the public network is greater, that is the difference $v(p_e,K)-v(p_a)$ is higher. As we have seen before, this implies that the number of potential consumers is greater and the per-capita contribution is lower. However, we know from section 2.2 that the function $v(p_e,K)$ has to be strongly concave in K in order to have an interior solution. Consequently, we may consider that the case where p^{SB} is an increasing function of K is probably more common.[12]

Knowing the second-best price, we now compute the optimal level of investment under budget constraint.

3.2 Investment in quality

Taking into account the price p^{SB} which allows the operator to balance its budget, the best choice in terms of common equipments is given by:

[11] We remark that if $K \to 0$, the budget constraint is trivially met with $p = c/f(\theta)$. At the other end of the validity interval, the infrastructure costs are so high that pricing at average cost prevents consumers from connecting to the network.

[12] See an example in appendix B.2.

$$\max_K \int_0^{\widehat{\theta}(p^{SB},K)} \left[v(p_e,K) - v(p_a) - \frac{\theta c}{f(\theta)} \right] dF(\theta) - rK$$

When consumers are uniformly distributed, the program can be written as follows:

$$\max_K \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \left(\widehat{\theta}(p^{SB},K) \right)^2 - rK$$

The first order condition that gives K^{SB}, is:

$$-\frac{\widehat{\theta}^2}{\bar{\theta}} \frac{\partial p^{SB}}{\partial K} \left(\frac{p^{SB} - \bar{\theta}c}{p^{SB}} \right) + 2\widehat{\theta} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \frac{\partial \widehat{\theta}}{\partial K} = r \tag{7}$$

Assume first that $\frac{\partial p^{SB}}{\partial K}$ is negligible. To compare K^{SB} and K^*, we can write from equations (4) and (7) that:

$$\frac{v(p_e,K^*) - v(p_a)}{c\bar{\theta}^2} \frac{\partial v(p_e,K^*)}{\partial K} = \frac{v(p_e,K^{SB}) - v(p_a)}{p^{SB}} \frac{\left(2p^{SB} - \bar{\theta}c\right)}{\bar{\theta}p^{SB}} \frac{\partial v(p_e,K^{SB})}{\partial K} \tag{8}$$

Given that $\frac{1}{\bar{\theta}c} > \frac{2p - \bar{\theta}c}{p^2}$, we have:[13]

$$\left[v(p_e,K^*) - v(p_a) \right] \frac{\partial v(p_e,K^*)}{\partial K} < \left[v(p_e,K^{SB}) - v(p_a) \right] \frac{\partial v(p_e,K^{SB})}{\partial K} \tag{9}$$

The function $v(.)$ is strongly concave in K, so the function $\left[[v(p_e,K) - v(p_a)] \frac{\partial v}{\partial K} \right]$ is decreasing in K. Then inequality (9) is satisfied only for $K^{SB} < K^*$. If now, we consider that $\frac{\partial p^{SB}}{\partial K} \neq 0$, equation (8) becomes:

$$\frac{v(p_e,K^*) - v(p_a)}{c\bar{\theta}^2} \frac{\partial v(p_e,K^*)}{\partial K} = -\frac{\widehat{\theta}^2}{\bar{\theta}} \frac{\partial p^{SB}}{\partial K} \left(\frac{p^{SB} - \bar{\theta}c}{p^{SB}} \right) + \frac{v(p_e,K) - v(p_a)}{p^{SB}\bar{\theta}} \frac{\left(2p^{SB} - \bar{\theta}c\right)}{p^{SB}} \frac{\partial v(p_e,K^{SB})}{\partial K} \tag{10}$$

Keeping the assumption of a price increasing w.r.t. K, the equality in (10) is reached only if K^{SB} is lower than when $\frac{\partial p^{SB}}{\partial K}$ is negligible. Indeed, reducing the level of installed capital would increase the marginal utility $\partial v(p_e,K^{SB})/\partial K$,[14] and then this would compensate the fact that $\frac{\partial p^{SB}}{\partial K} \neq 0$. In the other case, when $\frac{\partial p^{SB}}{\partial K} < 0$, we cannot give a clear answer concerning the ranking between K^{SB} and K^*.

To sum up, the budget constraint of the network operator implies that the tariff per kilometer is higher than in the first best solution (where $p^* = c/f(\theta)$). Moreover, the optimal level of equipment that should be installed is lower than in the first best solution.[15] Hence, the size of the network under the budget constraint is reduced for two reasons illustrated in Figure 1:

[13] This is true for any $\{\bar{\theta}, c\}$ such as: $\bar{\theta}c > 1$.

[14] Remember that the net utility function is concave in K.

