7 The results are almost identical for the cases with and without transaction costs because those costs apply to operations both on the spot market and the futures market, and because the limit on futures contracts to those with physical backing implies that the total number of spot and futures contracts is the same in both cases.

8 Recall that the model implies that if there are no transaction costs and the agent is risk neutral ($\gamma = 1$), the solution to the model will entail infinitely long positions in futures markets.

9 Source: Codelco. Estimate as of December 31, 1994.

10 It is interesting to note that the largest losses generated by the model occur during the second half of 1994 when the rapid and sustained increase in copper prices was difficult to predict *ex ante*. See Figures 3 and 6a.

References

ARRAU, P. (1990). "Intertemporal Substitution in a Monetary Framework: Evidence from Chile and Mexico." PRE Working Paper No. 549, *The World Bank*, December.

BASCH, M. and E. ENGEL (1993). "Temporary Shocks and Stabilization Mechanisms: The Chilean Case." In Eduardo Engel and Patricio Meller, eds., *External Shocks and Stabilization Mechanisms*. Washington: Inter-American Development Bank, 25-111.

DEL SOLAR, B. (1994). "Los Laberintos Recorridos por Dávila." *Qué Pasa*, March 5.

ENGLE, R.F. (1982). "Autoregressive Conditional Heteroskedasticity with Estimates of the Variance of United Kingdom Inflation." *Econometrica* 50:987-1007.

GALLANT, A. R., D.A. HSIEH, and G. TAUCHEN (1991). "On Fitting a Recalcitrant Series: The Pound/Dollar Exchange Rate, 1974-83." In W. A. Barnett, J. Powell, and G. Tauchen, eds., *Non-parametric and Semiparametric Methods in Economics and Statistics. Proceedings of the Fifth International symposium in Economic Theory and Econometrics*. Cambridge: Cambridge University Press.

Revista de Análisis Económico, Vol. 12, Nº 1, pp. 85-116 (Junio 1997)

GAS PIPELINE TRANSPORTATION: COMPETING WITHIN EX-ANTE INCREASING RETURNS TO SCALE AND SUNK COSTS*

RICARDO RAINERI
Pontificia Universidad Católica de Chile

Abstract

In the present decade the Chilean economy has witnessed a vigorous development in the natural gas industry, with cruel battles among competing corporations that look for the success of their gas pipeline projects. This paper analyzes industrial organization implications of gas pipeline transportation technology providing a theoretical foundation for what current believes on natural monopoly's saw as impossible: three gas wars and one gas-electric war. There are two key components that determine the capacity of a gas pipeline: ex-ante *increasing returns to scale, and the commitment value of sunk costs. Contrarily to the standard paradigm on natural monopolies, it is shown that* ex-ante *increasing returns to scale with sunk costs are not sufficient to preclude entry by competing firms, implying that the scale economy in the natural gas pipeline industry does not make it a natural monopoly. Welfare analysis show that strategic entry deterrence has a positive effect on welfare, effect that results from the threat that the potential intruders impose on the incumbent firm.*

* A prior version of this paper circulated under the title "Gas Pipeline Transportarion: Ex-Ante Increasing Returns to Scale With Sunk Costs" was presented at the XIII Latin American Meeting of the Econometric Society, Caracas - Venezuela, August 2-5, 1994. Also, a short version of it was presented at the XVIII IAEE International Conference, Washington, DC, July 5-8, 1995. I am grateful to Simon P. Anderson, Ronald D. Fischer, and participants for helpful comments. I thank an anonymous referee that lead to the actual version of the paper. Financial support from Fondecyt 1960397 is acknowledge.

I. Introduction

In the last years the Chilean economy has witnessed a tight competition among large multinational corporations for the introduction of natural gas in the centre and north of the country. The chances to import natural gas from Argentina and Bolivia, and his adoption as a substitute for other fuels, are considered as unique by the Chilean authorities who believe that in the short and medium term there are no competitive sources for this fuel. In this paper I analyze the industrial organization implications of gas pipeline transportation technology within a competitive enhancement regulatory regime leading to an explanation for the recent developments in the Chilean gas industry.[1]

The natural gas industry is characterized by a geographic isolation between producers and consumers. This isolation allows the distinction of two goods: the commodity gas as a raw material, and transportation.[2] The industry greatest complexity is in transportation, where we can distinguish between the pipeline capacity and the transportation service. Gas pipelines have two key technological elements that set their transportation capacity: *ex-ante* increasing returns to scale, and the commitment value of sunk costs. Since the capital invested in a gas pipeline is specific, then it's a natural instrument to commit to the market. I combine the power of capital commitment with *ex-ante* increasing returns to scale to analyze some alternative market allocations: the case of a protected monopoly, and the case of a duopoly with one incumbent and one potential entrant. For them, I do some numerical experiments to analyze how *ex-ante* increasing returns to scale and sunk costs mix into entry barriers.[3] The objective of these numerical experiments is to provide an understanding of three gas wars and one gas-electric war testified by the Chilean economy.

A distinctive feature in previous economic literature that analyzed cost functions to find out the attendance of innocent or strategic entry barriers are the use of cost functions that hide a constant marginal cost, the use of two period models' where sunk costs of a potential entrant cannot be explicitly accounted, and the fact that *ex-ante* the agents choose a capacity level that cannot be changed *ex-post*.[4] This paper overcomes these deficiencies accounting for a model where the marginal cost is not constant and, following Ware (1984), considered a three-stage game where the idea of sunk costs is modeled naturally. In Ware's model the incumbent and the entrant firm have a constant variable cost per unit of output, but here I use a nonlinear cost function. In the model, and *ex-post*, the cost function raise increasing marginal costs, where large *ex-ante* pipes' investment implies a small *ex-post* variable cost. That is, in the model pipes' investment is a cost reducing investment, the larger the *ex-ante* investment the more competitive the incumbent can be in the second period.

Numerical experiments for the gas industry show that *ex-ante* increasing returns to scale with sunk costs are not sufficient to preclude entry by a competing firm. For different sets of parameter values I get equilibrias that are: blockaded, deterred, or accommodated. If the incumbent firm cannot preclude entry, then he enjoys a first mover advantage, chooses a large pipeline and receives a large share of the

market; and if the incumbent firm strategically deters entry, then he over invests with respect to what a protected monopoly does. Welfare analysis shows that strategic entry deterrence has a positive effect on welfare. This positive effect results from the threat that the potential intruders impose on the incumbent firm. Ultimately, I get that welfare with a protected monopoly is larger than welfare with accommodated entry, but lower than welfare with entry deterrence.

The paper is organized as follow. Section II presents a brief resume of the major developments in the Chilean electric industry that leaded to the sharp developments in the gas pipeline industry. Section III sketch gas pipeline transportation capacity technology and the related cost structure. Section IV provides numerical examples for alternative market structures that backup the empirical evidence shown by the Chilean gas industry, where welfare implications are derived. Finally, section V concludes.

II. Gas Wars in the Chilean Energy Industry

The Chilean energy industry is among the most dynamics in the world. This dynamism results from the design of a competitive enhancement regulation for electricity and natural gas. In the world context, Chile has pioneer the process of privatization and deregulation of public utilities. Early, back in 1982, was promulgated the law decree DFL1 from the Mining Ministry that define the basis for the operation of electric utilities in a decentralized and privately owned industry. The basic principles of the DFL1 are:

- Explicit separation of generation, transmission and distribution.
- Competition at the power generation level.
- Generating companies are centrally dispatched by an independent operator.
- Licensed operation of transmission and distribution companies.
- Licensed construction of hydroelectric plants, and no licensing construction of thermal plants.
- Open-access schemes, where transport concessionaires must allow an open and nondiscriminatory use of their transmission systems.
- A pricing system for generation and transmission with operational or capacity expansion marginal prices or both.

It is within this framework that the transmission grid becomes a key player by providing open access to other players of the market (mostly generating companies, and large customers who demand over 2MW of capacity). That is, making power production competitive, and allowing distribution companies and large users to buy energy from generating companies, no matter their location in the grid.

It was only in the late 1980's, when electric utilities were private,[5] that competition begun. Open access in the transmission network and the fact that anyone can own and operate a power generation plant promoted new investments in generation capacity. The requirement for generating companies to be centrally dispatched by an independent operator was seen as a guarantee for the efficient operation of the system.[6]

In this competitive enhancement environment energy providers start looking for alternative fuels with which they can compete more effectively with other utilities. In the early 1990's, the more rational and non hydroelectric alternative to satisfy the growing energy requirements of the country it is found looking nearby. Argentina and Bolivia, two of the three Chilean neighborhood countries, have the advantage of owning large natural gas reserves that can be exported to Chile. Thus, natural gas appears as a cleaner fuel that can be used for domestic, commercial, and industrial purposes, but mostly as a fuel for thermoelectric generation.

The process by which natural gas is introduced in the country is long and disturbed. On one hand, a key role in the process was played since 1994 by the Energy Minister, Alejandro Jadresic, who pursued a strategy where the government stays off the discussion and political pressures of the industry. The justification was that a proper regulatory regime for the industry must be work out perfectly before the granting of any private gas pipeline transportation concession; and second, to avoid the same upheavals of the political process behind the design of the regulatory regime under the Energy Minister that preceded Alejandro Jadresic. In July 1995 the uncertainty on the regulatory framework for the gas industry ended by the publication of the new code that regulate transportation and distribution of natural gas.[7] In brief, this new law, Decree Nº 263 of the Economic Ministry, in its basics principles establishes:

- Explicit separation of gas transportation and distribution.
- Licensed operation of transportation and distribution companies.
- Competition among firms that transport natural gas, allowing in the same zone more than one private concession for the provision of the service.
- Open-access schemes, where transport concessionaires must allow open and nondiscriminatory use of the gas pipeline to those who ask for transportation services. Open-access applies up to available transportation capacity. Open-access also means that each transportation contract should be signed after the gas pipeline owner runs an open tender among those who are interested in a transportation contract.
- A free pricing system for gas transportation where transportation charges are predetermined by the concessionaire firm. Free prices at the distribution level apply as long as the rate of return obtained by distribution companies remains in a ± 5% band around the industry cost of capital.

Another important ingredient that contributed to the development of a competitive industry is the Argentinean and Chilean governments' suppression of all the restraints that apply to natural gas import and export.

Table 1 summarize the major structural changes in the Chilean Energy Industry that leaded to the sharp changes in the gas industry.

For the design of a competitive enhancement regulatory regime for the gas industry was needed a mayor change in the authorities' current beliefs, who by late 1993 considered gas pipeline transportation as a natural monopoly that needed an exclusive concession to assure the feasibility of the project. In early 1994, the change in government authorities came with a change in beliefs. The new Energy Minister was convinced that competition among gas pipelines was feasible, leading for the design of a competitive enhancement regulatory regime for the gas industry.

TABLE 1

STRUCTURAL CHANGES IN THE ENERGY INDUSTRY THAT LEAD THE CHANGES IN THE GAS INDUSTRY

1982	Law Decree DFL1 that define a competitive regulatory regime for privately owned electric utilities'
Second part of the 1980's decade	Large privatization process where most public electric utilities were privatized
Since 1992	Internationalization of Chilean electric utilities
1995	By-law Nº 263 that define the rules for natural gas transportation and distribution.

While competition among different gas pipeline projects started before the publication of the regulation code for the industry, it was only with the publication of the by-law Nº 263 that competition strongly shaped up. Today we know from four gas wars among alternative projects in different regions of Chile. Table 2 summarize the four wars and the competing projects. From all of them, the most known war is the one between GasTrasandino and GasAndes, a war that started even before the new by-law for the gas industry was known.

In the early 1990's only one firm, GasTrasandino, publicly promoted a gas pipeline to supply natural gas to the central zone of the country. GasTrasandino projected a gas pipeline that crossed the Andes Mountains from Neuquen-Argentina to Chillan-Chile, and from there to Santiago-Chile. Notwithstanding, the delays that suffer the design of the regulatory regime provided enough time for a second firm, Gas-Andes, to plan an alternative project also to supply natural gas in the central zone of the country. At odds with GasTrasandino project, GasAndes considered a much shorter gas pipeline, crossing the Andes Mountains from Mendoza-Argentina straight to Santiago-Chile. Thus, with both projects surrounding the market and the publication in 1995 of the by-law Nº 263, GasTrasandino and GasAndes applied for a concession to transport natural gas to the central zone of the country. Finally, in September 1995 the government granted both concessions.

Once GasTrasandino and GasAndes obtain their concessions' a cruel battle for success begun. Politicians and entrepreneurs that witness the battle agreed that the winner will be the first who compromises enough long term contracts for natural gas transportation that make the project economically feasible. After each consortium announced his "Open Seasons" asking for natural gas transportation contracts, only GasAndes have secure enough long term contracts that assure the success of the project. GasTrasandino was forced to postpone his project until future demand increases justify the construction of a second gas pipeline.

As this section shows, regulation in Chile has been intended to promote private decisions based on economic signals sent through prices. Consequently, the developments of the electric and gas industries have been decided by private agents

TABLE 2

GAS-ELECTRIC WARS IN THE CHILEAN ECONOMY

1994-1996	Gas pipeline War 1: • GasTrasandino (1.200km gas pipeline from Neuquen-Argentina to the VIII Region of Chile and to Santiago-Chile). • GasAndes (465km gas pipeline from Mendoza-Argentina to Santiago-Chile).
1994-1997	Gas pipeline War 2: • GasSur (400km gas pipeline from Neuquen-Argentina to Concepción-VIII Region of Chile). • GasTrasandino (400km gas pipeline made from the GasTrasandino pipeline between Neuquen-Argentina and Chillan-VIII Region of Chile, and then an extension from Chillan to Concepción-VIII Region of Chile).
1996-1997	Gas pipeline and Electric War 3: • Gasoducto Atacama (900km gas pipeline from Campo Durán-Argentina to Mejillones-II Region, Chile). • ElectroAndes (500km high voltage transmission line from Salta-Argentina to Antofagasta-II Region, Chile.) • Norgas (880km gas pipeline from Tartagal-Argentina to Tocopilla-II Region, Chile).
1996-1997	Gas pipeline War 4: • GasAndes (115km gas pipeline from Santiago to Quillota-V Region, Chile). • ElectroGas (115km gas pipeline from Santiago to Quillota-V region Chile).

attracted to compete for investment opportunities, where exclusive rights have not been provided.

III. Technology and Costs

For a gas pipeline the capacity or maximum gas flow depends on three elements:[8] pipeline diameter, number of compression stations, and the number of parallel pipes or looping in some sections of the tube.

Given a d inches diameter pipe, gas pipeline capacity can change only by shrinking the distance between the compression stations, and/or adding parallel pipes. It is reasonable to think that pipeline diameter is a variable that belongs to the input choice set before the gas pipeline is built. Once the gas pipeline is build, the pipe diameter is no longer a part of the input choice set. It is also reasonable to think that after the gas pipeline is build the unique variable that affects the pipeline capacity is the number of compression stations. For simplicity here I do not allow for looping, because this is an intermediate step of building another pipeline.[9]

There is a sharp distinction between fixed cost and sunk cost.[10] In a timeless view of the world fixed costs are those costs that a firm incurs to produce and are independent of the scale of production. However, with sunk cost we cannot endure a timeless view of the world. Sunk costs are by definition a multiperiod phenomena. Sunk costs are costs that cannot be eliminated in a short or medium term even by the total cessation of production. Sunk costs are fixed costs that go beyond the current period of production. Sunk costs differ from fixed costs in the sense that only fixed costs are part of the current opportunity cost of production. Gas pipes imply an investment that produces a stream of benefits over a long horizon. But this investment cannot be reversed without a considerable loss. That is, gas pipeline investors are stuck with it for many periods.

Once a gas pipeline is built, the pipe diameter becomes a fixed factor and pipe investment becomes a sunk cost. This dichotomy between fixed versus variable factors, and sunk versus non sunk costs makes reasonable an analysis of the cost functions before and after the gas pipeline diameter becomes a fixed factor of production. To analyze the cost function I build a simple two period model. In the first period the firm commits to the pipeline diameter, and pays out the investment related to it. Then, in the second period it chooses the number of compression stations, and with it the pipeline capacity.

Let Y be the per-period gas pipeline capacity. When the decision to build a gas pipeline is made the capacity is given by an increasing return to scale technology.[11] This technology is represented by:

$$Y = Ad^{\alpha}n^{\gamma}$$

where $\alpha > 1$, $0 < \gamma < 1$, d is the pipe diameter, n is one divided by the distance between the compression stations, i.e., the number of compression stations divided by the pipeline length, and A is an efficiency parameter.[12]

For the parameters α and γ within these ranges we have that the gas pipeline capacity is given by an increasing returns to scale technology, with increasing returns to the factor in the pipeline diameter, and decreasing returns to the factor in the number of compression stations.