[15] As said repeatedly, this is the most likely outcome but it is not guaranteed, since the effect of the capital installed on the price p^{SB} is ambiguous.

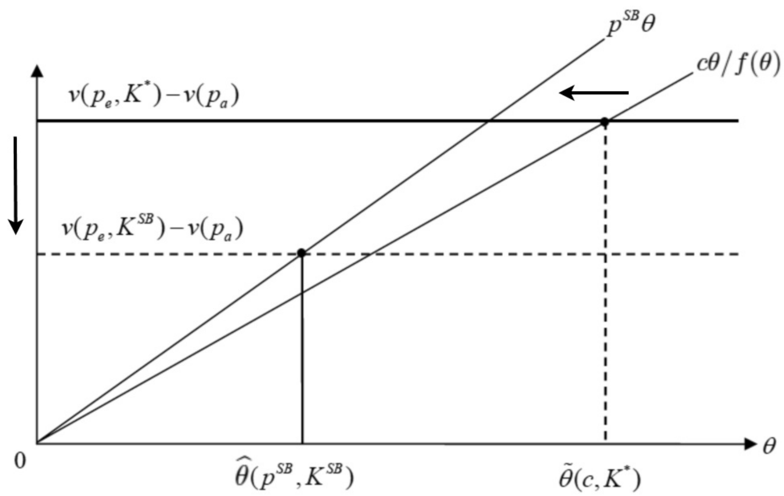

Figure 1: Linear tariff and budget constraint

- a lower level of installed capital reduces the willingness to pay of potential consumers, so the marginal consumer is nearer to the source point, which means that the number of connected people decreases;
- the level of price, higher than the marginal cost per consumer $c/f(\theta)$, weakens the incentive of consumers to be connected. Here again, the marginal consumer is closer to the entry point of electricity $\left(\widehat{\theta} < \widetilde{\theta}\right)$.

4 Two-part tariff

For practical and/or political reasons, uniform pricing independently of distance is an obligation for the managers of distribution networks. Hereafter, we show that the constraint of uniform linear price joint with the obligation of budget balancing leads to a corner solution. It means that either everyone or nobody will be connected. Then, we assume that the price constraint only applies to the common costs and we introduce a two-part tariff. We consider two solutions to approximate first best: either pricing distance at marginal cost or serving the same number of consumers as at first best. In the latter case, the tariff can be viewed as a redistributive tool from the consumers who are located close to the head of the network to those who are at remote locations.

4.1 Uniform linear tariff and two-part tariff

A uniform linear price p^u covering all the costs is such that:

$$
\begin{aligned}
&p^u F\left[\theta^u(p^u,K)\right] - \int_0^{\theta^u(p^u,K)} \frac{c\theta}{f(\theta)}\, dF(\theta) - rK \geqslant 0 \\
&\theta^u(p^u,K):\ v(p_e,K) - p^u = v(p_a)
\end{aligned}
$$

Since the only difference between agents is the distance between their location and the head of the network, if the operator fixes a uniform price per consumer, all potential consumers will react in the same way. If the price p^u is very low, everyone would be connected to the network since $v(p_e,K) - p^u > v(p_a)$ for all θ. Otherwise, nobody would be in the network. That is, depending on the value of p^u, either $\theta^u = 0$ or $\theta^u = \bar{\theta}$. These two solutions are far from the optimal criterion established previously. In other words, under a uniform linear tariff, the choice of the network size is political.[16]

Remember that the distributor has to balance his budget. When everybody is connected, he fixes a price p^u to cover total cost:

$$
p^u \geqslant cE(\theta) + rK
$$

where $E(\theta) = \int_0^{\bar{\theta}} \theta\, d\theta$ is the average distance between consumers and the head of the network. The optimal level of investment is determined by maximizing social welfare:

$$
\max_K \ \left[v(p_e,K) - v(p_a)\right] - cE(\theta) - rK
$$

So that K^u is the solution to:

$$
\frac{\partial v(p_e,K^u)}{\partial K} = r
$$

Now, depending on p^u and K^u, we face two cases:

- $v(p_e,K^u) - v(p_a) \geqslant p^u \geqslant cE(\theta) + rK^u$; then the operator can connect everyone without losing money;
- $v(p_e,K^u) - v(p_a) \leqslant cE(\theta) + rK^u$; to persuade consumers to be connected, the operator should fix a uniform price per consumer which is so low that its accounts would not be balanced.

Both cases may appear in different regions of a given country since costs are highly related to the geographical area under consideration.

[16] In developed countries, the political choice is generally to connect everyone. Universal service obligations also exist in water distribution where it can be justified by public health considerations. By contrast, there is no obligation to connect agents in natural gas or cable-tv distribution.