Since the technology that defines a gas pipeline capacity is with increasing returns to scale, we have that gas pipelines qualify as a natural monopoly.[13] However, this qualification of natural monopoly applies only before the pipeline is build. *Ex-post*, when the gas pipeline is in place, pipes' diameter cannot change. Thus, *ex-post* the only variable factor is the number of compression stations. *Ex-post*, we can distinguish between sunk and variable costs. Pipes' investment is a sunk cost, while the investment in compression stations is an *ex-post* variable cost.[14]

Ex-post, for the above technology we have that the cost functions for total cost, variable cost, sunk cost, marginal cost, average variable cost, and average total cost are:[15]

1. $C(\omega, Y; \bar{d}) = VC(\omega, Y; \bar{d}) + SC(\omega; \bar{d})$,

2. $VC(\omega,Y;\overline{d}) = Y^{\frac{1}{\gamma}} A^{\frac{-1}{\gamma}} \overline{d}^{\frac{-\alpha}{\gamma}} \omega_n$,

3. $SC(\omega;\overline{d}) = \omega_d \overline{d}$,

4. $MC(\omega,Y;\overline{d}) = \frac{1}{\gamma} Y^{\frac{1-\gamma}{\gamma}} A^{\frac{-1}{\gamma}} \overline{d}^{\frac{-\alpha}{\gamma}} \omega_n$,

5. $AVC(\omega,Y;\overline{d}) = Y^{\frac{1-\gamma}{\gamma}} A^{\frac{-1}{\gamma}} \overline{d}^{\frac{-\alpha}{\gamma}} \omega_n$,

6. $AC(\omega,Y;\overline{d}) = AVC(\omega,Y;\overline{d}) + \frac{SC(\omega;\overline{d})}{Y}$,

where $\omega = (\omega_d, \omega_n)$ is the input price vector. For a given pipeline length, ω_d is the pipes' price per unit of diameter, and ω_n is the per-unit compression stations' price. Since $0<\gamma<1$ we have that *ex-post* the marginal cost is always larger than the average variable cost. Also, the marginal cost and the average variable cost, are increasing in the capacity. When we compare the *ex-post* marginal cost with the average variable cost we obtain that their difference is increasing in the capacity.

Ex-ante, for the above technology we can show that the cost functions for total cost, average cost, and marginal costs are:

1. $C(\omega,Y) = Y^{\frac{1}{\alpha+\gamma}} \kappa(\omega)$,

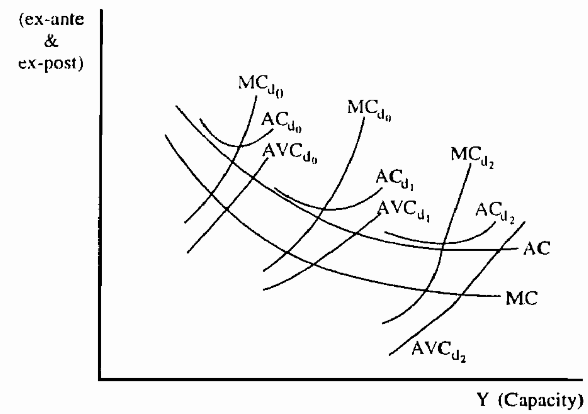
2. $AC(\omega,Y) = Y^{\frac{1-\alpha-\gamma}{\alpha+\gamma}} \kappa(\omega)$,

3. $MC(\omega,Y) = \frac{1}{\alpha+\gamma} Y^{\frac{1-\alpha-\gamma}{\alpha+\gamma}} \kappa(\omega)$,

where $\kappa(\omega)$ is the per-unit of capacity cost function when the input price vector is ω.[16] Because $\alpha+\gamma>1$ we have that the marginal cost is always below the average cost for each pipeline capacity level. As we expect for a technology with increasing returns to scale, we get that the marginal cost and the average cost are decreasing in the capacity. Also we get that the *ex-post* marginal cost isn't always below the *ex-ante* marginal cost.

Figure 1 shows the *ex-ante* and the *ex-post* cost curves' for pipe diameters d_0, d_1 and d_2. *Ex-post* marginal cost and average variable cost curves' are increasing in the capacity. Also, *ex-post* the marginal cost is above the average variable cost. The *ex-post* total average cost has a U shape because it adds to the average variable cost the pipes' investment or sunk cost. The *ex-ante* average cost is the envelope of the *ex-post* total average cost curves. The *ex-ante* marginal cost is obtained from the *ex-post* marginal cost curves. It's build by choosing for each pipeline capacity level the diameter that gives the small *ex-ante* average cost, where the *ex-ante* marginal cost is given by the *ex-post* marginal cost of that capacity. *Ex-ante*, the marginal cost and average cost curves are decreasing in the level of capacity, and the average cost curve is always above the marginal cost curve.

FIGURE 1



IV. Market Structure

In this section I present the two alternative environments used to represent the industry. The first one, characterizing the old natural monopoly wisdom, is a two period economy, where only one firm confronts the whole market demand. This firm in the first period chooses pipeline investment, and in the second period is a protected monopoly with a fixed pipeline diameter where pipeline investments is a sunk cost. The second economy that appeals to the new gas pipeline industry wisdom, is a duopoly in a three period economy, where one incumbent firm and one entrant firm compete for the market. Sequentially in the first and second period each firm chooses pipeline investment, having both firms in the third period a fixed pipe diameter, where pipes' investments are a sunk cost. At the third period the firms compete supplying the compromised capacity. For different sets of parameter values for the protected monopoly and the duopoly with one incumbent and one potential entrant I carry out some numerical experiments. The objective of these experiments is to get some insight about market structure and welfare implications of the different equilibrias.

4.1 Protected monopoly

In the case of the protected monopoly and to treat pipeline investment as a sunk-cost we have to assume a two period world. In the first period the firm chooses the pipeline diameter and pays pipeline investment. In the second period, the firm chooses the number of compression stations and the market supply of capacity units. The equilibrium concept is defined by the idea of a sequentially rational production plan. To found it we work backward. In the second period, and for a given pipeline, we solve for the number of compression stations and the market supply of capacity units. Then, in the first period, we solve for the pipeline diameter. Appendix 1 provides a formal proof for the existence and properties of the unique Equilibrium for this economy. It should be notice that the solution obtained here is the same as the one that we would obtain with a protected monopoly that chooses simultaneously the pipeline diameter and the supply of capacity units.

4.2 One incumbent and one entrant

Here, in the one incumbent and one entrant three-stage game, the idea of sunk costs emerges naturally. Ware (1984) notes that in a three-stage game we can separate the entrant capacity decision, involving a sunk cost, from the quantity equilibrium established after entry.[17] Here the idea is that with a three stage game we can separate the entrant cost efficiency decision from the quantity equilibrium establish after entry.

The time description of the game is as follow. In the first period an incumbent firm chooses a pipeline diameter d_I, and pays for pipeline investment $\omega_d d_I$. In the second period, conditional on the incumbent pipeline diameter d_I, an entrant firm chooses a pipeline diameter d_2, and pays for pipeline investment $\omega_d d_2$. Finally, in the third period, and conditional on pipeline diameters, each firm chooses a supply of capacity units. For structures like this, but with linear cost functions, exist three different types of equilibria:[18] blockaded, deterred, and accommodated.

Equilibria are *blockaded* when the incumbent firm behaves as if there is no threat of entry by the entrant firm. This can be the case of a small market, where with two or more competing firms profits can drop below zero. Equilibria are *deterred* when the incumbent firm successfully precludes entry by the entrant firm. But to achieve this, the incumbent modifies his strategy. Then precluding entry is a costly strategy. Finally, equilibria are *accommodated* when for the incumbent firm is more attractive to allow the entrance of new competitors instead of attacking them to successfully preclude their entry.

The idea of scale economies as an entry barrier is an old idea in the literature. Schmalensee (1981) investigates the effects of scale economies and sunk costs as an entry barrier. He uses a two-stage game, where exist an exogenous plant size k_0 that determines the minimum efficient scale of production. In his model scale economies are such that firms with a capacity below k_0 have prohibitively high costs, if firms can buy units of capacity above k_0 at a constant per-unit cost. He finds that the pre-entry present value of the excess profits that exceed the capital cost of a firm of minimum efficient scale, cannot be protected from entry. As he argues, *this upper bound and widely accepted estimate of scale economies imply that the entry barrier considered here are generally of little quantitative importance*. At odds with the model developed by Schmalensee, the present is one where *ex-ante* increasing returns to scale are an instrument by which investment reduce *ex-post* variable costs. Large pipelines have small variable costs. That is, pipeline investment is a cost reducing investment. The incumbent firm by choosing different pipeline diameters changes the entrant minimum efficient scale of production, i.e., the minimum efficient scale of production is endogenously determined by the incumbent firm in the model. The incumbent can trust on scale economies to choose *ex-post* variable costs, and use this to determine the entrant minimum efficient scale of production. Therefore, in this model we have that scale economies act as a strategic variable to deter entry, and play a large role than the one that they play in Schamelensee paper. In this sense, we can say that the strategic advantage available to the first mover is stronger.

Equilibria

An equilibrium in this economy is defined by the idea of Subgame Perfect Equilibrium. The idea of Subgame Perfect Equilibrium is that the behavior that in any part of the game can be regarded as a game should be a Nash Equilibrium of that Subgame. Appendix 1 provides a formal definition and proof of the existence and properties of the unique Subgame Perfect Equilibrium of this economy.

In the following subsection, and for different sets of parameter values, I do some numerical experiments to analyze some properties of the alternative economies.

4.3 Experiments

For different sets of parameter values in this section for the protected monopoly and the duopoly with one incumbent and one potential entrant I carry out some numerical experiments. The objective of these experiments is to get some insights on industrial organization. Also, I carry a welfare ranking of the equilibria under the protected monopoly and duopoly.

For a better interpretation of the numerical experiments that follow it should be kept in mind, as proven in Appendix 2, that *ex-ante* increasing returns to scale implies that at any period, when a pipeline is built, economic efficiency calls in to build just one pipeline. However, this says nothing on the efficiency to build additional pipelines at other periods.[19] Also, once a gas pipeline is built, increasing returns to scale are sink, and the investment associated to the pipes becomes a sunk cost. In this sense, the social planner second best Ramsey solution, where the price is equal to the average cost, is time inconsistent. This is because *ex-post*, the social planner has an incentive to renege on sunk investments, so the firm could not recoup all his costs. As an alternative, in Appendix 2, I propose an alternative Ramsey solution that is *ex-post* efficient and time consistent. This solution demands a small pipe and calls for a more intensive use of it. The alternative Ramsey solution is one that equates the market price of the capacity with the *ex-post* marginal cost, and the average cost. Assuring that the firm can recoup all his costs.

For the experiments that follow assume that the inverse demand function for capacity units is linear, i.e., $P(Y) = a - bY$, where $a > 0$ and $b > 0$. Also, we must choose production function parameters A, α, γ; inverse demand function parameters

a, b; and the market price per unit of pipe diameter and compression station (ω_d, ω_n).

Following Lévy-Lambert and Dupuit (1975) I choose values for $\alpha = 8/3$ and $\gamma = 1/2$. The efficiency parameter value A, the inverse demand function parameter values a and b, and the factor prices ω_d and ω_n are freely chosen to get an interesting set of equilibria. In the duopoly and for each set of parameter values I solve backward for the Subgame Perfect equilibria.[20] The different parameter values and experiment results appear in Tables 3 to 5. In Table 3, I show six different sets of parameter values; in Table 4, I show incumbent, entrant, and pure monopoly choices of pipeline diameter, supply of capacity units, and profits at the equilibrium; and finally, in Table 5, I show the level of welfare associated to each equilibrium, where welfare is measure as the sum of consumer and producer surplus.

TABLE 3

PARAMETER VALUES

Exp.	A	a	b	ω_d	ω_n
1	1.00	2.50	1.00	0.90	0.10
2	1.00	3.00	1.00	0.90	0.10
3	1.00	3.50	1.00	0.90	0.10
4	2.50	2.50	1.00	0.90	0.10
5	3.00	2.50	1.00	0.90	0.10
6	1.00	2.50	1.00	0.40	0.60

In experiment number 1, see Table 4, we find that the incumbent firm successfully precludes entry by the entrant firm. The incumbent chooses a pipeline diameter of 0.9502, in the third period has a supply of capacity units equal to 1.1049, and receives profits of 0.5260. For this case we get that the protected monopoly and the duopoly allocation are the same. In the duopoly and in Bain's terminology we have that entry is blockaded.

With respect to experiment number 1, in experiment number 2 we increase the size of the market by a parallel shift in a northeast direction of the demand function. In this situation the incumbent firm precludes entry by the entrant firm. However, now the protected monopoly and the duopoly allocation differ. With respect to the protected monopoly, in the duopoly the incumbent chooses a large pipeline diameter, supply a large number of capacity units, and obtain small profits. Now we have that for the incumbent firm precluding entry is a costly strategy. In the duopoly and in Bain's terminology we have that the equilibrium is deterred.

In experiment number 3 we increase the size of the market a bit more by a parallel shift in a northeast direction of the demand function. Now in the duopoly the incumbent and the entrant firm share the market, where the incumbent firm enjoys a first mover advantage. The incumbent chooses a large pipeline diameter, supply a large number of capacity units, and receive large profits. The pure monopoly is one with a pipeline diameter larger than any other firm in the duopoly case, has a small total supply of capacity units, and obtains large profits. In the duopoly and in Bain's terminology we have that the equilibrium is accommodated.

TABLE 4

EXPERIMENTS

Exp.	Incumbent			Entrant			Monopoly		
	d_1	Y_1	π_1	d_2	Y_2	π_2	d_m	Y_m	π_m
1	0.9502	1.1049	0.5260	0.0000	0.0000	0.0000	0.9502	1.1049	0.5260
2	1.2500	1.4557	1.0586	0.0000	0.0000	0.0000	1.0200	1.3762	1.1463
3	1.0190	1.1017	0.4065	1.0140	1.0973	0.4032	1.0762	1.6392	1.9000
4	0.8200	1.1950	0.7556	0.0000	0.0000	0.0000	0.7200	1.1444	0.7825
5	0.6455	0.7769	0.0918	0.6383	0.7680	0.0872	0.6802	1.1502	0.8256
6	1.3833	0.7812	0.1219	1.3652	0.7714	0.1168	1.4536	1.1557	0.8632

With respect to experiment number 1, in experiment number 4 we increase the efficiency parameter A from 1.0 to 2.5. Now for the duopoly we get that the incumbent strategically deters entry. We have that the protected monopoly and the duopoly allocations differ. With respect to the protected monopoly, in the duopoly the incumbent chooses a large pipeline diameter, supply a large number of capacity units, and obtain small profits. That is, entry deterrence is a costly strategy.

With respect to experiment number 4, in experiment number 5 by a further increase in the efficiency parameter A up to 3, in the duopoly we get accommodated entry. The incumbent firm fails to preclude entry, but enjoys a first mover advantage. He chooses a large pipeline diameter, supply a large number of capacity units, and receives large profits. The protected monopoly is one with a large pipeline than any other firm in the duopoly, has a small supply of capacity units, and obtains large profits.

Finally, in experiment number 6 we change the pipe diameter price and the compression station price. Pipeline price per unit of diameter decreases from 0.9 to 0.4, and compression station's price increases from 0.1 to 0.6. For the duopoly game we get an equilibrium with accommodated entry. The incumbent cannot preclude entry, but enjoys a first mover advantage. He chooses a large pipeline diameter, supply a large number of capacity units, and receives large profits. The protected monopoly is one with a large pipeline than any other firm in the duopoly, has a small supply of capacity units, and obtain large profits.

From these experiments we see that increases in market size, or improvements in productivity, lessen the incumbent protection against competition. In fact, the incumbent prefers a situation where he is alone in a small market, instead of having to share a big one with someone else; and he prefers a stagnation in technological innovation, instead of having to share the market when some more advanced technologies become available. Now, when we compare the duopoly in experiment number 1 with the one in experiment number 6 we find that the first mover strategic advantage is lessened when the proportion of total costs that can be sunk before production takes place, decrease. That is, sunk costs are an important strategic parameter in the model.[21] Sunk costs are important not by being sunk, but because they commit the firm to put something that confine it to be around in the following periods.

TABLE 5

EXPERIMENTS

Exp.	Welfare	
	Duopoly	Monopoly
1	1.1364	1.1364
2	2.1181	2.0932
3	3.2273	3.2435
4	1.4695	1.4374
5	1.3724	1.4870
6	1.4441	1.5310

For the different parameter values, in Table 5 we compare welfare between the duopoly and the protected monopoly, where we measure welfare as the sum of consumer and producer surplus. In the table we find that if the incumbent firm accommodates entry, then welfare is larger with the protected monopoly than the duopoly; if the incumbent firm strategically deters entry, then welfare is larger with the duopoly than the protected monopoly; and if entry is blocked, then welfare is the same with the protected monopoly and the duopoly. What happen is that with accommodated entry the increase in the consumer surplus, due to a small price and a large supply of capacity units, does not compensate for the additional investment required when both firms are in the market. Here entry prevention has desirable welfare consequences, as consumers benefit from lower prices, and the avoidance of sunk investment by the second firm is a net social gain.[22] However, if we only look at the consumer surplus, from Tables 4 and 5 we find that the consumer surplus in the duopoly is large or equal to the consumer surplus in the protected monopoly. Thus, in this sense, actual competition is better.

The experiments show us that gas pipeline sunk costs rise different market structures. The particular market structure depends on parameter values. In particular, in the one incumbent and one entrant game we find that the incumbent firm can deter, block or accommodate entry by a competing firm. Welfare comparisons between the different market structures show that actual competition can be worse than the pressure imposed by a potential competitor on the incumbent firm. This is because actual competition on one side increase the consumer surplus through a large supply of capacity units at a lower price, but on the other it requires additional investment by the competing firm that does not compensate for the gain in the consumer surplus. In this sense, the threat of potential competition is better than actual competition.[23]

From the last results we can conclude that *ex-ante* increasing returns to scale is not sufficient to preclude entry by competing firms when the factor that feeds them becomes a fixed factor of production.

V. Summary

In this paper I analyze the gas pipeline transportation industry. I find that gas pipelines have two key elements that decide their transportation capacity: *ex-ante* increasing returns to scale, and the commitment value of sunk costs.

Ex-ante, pipeline capacity is determined by an increasing return to scale technology, where large investments impel a reduction in the *ex-post* variable cost. *Ex-post*, once the gas pipeline is built, the technology is driven by decreasing returns with respect to the pipeline capacity. *Ex-post*, pipeline investment is sunk, and this is a natural mean by which the firm commits to the market.