An intermediate solution between a linear tariff per kilometer and a uniform fee per consumer rests on the combination of a fixed part and a variable one, that is on a two-part tariff. The operator implements a tariff $p_f + \theta p$ for consumers connected at distance θ from the entry point of energy in the network. Under two-part tariff, the marginal consumer is defined by:

$$\begin{aligned} \breve{\theta}(p_f, p, K) &= \frac{\Delta v - p_f}{p} \\ \textit{where } \Delta v &\stackrel{def}{=} v(p_e, K) - v(p_a) \end{aligned}$$

In what follows, we consider successively two types of two-part tariff, each having a characteristic of the first-best solution. We first consider a two-part tariff constrained by a service obligation, i.e. the operator has to serve the same area (same marginal consumer $\widetilde{\theta}(c, K)$) and invest the same amount of capital K^* as in the first best solution. Then, we consider a two-part tariff for which the coefficient of the variable part is equal to the marginal cost per kilometer.

4.2 Second-best two-part tariffs

We know that the social welfare is maximum at $\widetilde{\theta}(c, K^*) = \Delta v / c\bar{\theta}$ since it is the first-best solution. The marginal consumer $\breve{\theta}(p_f, p, K^*) = \Delta v / c\bar{\theta}$ can be reached by any combination p, p_f such that

$$\begin{aligned} & p_f + \frac{p\Delta v}{c\bar{\theta}} - \Delta v = 0 \\ \textit{where} \qquad & p > 0 \textit{ and } p_f < \Delta v. \end{aligned} \tag{11}$$

For any prices above this frontier, the marginal consumer is smaller than $\widetilde{\theta}(c, K^*)$, that is closer to the head of the network. For instance, if p and p_f satisfy $p_f + p\Delta v / 2c\bar{\theta} - \Delta v = 0$, the marginal consumer is $\widetilde{\theta}(c, K^*)/2$.

We now examine under which conditions a pair of prices satisfying first best could also balance the budget of the operator. The budget constraint is:

$$\breve{p}_f \frac{\widetilde{\theta}(c, K^*)}{\bar{\theta}} + \frac{\widetilde{\theta}(c, K^*)^2}{2} \left(\frac{\breve{p}}{\bar{\theta}} - c \right) - rK^* = 0$$

Replacing p_f from the relation (11) we obtain:

$$\begin{aligned} & \frac{p}{2\bar{\theta}} \left(\frac{\Delta v}{c\bar{\theta}} \right)^2 + \left(\Delta v - p \frac{\Delta v}{c\bar{\theta}} \right) \frac{\Delta v}{c\bar{\theta}^2} - \frac{c}{2} \left(\frac{\Delta v}{c\bar{\theta}} \right)^2 - rK^* = 0 \\ \Leftrightarrow \qquad & \frac{\Delta v^2}{2(c\bar{\theta})^2} \left[c - \frac{p}{\bar{\theta}} \right] - rK^* = 0 \end{aligned}$$

It clearly appears that this equation can be satisfied only for $p < c\bar{\theta}$, i.e. if the variable part of the tariff is below the marginal cost per kilometer.

As illustrated in Figure 2, whereas a second-best linear price would require $p^{SB} > p^* = c\bar{\theta}$, the two-part tariff $\breve{p}_f$, $\breve{p}$ requires $\breve{p} < c\bar{\theta}$ and the financial equilibrium is reached thanks to the fixed part of the tariff.

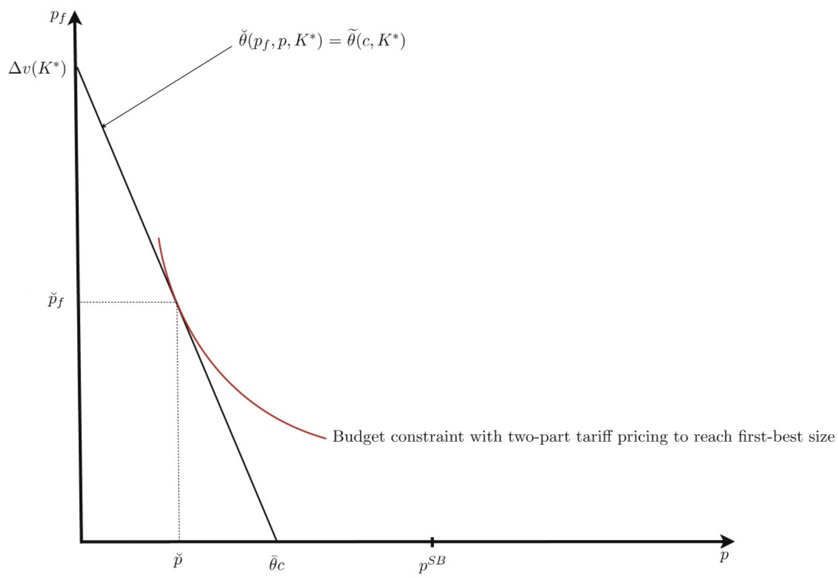

Figure 2: Two-part tariff

4.3 Characteristics of the second-best two-part tariff

From the former section, the pair $\breve{p}_f$, $\breve{p}$ that maximizes welfare under the budget balancing constraint satisfies the pair of equations:

$$\begin{cases} \breve{p}_f \frac{\widetilde{\theta}(c,K^*)}{\bar{\theta}} + \frac{\widetilde{\theta}(c,K^*)^2}{2}\left(\frac{\breve{p}}{\bar{\theta}} - c\right) - rK^* = 0 \\ \\ \breve{p}_f = \Big(v(p_e, K^*) - v(p_a)\Big)\left(1 - \frac{\breve{p}}{\bar{\theta}c}\right) \end{cases} \tag{12}$$

Solving this system, we obtain:

$$\begin{cases} \breve{p} = \bar{\theta}c\big(1 - A^*\bar{\theta}c\big) & \textit{per kilometer} \\ \\ \breve{p}_f = \big(v(p_e, K^*) - v(p_a)\big)A^*\bar{\theta}c & \textit{per consumer} \end{cases} \tag{13}$$

where A^* is the function defined in (6) valued at K^*.

Clearly the price per kilometer $\breve{p}$ is lower than the marginal cost per consumer $\bar{\theta}c$. The fixed part of the tariff is used to balance the accounts.

The fixed part of the tariff plays two roles. It simultaneously allows the operator to balance its accounts and it is a redistributive tool between customers. Indeed, since it is required both to connect as many clients as at first best and to balance the budget, one has to decrease the cost per kilometer of marginal consumers, and therefore to price the kilometer below marginal cost. As compared with first best and with second best under linear price, the clients close to the head of the network are worse off since they have little advantage from paying less for the small number of kilometers of line necessary to connect them; indeed they consume only a small amount of this service. On the other hand, they have to pay a fixed part which is higher for two reasons: i) it is used to balance the accounts and ii) the common cost is bigger since equipments at first best are more important than under second-best linear pricing. There exists a cross-subsidy from customers located close to the grid head to consumers located far from it. The graph of Figure 3 illustrates this redistributive effect.

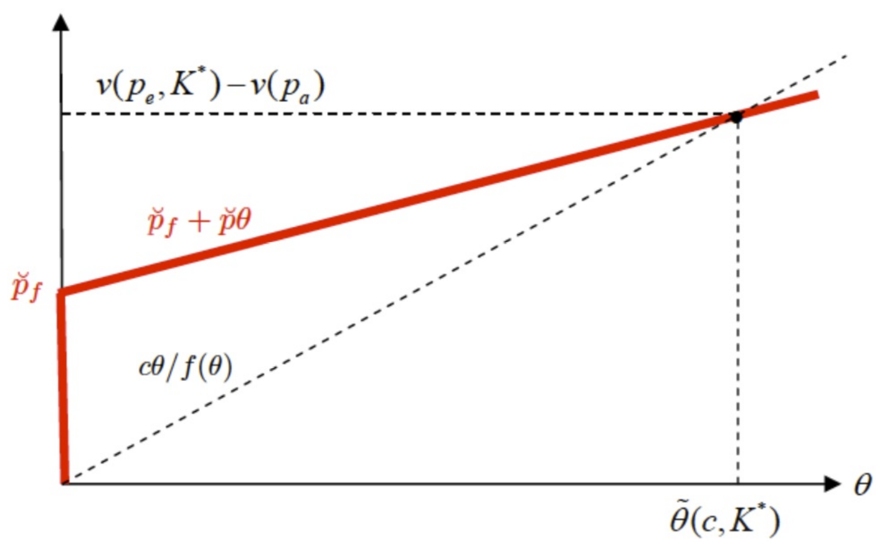

Figure 3: Two-part tariff under service constraint

4.4 Two-part tariff with marginal cost per kilometer

Pricing below marginal cost can be viewed as unfair as it results in the redistributive effect analyzed in the former section. Assume then that some regulation imposes that the variable part of the tariff charged to each consumer must reflect the unit kilometer cost of connection, $p = c\bar{\theta}$. Hence, the operator is left with financing the common costs, rK, through the fixed part of the tariff. One possible allocation of the common cost is the average value:

$$p_f = \frac{rK}{F\left[\check{\theta}(p_f, c, K)\right]}$$

$$where\ \check{\theta}(p_f, p, K) = \frac{(v(p_e, K) - v(p_a) - p_f)f(\check{\theta})}{c}$$