I analyze some alternative market allocations: the case of a protected monopoly, and the case of a duopoly with one incumbent and one potential entrant. For them, and with different sets of parameter values, I do some numerical experiments. They show that gas pipelines rise different market structures. In particular, in the duopoly I find that the incumbent firm can deter, block or accommodate entry of a competing firm. What equilibria we get depend on market size, productivity, and the weight of sunk costs. Welfare analysis shows that true competition can be worse than potential competition. For the duopoly this is because the increase in the consumer surplus, due to a small price and a large supply of capacity units, does not compensate for the additional investment that is required when both firms are in the market. In this sense, the threat of potential competition is better than actual competition. Finally, we conclude that *ex-ante* increasing return to scale with sunk costs is not sufficient to preclude entry by competing firms when the factor that feeds the scale returns becomes a fixed factor of production.

The Chilean government decision to stay off the upheavals of the political process during the design of the regulatory mechanism was a clear change in the traditional belief that gas pipeline transportation is a natural monopoly. The authority designed a set of rules that transfer to private agents the investment decision based on the feasibility of the alternative projects. Seeking for successful investment opportunities, investors are confronted with a tight competition from other agents that purse the same objective. There are no privileges, so the cruel market chooses on the kindness of the different projects. Further, the concept of "open access" present in the Decree Nº 263 of the Economic Ministry imply that any potential user of the pipeline can ask for transportation services at a non discriminatory price. The supply of the install capacity is not completely under the gas pipeline owner's control, being requested to run a public bid among those interested to sign a contract to reserve gas pipeline capacity. But, the *ex-post* competition in the supply of capacity units is still an open issue. The relevance of the concept of "open access" for competition rest on the large lumpy investment that are required by a gas pipeline, investment that through the idea of "open-access" become spray for individual customer giving them a real chance to access transportation services.

Even though the analysis in this paper focuses on the chances of competition among gas pipeline transportation services, the analysis can be easily extended to other environments such as high voltage transmission lines or water supply. For example, we have already witnessed competition in electricity transmission, where two large generating companies, Endesa-Transelec and Colbún, have installed competing transmission lines within the central interconnected electric system of Chile. The analysis can be extended further where, for example, a geographically isolated hydroelectric power generation plant plus transmission services is a competing project to an on site gas fueled power generation plant plus gas pipeline transportation services.

The proper design of the regulatory mechanism for gas pipelines has succeeded promoting an ***ex-ante*** tight competition among competing projects, where commitment has taken place in the "Open Seasons" races to assure enough contracts for natural gas transportation. The most benefited from competition have been those in the need of transportation services. Future natural gas fueled electric power plants are among the winners, acceding to more competitive gas pipeline charges that put them in good stand to compete with hydroelectric power plants. At the end, the increased competition among electricity generation will benefit small customers. Nevertheless, the *ex-post* competition in the supply of gas pipeline transportation services is an open issue.

APPENDIX 1
MARKET STRUCTURE

In this appendix I prove the existence of an equilibrium and present the properties of the two environments analyzed in section IV. The first one is a protected monopoly in a two period world, where at the second period the firm has a fixed pipeline diameter where pipeline investments are a sunk cost. The second one is a duopoly defined in a three period economy, where one incumbent firm and one entrant firm compete for the market. In the third period both firms have fixed pipes' diameters, and pipes' investments are a sunk cost, so they compete supplying capacity units.

For the demonstrations that follow let's assume that $P(Y)$ is the inverse demand function, and that:

(1) $P(Y) \in C^2$ and $P'(Y) < 0$,

(2) $\exists \overline{Y} \in \Re_{++}$ s.t. $P(\overline{Y}) = 0$,

(3) $P''(Y) + 2P'(Y) \leq 0$.

The first assumption refers to the continuity and the slope of the demand function. The second assumption assures that any production plan chosen by a firm is in a non empty, compact and convex set. The third assumption is a restriction on the curvature of the demand function.

Protected Monopoly:

Given ω and d we have that $VC(\omega,Y;d)$ is a C^2, and strictly convex function of Y, and that $P(Y)Y$ is concave in Y. Thus the firm second period optimization problem is:

$$\pi(d,\omega) = Max_{Y \geq 0} P(Y)Y - VC(\omega,Y;d).$$

Where given ω and d, $\pi(d,\omega)$ is the *ex-post* gross profit function. We have an optimization problem of a strictly concave function, in a non-empty, compact and convex set. Therefore, a maximum exists and is unique. For an interior solution first order conditions imply that $P'(Y)Y + P(Y) = MC(\omega,Y;d)$. From the first order conditions define the function $f(Y,d,\omega) = P'(Y)Y + P(Y) - MC(\omega,Y;d)$. For an interior solution we have that $f(\hat{Y},d,\omega) = 0$, and that $f(\hat{Y},d,\omega)$ is a C^1 function on Y, d and ω. With the Implicit Function Theorem is easy to verify that $\frac{\partial Y}{\partial d} > 0$.

Thus, a large *ex-ante* pipeline diameter, associated to a large investment, imply a large supply of capacity units. Let $Y(d,\omega)$ be the supply of capacity units, where $Y(d,\omega) = Argmax_{Y \geq 0} P(Y)Y - VC(\omega,Y;d)$. The Theorem of the Maximum imply that $\pi(d,\omega)$ and $Y(d,\omega)$ are continuous functions. With the Envelope Theorem and for an interior solution we see that $\frac{\partial \pi(d,\omega)}{\partial d} > 0$, and that $\frac{\partial^2 \pi(d,\omega)}{\partial^2 d} > 0$.

A production plan that is sequentially rational implies that in the first period the firm solves:

$$Max_{d \geq 0} \pi(d,\omega)$$

$$\text{s.t. } \pi(d,\omega) \geq \omega_d d$$

Since $VC(\omega,Y;d)$ is a strictly convex function in d, we have that $\pi(d,\omega)$ is strictly concave in d. Thus, we get that there exist a unique solution for this optimization problem. Let $\hat{d}$ be this solution, where $\hat{d} = Argmax_{d \geq 0} \pi(d,\omega)$ $s.t.$ $\pi(d,\omega) \geq \omega_d d$. It is easy to verify that this solution is the same as the one that we would get with a protected monopoly that chooses simultaneously the pipeline diameter and the supply of capacity units.

One Incumbent and One Entrant:

As disclosed in section IV, an equilibrium in this economy is defined by the idea of Subgame Perfect Equilibrium.

Definition:

A behavior strategy profile that specifies incumbent and entrant pipeline diameters and third period market supply of capacity units, $(\hat{d}_1, \hat{Y}_1)$ and $(\hat{d}_2, \hat{Y}_2)$, is a Subgame Perfect Equilibrium if the restriction of the strategy profile to a proper subgame, is a Nash Equilibrium for every proper subgame of the proper subgame.

Existence of Equilibria

To analyze equilibria in this one incumbent one entrant game we analyze first third period competition in capacity units, and then we solve backward for pipes' diameters. But before we go into that we look first at the firms third period profit and best response functions.

In the third period pipeline diameters are fixed. Given d_1, d_2 and Y_j, firm i chooses Y_i to solve the problem:

$$\pi^i(Y_j, d_i, \omega) = Max_{Y_i \geq 0} P(Y)Y_i - VC(\omega, Y_i; d_i) \tag{4}$$

where $Y = Y_1 + Y_2$, and $\pi^i(Y_j, d_i, \omega)$ is firm i gross profit function. The objective function is strictly concave in Y_i since $P(Y)Y_i$ is at least concave in Y_i, and $VC(\omega,Y_i;d_i)$ is strictly convex in Y_i, and C^2 in Y_i, Y_j, ω, and d_i. Let $Y_i(Y_j, d_i, \omega)$ be the firm i third period best response function, defined from

$Y_i(Y_j, d_i, \omega) = Argmax_{Y_i \geq 0} P(Y)Y_i - VC(\omega, Y_i; d_i)$. Since the objective function is continuous in Y_j, ω, and d_i (it does not depend explicitly in d_j), by the Theorem of the Maximum we have that $\pi^i(Y_j, d_i, \omega)$ is continuous in Y_j, d_i, and ω. Also, by the Theorem of the Maximum we have that $Y_i(Y_j, d_i, \omega)$ is an upper-hemicontinuous function in Y_j, d_i, and ω. By the strict concavity of the objective function in Y_i we get that the solution for the last optimization problem is unique. Then, since $Y_i(Y_j, d_i, \omega)$ is singled valued, we have that $Y_i(Y_j, d_i, \omega)$ is continuous in Y_j, d_i, and ω. Because $VC(\omega, Y_i; d_i)$ is strictly convex in d_i, we have that $\pi^i(Y_j, d_i, \omega)$ is strictly concave in d_i. And as in the protected monopoly case, by the Envelope Theorem $\pi^i(Y_j, d_i, \omega)$ is strictly increasing in d_i. Too, $VC(\omega, Y_i; d_i)$ is linear in ω_n, so $\pi^i(Y_j, d_i, \omega)$ is linear in ω_n, and by the Envelope Theorem it is also decreasing in ω_n. Again, by the Envelope Theorem we have that $\pi^i(Y_j, d_i, \omega)$ is strictly decreasing in Y_j, and the curvature of $\pi^i(Y_j, d_i, \omega)$ respect to Y_j is given by the curvature of $P(Y)Y_i$ respect to Y_j. That is, the sign of $P''(Y)Y_i$.