In the case where consumers are uniformly distributed between 0 and $\bar{\theta}$, the fixed part is equal to:

$$p_f = \frac{v(p_e, K) - v(p_a)}{2}\left(1 - \sqrt{1 - 2\bar{\theta}Ac}\right) \tag{14}$$

where A is defined in equation (6). The fixed part of the tariff is an increasing function of both the marginal cost of the capital installed r and the dispersion of consumers. Indeed, if potential consumers are highly dispersed the number of agents for whom connection is socially profitable is lower. Then, the operator has to increase the fixed fee per capita in order to cover the common costs. Moreover, when the marginal cost per kilometer c increases, the marginal consumer is nearer to the head of the network. Then there will be less consumers connected to the network and, hence, the operator has to charge each connected consumer more in order to cover the common cost rK. Here again, the impact of a variation of K on the fixed part p_f is ambiguous. However, assuming that the fixed part of the tariff is an increasing function of the level of capital installed is a reasonable assumption.

Given the coefficients of the two-part tariff constrained by the pricing rule of kilometers, the optimal level of capital under the uniform distribution of θ is determined by the following program:

$$\max_K \frac{\check{\theta}(p_f, c, K)}{\bar{\theta}}\left[\check{\theta}(p_f, c, K)\frac{c\bar{\theta}}{2} + p_f\right] - rK$$

The optimal level of capital is K^f, implicitly defined by:

$$-\frac{p_f}{c\bar{\theta}^2}\frac{\partial p_f}{\partial K} + \frac{v(p_e, K^f) - v(p_a)}{c\bar{\theta}^2}\frac{\partial v(p_e, K^f)}{\partial K} = r \tag{15}$$

The second term in the left-hand-side of equation (15) has the same form as the marginal gain in the first best solution (see equation (4)). Since we have assumed that the fixed part of the tariff is an increasing function of the level of capital, the first term in the LHS is negative. Thus, to satisfy the equality, we must have:

$$\left[v(p_e, K^f) - v(p_a)\right]\frac{\partial v(p_e, K^f)}{\partial K} > \left[v(p_e, K^*) - v(p_a)\right]\frac{\partial v(p_e, K^*)}{\partial K}$$

hence, $K^f < K^*$. We observe the same bias as in the linear tariff, but the distortion is, *a priori*, weaker since the cost per kilometer is constrained to be equal to the marginal cost per consumer $c/f(\theta)$.

5 Concluding remarks

In this paper, we have given economic foundations to the pricing of access to electricity distribution networks. We have shown when it is and when it is not optimal to connect all households to the network. Depending on the common costs and on the energy price differential, $p_a - p_e$, the marginal consumer is close or far from the head of the network. The implementation of first best through linear tariffs would entail two drawbacks: i) the net profit of the operator would be negative and ii) the charge paid by each consumer would be proportional to the distance, which would be viewed as discriminatory by politicians.

To skip these drawbacks, we have studied the behavior of a regulated distributor concerning the linear price level and the amount of capital installed. As we can suspect, under the obligation to balance the budget, the number of individuals for which the connection to the network is optimal is lower than at first best. Moreover, as we know for such activities with public service obligations, the distributors face additional constraints. We have studied the implementation of a uniform tariff across customers. When the operator implements a two-part tariff with a variable part equal to the marginal cost per kilometer for each consumer, the distortion is slighter than in the non uniform linear tariff case. Finally, when distributor has to serve as many consumers as at first best, we have found that the two-part tariff requires a variable part lower than the marginal cost per kilometer and the financial equilibrium is reached thanks to the fixed part of the tariff.

For further research, several ways may be followed to obtain a model closer to the real activity of the electricity distribution. In particular, we may introduce in the model thermal losses that are an important part of the distribution activity. Taking into account regional differences in the geographical distribution of consumers would allow to address distributive effects among regions. Finally, it would also be interesting to include embedded intermittent sources of electricity and to see how these new energy sources may change the design of the network and the behavior of the distributors.

Appendices

A Restriction of the shape of the function $v(p_e, K)$

To have an interior solution for the social surplus maximization at first best, we need to have a social surplus function concave in K. So, we have:

$$
\begin{aligned}
& \frac{\partial^2 S}{\partial K^2} < 0 \\
\Leftrightarrow \quad & \frac{\partial v}{\partial K}\frac{1}{c\bar{\theta}^2}\frac{\partial v}{\partial K} + \frac{\Delta v}{c\bar{\theta}^2}\frac{\partial^2 v}{\partial K^2} < 0 \\
\Leftrightarrow \quad & \frac{\Delta v}{c\bar{\theta}^2}\frac{\partial^2 v}{\partial K^2} < -\left[\frac{\partial v}{\partial K}\right]^2 \frac{1}{c\bar{\theta}^2} \\
\Leftrightarrow \quad & \frac{\partial^2 v}{\partial K^2} < -\frac{1}{\Delta v}\left[\frac{\partial v}{\partial K}\right]^2
\end{aligned}
$$

hence, we see that to have a positive interior solution, we need to have a function $v(p_e, K)$ strongly concave in K.

B The optimal network under budget constraint

B.1 Determination of the optimal price

From the budget constraint, we know that the optimal price is such that:

$$
\begin{aligned}
& \int_0^{\widehat{\theta}(p,K)} \left(p - \frac{c}{f(\theta)}\right)\theta dF(\theta) - rK = 0 \\
\Leftrightarrow \quad & \int_0^{\widehat{\theta}(p,K)} p\theta f(\theta)d\theta - \int_0^{\widehat{\theta}(p,K)} c\theta d\theta - rK = 0
\end{aligned}
$$

Since θ is uniformly distributed between 0 and $\bar{\theta}$, the previous equation is equal to:

$$
\begin{aligned}
& \frac{p}{\bar{\theta}} - rK = 0 \\
\Leftrightarrow \quad & \left(\frac{p}{\bar{\theta}} - c\right)\left[\frac{\theta^2}{2}\right]_0^{\frac{\Delta v}{p}} - rK = 0 \\
\Leftrightarrow \quad & \frac{(\Delta v)^2}{2\bar{\theta}p} - c\frac{(\Delta v)^2}{2p^2} - rK = 0 \\
\Leftrightarrow \quad & 2rKp^2 - \frac{(\Delta v)^2}{\bar{\theta}}p + c(\Delta v)^2 = 0 \qquad (16)
\end{aligned}
$$

Since the social welfare is a decreasing function of the price that should be fixed, p^{SB} is the smallest price which is compatible with the equation (16). So we find that p^{SB} is equal to:

$$p^{SB} = \frac{\frac{(\Delta v)^2}{\bar{\theta}} - \sqrt{\frac{(\Delta v)^4}{\bar{\theta}^2} - 8rKc(\Delta v)^2}}{4rK}$$

Let us set that:

$$A = \frac{2rK\bar{\theta}}{[v(p_e, K) - v(p_a)]^2}$$

Hence, we have:

$$p^{SB} = \frac{1 - \sqrt{1 - 4\bar{\theta}Ac}}{2A}$$

It is easy to check that p^{SB} exists if and only if $A \in [0, \frac{1}{4\bar{\theta}c}]$.

B.2 Example

Consider the example where $v(p_a) = 0$ and $v(p_e, K) = \frac{K^n}{p_e}$ with $n > 0$ and $p_e = 1$. Thus, we have:

$$\frac{\partial v}{\partial K} = nK^{n-1} \textit{ and } \frac{\partial^2 v}{\partial K^2} = n(n-1)K^{n-2}$$

To have an interior solution for the maximization of the social welfare under balancing budget, the second order condition leads to $0 < n < 1$. Let us assume that $n < 1/2$, in this case, we have a maximum in which $A = 2r\bar{\theta}K^{1-2n}$. For such n, we see easily that A increases with respect to K. We have to determine if p^{SB} is an increasing function of A:

$$\begin{aligned}
\frac{\partial p^{SB}}{\partial A} &= \frac{2A\frac{4\bar{\theta}c}{\sqrt{1-4\bar{\theta}Ac}} - 2\left(1 - \sqrt{1 - 4\bar{\theta}Ac}\right)}{(2A)^2} \\
&= \frac{8\bar{\theta}Ac - 2\left(\sqrt{1 - 4\bar{\theta}Ac} - (1 - 4\bar{\theta}Ac)\right)}{\left(\sqrt{1 - 4\bar{\theta}Ac}\right)(2A)^2} \\
&= \frac{2\left(1 - \sqrt{1 - 4\bar{\theta}Ac}\right)}{\left(\sqrt{1 - 4\bar{\theta}Ac}\right)(2A)^2} > 0
\end{aligned}$$

Hence, the price at second best is an increasing function of parameter A. As we have seen above, A increases w.r.t. K since K has a positive effect on the quality of the network; so the price in that case is an increasing function of the level of installed capital.