First order conditions on 4 imply that:

$$P'(Y)Y_i + P(Y) - MC(\omega, Y_i; d_i) \leq 0, \tag{5}$$

$$Y_i\left[P'(Y)Y_i + P(Y) - MC(\omega, Y_i; d_i)\right] = 0,$$

$$Y_i \geq 0$$

Notice that if $d_i = 0$, then $VC(\omega, Y_i; d_i) = 0$ and $MC(\omega, Y_i; d_i) = +\infty$. From the first order conditions define the function $f_i(Y_i, Y_j, d_i, \omega) = P'(Y)Y_i + P(Y) - MC(\omega, Y_i; d_i)$. For an interior solution $f_i(Y_i, Y_j, d_i, \omega)$ is a C^1 function on Y_i, Y_j, d_i, and ω. Given $Y_i > 0$, at the optimum $f_i(Y_i, Y_j, d_i, \omega) = 0$, therefore we can use the Implicit Function Theorem to analyze how changes in Y_j, d_i, and ω affect the value of Y_i. Is easy to verify that $\frac{\partial Y_i}{\partial d_i} > 0$. Thus, large *ex-ante* pipeline diameters imply an *ex-post* large market supply of capacity units. Also, we can verify that $\frac{\partial Y_i}{\partial \omega_n} < 0$. With the Implicit Function Theorem we get that:

$$\frac{\partial Y_i(\bullet)}{\partial Y_j} = -\frac{P''(Y)Y_i + P'(Y)}{P''(Y)Y_i + 2P'(Y) - \frac{\partial MC(\omega, Y_i; d_i)}{\partial Y_i}} \tag{6}$$

By assumption we have that the expression in the denominator is always negative, so the effect from a change in Y_j on Y_i depends on the numerator's sign. Notice the assumption $P''(Y)Y + 2P'(Y) < 0$.

Third Period Capacity Competition

The third period capacity competition between the incumbent and the entrant is a proper subgame of the game itself. For $i=1,2$ and $j=1,2$, $i \neq j$ let

$$\hat{Y}_i(d_1, d_2, \omega) = Y_i(\hat{Y}_j, d_i, \omega)$$

be the third period Pure Strategy Nash Equilibrium. Notice that since $Y_i(Y_j, d_i, \omega)$ is a continuous function in Y_j, d_i and ω, $\hat{Y}_i(d_1, d_2, \omega)$ is also a continuous function in d_1, d_2 and ω. Also, $\hat{Y}_i(d_1, d_2, \omega)$ is C'.

Given d_1, d_2 and ω, to prove the existence of a Pure Strategy Nash Equilibrium in the third period of the game we use Brower's Fixed Point Theorem. Define the function $Y{:}[0,\bar{Y}]^2 \rightarrow [0,\bar{Y}]^2$, where $Y = (Y_1, Y_2)$, and Y_i is the firm i third period best response. Y is a continuous function in a compact, convex and non-empty set $[0,\bar{Y}]^2$. Then, by Brower's Fixed Point Theorem we get that Y has a fixed point in $[0,\bar{Y}]^2$.

Given d_1, d_2 and ω, to prove the uniqueness of a Pure Strategy Nash Equilibrium we use the fact that best responses $Y_1 = (Y_2, d_1, \omega)$ and $Y_2 = (Y_1, d_2, \omega)$ defined in the $[0,Y]^2$ space intercept just once. This proof follows.

For an interior solution and from the agents optimization problem we know that the effect on Y_i from a change in Y_j is given by the slope of the best response function. From equation (6) we have that for the incumbent and the entrant the slopes are:

$$\frac{\partial Y_1(\bullet)}{\partial Y_2} = -\frac{P''(Y)Y_1 + P'(Y)}{P''(Y)Y_1 + 2P'(Y) - \dfrac{\partial MC(\omega, Y_1; d_1)}{\partial Y_1}}$$

$$\frac{\partial Y_2(\bullet)}{\partial Y_1} = -\frac{P''(Y)Y_2 + P'(Y)}{P''(Y)Y_2 + 2P'(Y) - \dfrac{\partial MC(\omega, Y_2; d_2)}{\partial Y_2}}$$

Both denominators are negative, therefore the sign is given by the sign of the numerator. To prove the uniqueness of the Nash Equilibrium in the third period capacity competition we compare $\frac{\partial Y_2(\bullet)}{\partial Y_1}$ with $\frac{\partial Y_2}{\partial Y_1(\bullet)}$. The initial assumption

$P''(Y)Y + 2P'(Y) \leq 0$ imply that $P''(Y)Y_2 + P'(Y) \leq -(P''(Y)Y_1 + P'(Y))$ or $P''(Y)Y_1 + P'(Y) \leq -(P''(Y)Y_2 + P'(Y))$. Thus, neither $P''(Y)Y_j + P'(Y)$ can take $+\infty$ values, without violating the assumption $P''(Y)Y + 2P'(Y) \leq 0$. If $P''(Y)Y_j + P'(Y)$ is positive, then $P''(Y)Y_i + P'(Y)$ is negative, $i,j=1,2$, $i \neq j$

We distinguish three cases:

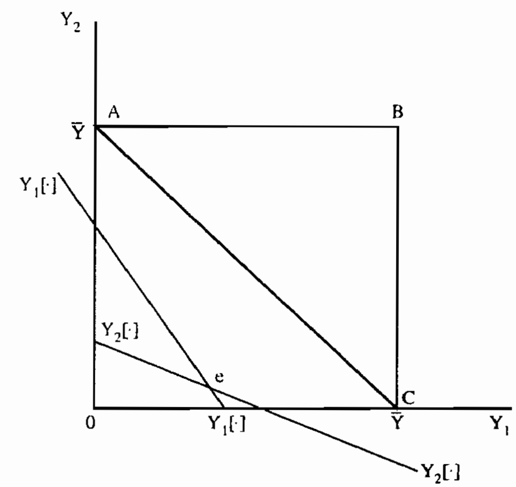
1. $P''(Y) \leq 0$.
2. $P''(Y) > 0$ and $P''(Y)Y_1 + P'(Y) > 0$.
3. $P''(Y) > 0$ and $P''(Y)Y_2 + P'(Y) > 0$.

Case 1: If $P''(Y) \leq 0$ we get:

$$-1 < \frac{\partial Y_2(\cdot)}{\partial Y_1} < 0 \quad \text{and} \quad \frac{\partial Y_2}{\partial Y_1(\cdot)} < -1$$

Notice that the -1 bound is not binding. Given d_1, d_2 and ω, Figure 2 show the third period best response function for each firm. The third period Nash Equilibrium in capacity competition is given by point e, where $Y_1 = (Y_2, d_1, \omega)$ and $Y_2 = (Y_1, d_2, \omega)$ intercepts. Notice that e must be somewhere inside the triangle OAC. Implicitly for the pictures I made the additional assumptions that $Y_i(Y_j, d_i, \omega)$, are straight lines. However, an inference about their concavity requires some

FIGURE 2



additional requirements on the inverse demand function. Assumptions with no substance for the present discussion.

A figure similar to figure 2 can be draw for cases 2 and 3.

Case 2: If $P''(Y) > 0$ and $P''(Y)Y_1 + P'(Y) > 0$ we get:

$$-1 < \frac{\partial Y_2(\cdot)}{\partial Y_1} < 0 \quad \text{and} \quad 0 < \frac{\partial Y_2}{\partial Y_1(\cdot)} < +\infty$$

With respect to case 1, this case is implied by a large Y_1 and a small Y_2.

Case 3: If $P''(Y) > 0$ and $P''(Y)Y_2 + P'(Y) > 0$ we get:

$$-1 < \frac{\partial Y_2(\cdot)}{\partial Y_1} < +\infty \quad \text{and} \quad \frac{\partial Y_2}{\partial Y_1(\cdot)} < -1$$

Contrarily to case 2, this case requires a large Y_2 and a small Y_1.

Thus, we can conclude that the slopes of the third period best responses are within one of three cases:

1. $-1 < \frac{\partial Y_2(\cdot)}{\partial Y_1} < 0$ and $\frac{\partial Y_2}{\partial Y_1(\cdot)} < -1$
2. $-1 < \frac{\partial Y_2(\cdot)}{\partial Y_1} < 0$ and $\frac{\partial Y_2}{\partial Y_1(\cdot)} < +\infty$
3. $0 < \frac{\partial Y_2(\cdot)}{\partial Y_1} < +\infty$ and $\frac{\partial Y_2}{\partial Y_1(\cdot)} < -1$

Thus, given d_1, d_2 and ω, and since $Y_1 = (Y_2, d_1, \omega)$ and $Y_2 = (Y_1, d_2, \omega)$ intercepts once, we find that in the third period exists only one Pure Strategy Nash Equilibrium.