B.3 Optimal level of capital

The optimal level of capital comes from the maximization of the social welfare, that is:

$$\begin{aligned}
& \max_K \int_0^{\widehat{\theta}(p^{SB},K)} \left[v(p_e,K) - v(p_a) - \frac{\theta c}{f(\theta)} \right] dF(\theta) - rK \\
\Leftrightarrow \quad & \max_K \frac{\Delta v}{\bar{\theta}} \left(\widehat{\theta}(p^{SB},K) \right) - \frac{c}{2} \left(\widehat{\theta}(p^{SB},K) \right)^2 - rK
\end{aligned}$$

We know that the last customer that should be connected is defined by:

$$\widehat{\theta}(p^{SB},K) = \frac{v(p_e,K) - v(p_a)}{p^{SB}}$$

Hence, the previous program becomes:

$$\begin{aligned}
& \max_K \frac{p^{SB}}{\bar{\theta}} \frac{\Delta v}{p^{SB}} \left(\widehat{\theta}(p^{SB},K) \right) - \frac{c}{2} \left(\widehat{\theta}(p^{SB},K) \right)^2 - rK \\
\Leftrightarrow \quad & \max_K \frac{p^{SB}}{\bar{\theta}} \left(\widehat{\theta}(p^{SB},K) \right)^2 - \frac{c}{2} \left(\widehat{\theta}(p^{SB},K) \right)^2 - rK \\
\Leftrightarrow \quad & \max_K \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \left(\widehat{\theta}(p^{SB},K) \right)^2 - rK
\end{aligned}$$

The first order condition is:

$$\begin{aligned}
& \frac{\widehat{\theta}^2}{\bar{\theta}} \frac{\partial p^{SB}}{\partial K} + 2\widehat{\theta} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \left(\frac{\partial \widehat{\theta}}{\partial K} + \frac{\partial \widehat{\theta}}{\partial p^{SB}} \frac{\partial p^{SB}}{\partial K} \right) = r \\
\Leftrightarrow \quad & \frac{\partial p^{SB}}{\partial K} \left(\frac{\widehat{\theta}^2}{\bar{\theta}} + 2\widehat{\theta} \frac{\partial \widehat{\theta}}{\partial p^{SB}} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \right) + 2\widehat{\theta} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \left(\frac{\partial \widehat{\theta}}{\partial K} \right) = r
\end{aligned}$$

We can easily express the first derivative of $\widehat{\theta}$ with respect to the price p^{SB}:

$$\frac{\partial \widehat{\theta}}{\partial p^{SB}} = -\frac{\Delta v}{(p^{SB})^2} = -\frac{\widehat{\theta}}{p^{SB}}$$

So, the first order condition derived above is:

$$\begin{aligned}
& \frac{\partial p^{SB}}{\partial K} \left(\frac{\widehat{\theta}^2}{\bar{\theta}} - 2\widehat{\theta} \frac{\widehat{\theta}}{p^{SB}} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \right) + 2\widehat{\theta} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \left(\frac{\partial \widehat{\theta}}{\partial K} \right) = r \\
\Leftrightarrow \quad & \frac{\partial p^{SB}}{\partial K} \frac{\widehat{\theta}^2}{\bar{\theta}} \left[1 - 2\frac{\bar{\theta}}{p^{SB}} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \right] + 2\widehat{\theta} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \left(\frac{\partial \widehat{\theta}}{\partial K} \right) = r \\
\Leftrightarrow \quad & \frac{\partial p^{SB}}{\partial K} \frac{\widehat{\theta}^2}{\bar{\theta}} \left[-1 + \frac{\bar{\theta} c}{p^{SB}} \right] + 2\widehat{\theta} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \left(\frac{\partial \widehat{\theta}}{\partial K} \right) = r \\
\Leftrightarrow \quad & -\frac{\partial p^{SB}}{\partial K} \frac{\widehat{\theta}^2}{\bar{\theta}} \left[\frac{p^{SB} - \bar{\theta} c}{p^{SB}} \right] + 2\widehat{\theta} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2} \right) \left(\frac{\partial \widehat{\theta}}{\partial K} \right) = r
\end{aligned}$$

Besides, we have:

$$\frac{\partial \widehat{\theta}}{\partial K} = \frac{1}{p^{SB}} \frac{\partial v(p_e, K)}{\partial K}$$