Define the set of third period Nash Equilibrium as:

$$\hat{y} = \left\{ (\hat{Y}_1, \hat{Y}_2) \in \left[0, \overline{Y}\right]^2 / \forall \omega \in \Re^2_{++},\ d_1 \geq 0, d_2 \geq 0, \right.$$
$$\left. \hat{Y}_1 = Y_1(\hat{Y}_2, d_1, \omega) \ \textit{and} \ \hat{Y}_1 = Y_1(\hat{Y}_2, d_1, \omega) \right\}$$

$\hat{y}$ is defined by a correspondence from third period state variables into third period market supply of capacity units. We just find that for each state variable vector there exists a unique third period Nash Equilibrium. Thus, we have that this

correspondence is single valued, i.e., is a function. Define the restriction of $\hat{y}$ to d_1, d_2 and ω as the set $\hat{y}(d_1, d_2, \omega) \equiv \left\{ (\hat{Y}_1, \hat{Y}_2) \in \hat{y} / d_1, d_2, \omega \right\}$. Given d_1, d_2, ω, $(\hat{Y}_1, \hat{Y}_2) \in \hat{y}(d_1, d_2, \omega)$ define the gross profit function at the third period Nash Equilibrium as:

$$\tilde{\pi}_i(d_1, d_2, \omega) \equiv \pi_i(\hat{Y}_j, d_i, \omega).$$

Since $\hat{y}(d_1, d_2, \omega)$ is a singleton, then the function $\tilde{\pi}_i(d_1, d_2, \omega)$ is singled valued.

Second and First Period Choices

In the second period the entrant firm chooses that pipeline diameter that maximizes his third period profits conditional on the incumbent's pipeline diameter and third period best response functions. Notice that here we are solving backward from third period pure strategies Nash Equilibrium. This can be done since for a given (d_1, d_2) pair each player has a strictly dominant strategy that implies in the third period a unique Nash Equilibrium. The entrant firm solves:

$$V(d_1, \omega) = Max_{\{d_2 \geq 0\}} \tilde{\pi}_2(d_1, d_2, \omega) \tag{7}$$

s.t.

$$\tilde{\pi}_2(d_1, d_2, \omega) \geq \omega_d d_2$$

Let $d_2(d_1, \omega)$ be the entrant firm second period best response, where $d_2(d_1, \omega) = Argmax_{d_2 \geq 0} \tilde{\pi}_2(d_1, d_2, \omega)$ $s.t.$ $\tilde{\pi}_2(d_1, d_2, \omega) \geq \omega_d d_2$. Finally, in the first period the incumbent firm chooses d_1 given second period and third period best response functions, i.e.,

$$Max_{\{d_1 \geq 0\}} \tilde{\pi}_1(d_1, d_2, \omega) \tag{8}$$

s.t.

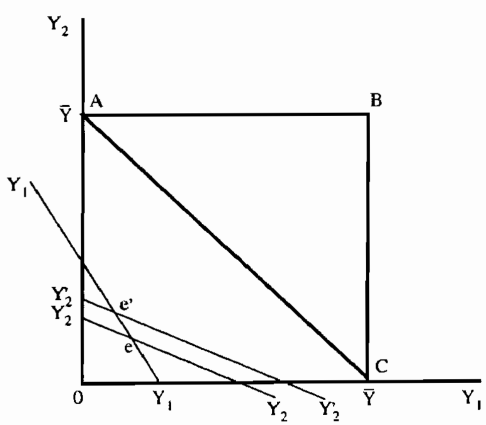
$$d_2 = d_2(d_1, \omega)$$
$$\tilde{\pi}_1(d_1, d_2, \omega) \geq \omega_d d_1$$

In this game the existence of a Subgame Perfect Equilibrium is guaranteed by Kuhn's Second Theorem (see Fundenberg and Tirole, 1992, chapter 3). Kuhn's Second Theorem roughly says that every game of perfect information has a pure strategy subgame perfect equilibrium, and that if there is no indifference between terminal nodes then there is exactly one subgame perfect equilibrium.

Comparative Static Exercise in Third Period Nash Equilibria

How changes in pipes' diameter affect the third period Nash Equilibrium? From above, we know that we can distinguish three cases that depend on the slopes of the best response functions. For this exercise we analyze an increase in d_2 (a change in d_1 can be analyzed in a similar way). To find the effects from changes in d_2 over the third period Nash Equilibrium we look at the shifts in the best responses $Y_i(Y_j, d_i, \omega)$. Notice that this is not an equilibrium analysis, is only an exercise that help us understand how the model works. See Dixit (1980) for a two period model where these comparative static exercises apply. In Dixit's model changes in firm one capacity does not drive direct changes in firm two capacity because it only chooses one variable, market supply. Since $\frac{\partial Y_i(\cdot)}{\partial d_i} > 0$, for $i=1,2$, we get that an increase in d_2 shift the best response function $Y_2 = (Y_1, d_2, \omega)$ in a north direction. But since $Y_1 = (Y_2, d_1, \omega)$ is not a function of d_2, it does not change. However, with the chain rule we can get how change Y_1 with changes in d_2. From the chain rule get that $\frac{\partial Y_i(\cdot)}{\partial d_j} = \frac{\partial Y_i(\cdot)}{\partial Y_j}\frac{\partial Y_j(\cdot)}{\partial d_j} \lessgtr 0$, i.e., the effect from a change in d_j over Y_i is an indirect effect that comes through his effect on Y_j, where as we saw above the sign of it is ambiguous. If $\frac{\partial Y_i(\cdot)}{\partial Y_j} \lessgtr 0$ then $\frac{\partial Y_i(\cdot)}{\partial d_j} \lessgtr 0$.

FIGURE 3



For the case depicted by Figure 2, Figure 3 shows the effect from an increase in d_2 on the third period Nash Equilibrium. The equilibrium moves from point e to point e', where an increase in d_2 has a positive effect in Y_2 and a negative effect in Y_1. The positive effect in Y_2 is understood when we recall that a large pipe diameter decreases the *ex-post* marginal cost, and this is expected to have a positive effect on the entrant market supply of capacity units. The decline in the incumbent supply of capacity units is explained by the substitutability between the entrant and the incumbent supply of capacity units, i.e., the negative sign of $\frac{\partial Y_1(\cdot)}{\partial Y_2}$.

For cases 2 and 3 above, a figure similar to Figure 3 can be draw to analyze the effects from an increase in d_2 on the third period Nash Equilibrium. For case 2 can be shown that an increase in d_2 has also a positive effect in Y_2, but also a positive effect in Y_1. The positive effect in Y_1 is explained by the complementary between the incumbent and the entrant supply of capacity units, i.e., the positive sign of $\frac{\partial Y_1(\cdot)}{\partial Y_2}$.

Notice that this requires that $P''(Y) > 0$, and that Y_2 is small with respect to Y_1. Finally, for case 3 can be shown that an increase in d_2 has a positive effect in Y_2 and a negative effect in Y_1. Again the positive effect in Y_2 is explained by the decline in the *ex-post* marginal cost; the negative effect on the incumbent supply of capacity units is explained by the negative sign of $\frac{\partial Y_1(\cdot)}{\partial Y_2}$.

APPENDIX 2
OPTIMUM CAPACITY

In this appendix is shown that when *ex-ante* increasing returns to scale and sunk costs mix the standard second best Ramsey solution, where prices are set equal to average cost, is time inconsistent. I present an alternative Ramsey solution that is *ex-post* efficient, time consistent, and the firm is compensated for all his costs. The analysis also shows that *ex-ante* increasing returns to scale imply that when a gas pipeline is built, economic efficiency calls in to build just one pipeline. However, this nothing say about the efficiency to build additional pipelines at other periods. In fact, there are two cases when is efficient to have one gas pipeline: when there is no concern for the future, and when the intertemporal discount rate is zero. Nevertheless, if there is concern for the future, or if the intertemporal discount rate is not equal to zero, it can be optimum to have more than one gas pipeline.

Is there an optimum capacity? In a world with perfect information and sunk costs there are alternative criteria's to analyze the welfare properties of the market equilibrium.