The first order condition can be rewritten as follows:

$$
\begin{aligned}
& -\frac{\partial p^{SB}}{\partial K} \frac{\widehat{\theta}^2}{\bar{\theta}} \left[\frac{p^{SB} - \bar{\theta}c}{p^{SB}}\right] + 2\frac{v(p_e,K) - v(p_a)}{p^{SB}} \frac{1}{p^{SB}} \frac{\partial v(p_e,K)}{\partial K} \left(\frac{p^{SB}}{\bar{\theta}} - \frac{c}{2}\right) = r \\
\Leftrightarrow \quad & -\frac{\partial p^{SB}}{\partial K} \frac{\widehat{\theta}^2}{\bar{\theta}} \left[\frac{p^{SB} - \bar{\theta}c}{p^{SB}}\right] + \frac{v(p_e,K) - v(p_a)}{p^{SB}} \frac{(2p^{SB} - \bar{\theta}c)}{p^{SB}\bar{\theta}} \frac{\partial v(p_e, K^{SB})}{\partial K} = r
\end{aligned}
$$

C Intra-zone price adjustment

C.1 Determination of the fixed part of the second-best two-part tariff

The relation between the fixed part and the variable part of the tariff is given by $\breve{\theta}(p_f, p, K^*) = \widetilde{\theta}(c, K^*)$. Then, the variable part of the tariff is given by the zero-profit condition:

$$
\begin{aligned}
& \Pi = 0 \\
\Leftrightarrow \quad & \breve{p}_f F(\widetilde{\theta}) + \int_0^{\widetilde{\theta}} \left(\breve{p} - \frac{c}{f(\theta)}\right) \theta dF(\theta) - rK^* = 0 \\
\Leftrightarrow \quad & \breve{p}_f \frac{\widetilde{\theta}}{\bar{\theta}} + \int_0^{\widetilde{\theta}} \left(\frac{\breve{p}}{\bar{\theta}} - c\right) \frac{(\widetilde{\theta})^2}{2} - rK^* = 0 \\
\Leftrightarrow \quad & \Delta v \left(1 - \frac{\breve{p}}{\bar{\theta}c}\right) \frac{\Delta v}{\bar{\theta}^2 c} + \left(\frac{\breve{p}}{\bar{\theta}} - c\right) \frac{(\Delta v)^2}{2\bar{\theta}^2 c^2} - rK^* = 0 \\
\Leftrightarrow \quad & \frac{(\Delta v)^2}{\bar{\theta}^2 c} \left[\left(1 - \frac{\breve{p}}{\bar{\theta}c}\right) + \frac{1}{2}\left(\frac{\breve{p}}{\bar{\theta}c} - 1\right)\right] - rK^* = 0 \\
\Leftrightarrow \quad & \frac{(\Delta v)^2}{2\bar{\theta}^2 c} \left(1 - \frac{\breve{p}}{\bar{\theta}c}\right) = rK^* \\
\Leftrightarrow \quad & 1 - \frac{\breve{p}}{\bar{\theta}c} = \frac{2\bar{\theta}^2 c r K*}{(\Delta v)^2} \\
\Leftrightarrow \quad & \frac{\breve{p}}{\bar{\theta}c} = 1 - \frac{2\bar{\theta}^2 c r K*}{(\Delta v)^2} \\
\Leftrightarrow \quad & \breve{p} = \bar{\theta}c(1 - A\bar{\theta}c)
\end{aligned}
$$

Then, we can easily derive the fixed part of the tariff:

$$\breve{p}_f = \Delta v \left(1 - \frac{\breve{p}}{\bar{\theta}c}\right) = \Delta v(1 - 1 + A\bar{\theta}c) = \Delta v A \bar{\theta}c$$

C.2 Determination of the fixed part of the two-part tariff with kilometers priced at marginal cost

If the variable part in the two-part tariff is equal to the marginal cost per kilometer, the fixed part balancing the budget is such that:

$$
\begin{aligned}
& p_f = \frac{rK}{F\left[\check{\theta}(p_f, c, K)\right]} \\
\Leftrightarrow \qquad & p_f = \frac{rK\bar{\theta}}{\check{\theta}(p_f, c, K)} \\
\Leftrightarrow \qquad & p_f = \frac{rK\bar{\theta}^2 c}{\Delta v - p_f} \\
\Leftrightarrow \qquad & (p_f)^2 - (\Delta v)p_f + rK\bar{\theta}^2 c = 0
\end{aligned}
$$

The aim of the distributors is not to make profit, so they fix the smallest fixed part for which the budget constraint is balanced, that is:

$$
\begin{aligned}
p_f &= \frac{\Delta v - \sqrt{(\Delta v)^2 - 4rK\bar{\theta}^2 c}}{2} = \frac{\Delta v}{2}\left(1 - \sqrt{1 - 2\bar{\theta} c \frac{rK\bar{\theta}}{(\Delta v)^2}}\right) \\
&= \frac{\Delta v}{2}\left(1 - \sqrt{1 - 2\bar{\theta} A c}\right)
\end{aligned}
$$

The reasoning to determine the level of capital that should be installed is the same as the one developed in appendix B.3.

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