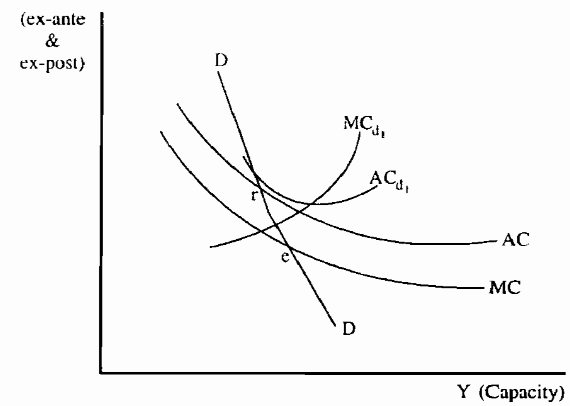
Assume a timeless world with an increasing return to scale technology. For this world is well known that the optimum or the first best solution is to choose a quantity for which the marginal cost is equal to the marginal benefit. But increasing returns to scale imply a strictly decreasing marginal cost function. Thus, if the natural monopoly operates with a price equal to his marginal cost then it incurs some losses. Therefore, to enforce the first best solution we have that, besides the price per-unit of output equal to the marginal cost, the firm must receive a subsidy that compensates that part of the total cost that is not recoup with the unit price. This means that with a natural monopoly the first best solution is feasible only if there is a subsidy (point *e* in Figure 4). An alternative, known as a second best or Ramsey solution is found when we look for prices that are socially optimal subject to the constrain that the firm incurs no losses. This second best or Ramsey solution is one at which the price per-unit of output is equal to the average cost of production (See point *r* in Figure 4, and Baumol et al. 1982).

Is verified that the Ramsey solution in a timeless world is time inconsistent for a world with *ex-ante* increasing returns to scale and sunk costs, such as the gas pipeline transportation industry. When the social planner chooses in the first period the Ramsey solution, then in the second period it has an incentive to enforce an allocation that renege of sunk investments, and with that pipes' investment is not recouped. I propose a complementary criteria to analyze the welfare properties of the gas pipeline industry. This alternative Ramsey solution is *ex-post* efficient subject to the constrain that gross profits are at least equal to pipes' investment.

At the second period, and given the pipeline diameter and the price vector for the inputs, a social planner chooses the supply of capacity units to maximize *ex-post* consumer and producer surplus:

(9) $$w(\omega,d) = Max_{\{Y\geq 0\}} \int_0^Y P(q)dq - VC(\omega,Y;d)$$

FIGURE 4



Where $w(\omega,d)$ is the *ex-post* consumer and producer surplus given the pipeline diameter and the price vector. Given $d>0$ and $\omega \in \Re^2_{++}$, we have an optimization problem of a strictly concave objective function in a non-empty, compact, and convex set, then a unique maximum exists. For an interior solution, first order conditions imply that:

(10) $$P(Y) = MC(\omega,Y;d),$$

i.e., in the second period the optimum is to have a capacity for which the market price is equal to the *ex-post* marginal cost. Define the function:

(11) $$f(Y,d,\omega) = P(Y) - MC(\omega,Y;d)$$

For an interior solution $f(Y,d,\omega)$ is a C^1 function on Y, d and ω, and from the implicit function theorem we have that Y is a C^1 function in d and ω. Since Y is C^1 in d and $VC(\omega,Y;d)$ is C^2 in d, we have that $w(\omega,d)$ is C^1 in d. Since $VC(\omega,Y;d)$ is strictly decreasing in d and by the envelope theorem $\frac{\partial w(\omega,d)}{\partial d} > 0$. By the envelope theorem and since $VC(\omega,Y;d)$ is strictly convex in d we have that $\frac{\partial^2 w(\omega,d)}{\partial^2 d} < 0$, i.e., $w(\omega,d)$ is strictly concave in d.

In the first period the social planner chooses that pipeline diameter that maximizes *ex-post* consumer plus producer surplus such that for the firm total income cover at least total costs:

(12) $$Max_{\{d\geq 0\}}\, w(\omega,d)-\omega_d d$$

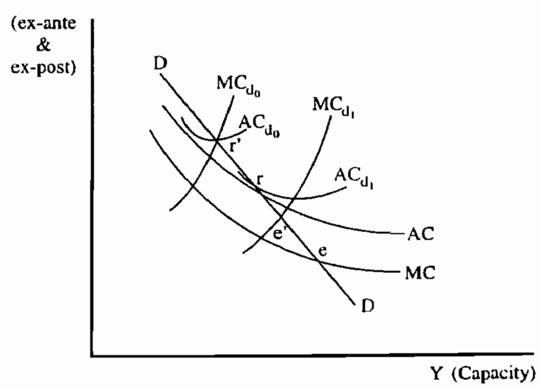
s.t.

$$P(Y)Y-C(\omega,Y;d)\geq 0.$$

At the optimum we get that $P(Y)=AC(\omega,Y;d)$. This and the condition that $P(Y)=MC(\omega,Y;d)$,imply that the Ramsey solution is time consistent. The intuition behind this is that *ex-ante* pipeline investment is an *ex-post* variable cost reducing investment. But *ex-post*, the *ex-ante* pipeline investment is sink and the social planner only cares about variable costs. Then, if *ex-post* the social planner only cares about variable costs, *ex-post* he chooses a supply of capacity units that equates the *ex-post* marginal cost with the marginal benefit of it. Thus, a time consistent Ramsey solution should assure *ex-ante* that *ex-post* the firm incurs no losses, and that the social planner honor his commitment (See Figure 5 for point r'). If $P(Y)=MC(\omega,Y;d)$ and $P(Y)>AC(\omega,Y;d)$. we don't have an input mix that minimizes total cost. The same production level can be achieved with lower costs if we choose a large pipeline diameter.

Since the transportation capacity of a gas pipeline is *ex-ante* given by an increasing return to scale technology, a static analysis suggests that for the society is optimum to have just one gas pipeline. However, in a dynamic world is still true that for the society is optimum to have just one gas pipeline?. We have that gas pipes' depreciate and that demand conditions change, what suggests that in the long term is not necessarily optimum to have just one gas pipeline. In a dynamic world, decision variables are: gas pipes' diameter, number of compression stations, and the number of gas pipelines. For example, we can imagine a situation where for many periods the demand for natural gas is expected to be small with respect

FIGURE 5



to what it is expected to be in the long term. Then, at the beginning between two locations could be better to build just a small diameter gas pipeline, saving on the pipes' investment that is demanded by a large diameter gas pipeline, and defer to the future the investment that is required to satisfy the expected increase in the demand for natural gas. Thus, we have that by increasing returns to scale, in any given period is optimum for the society to build just one gas pipeline between two locations. Nevertheless, since *ex-post* increasing returns to scale are sink, it can be optimum between two locations to have more than one gas pipeline if they are built at different periods.

To prove the last proposition let's use the following setting. Suppose that demand must be served in two periods, zero and one, with inverse demand functions $P_0(Y)$ and $P_1(Y)$, respectively. Assume that these inverse demand functions satisfy the above standard assumptions, and that $P_1(Y)\geq P_0(Y)$, $\forall Y\geq 0$. This last assumption is just to simplify the proof. Let $0\leq\beta\leq 1$ be the intertemporal discount factor between period zero and one. To see that it is not necessarily optimum for the society to have just one gas pipeline, we compare the social welfare function when the social planner is restricted to serve both markets with one gas pipeline, with the social welfare function when the social planner build one gas pipeline in the first period and is allow to build a second one in the second period. First let's look at the case where the social planner is restricted to build one gas pipeline. Here the social planner chooses the pipeline diameter d, first period supply of capacity units Y_0, and second period supply of capacity units Y_1, to solve:

(13)
$$\Omega(\omega,1)=Max_{\{d,Y_0,Y_1\}\in\Re^3_+}\int_0^{Y_0}P_0(q)dq-VC(\omega,Y_0;d)-\omega_d d+$$
$$\beta\left[\int_0^{Y_1}P_1(q)dq-(VC(\omega,Y_1;d)-VC(\omega,Y_0;d))\right]$$

Where $\Omega(\omega,1)$ is the discounted present value of consumer and producer surplus when the price vector is w. Notice that for a given pipeline here for simplicity I'm not accounting for the discount between the pipes' investment and the compression stations' investment. Second let's look at the case where the social planner builds a gas pipeline in the first period and is allowed to build another one in the second period. In this case the social planner chooses the first pipeline diameter d, first period supply of capacity units Y_0, second period supply of capacity units Y_{01} using the first pipeline, and second period supply of capacity units Y_1 using the second pipeline, to solve:

(14)
$$\Omega(\omega,2)=Max_{\{d,Y_0,Y_{01},Y_1\}\in\Re^4_+}\int_0^{Y_0}P_0(q)dq-VC(\omega,Y_0;d)-\omega_d d+$$
$$\beta\left[\int_0^{Y_1}P_1(q)dq-C(\omega,Y_1-Y_{01})-(VC(\omega,Y_{01};d)-VC(\omega,Y_0;d))\right]$$

Where $\Omega(\omega,2)$ is the discounted present value of consumer and producer surplus when the price vector is ω.

Now the question that comes up is how compares $\Omega(\omega,1)$ with $\Omega(\omega,2)$. Is easy to see that $\Omega(\omega,1)$ is a special case of $\Omega(\omega,2)$. If in $\Omega(\omega,2)$ we impose the restriction that $Y_{01} = Y_1$, we get that $\Omega(\omega,2) = \Omega(\omega,1)$. Thus, $\Omega(\omega,1) \le \Omega(\omega,2)$. Is easy to verify that if $\beta = 0$ or $\beta = 1$, then $\Omega(\omega,1) = \Omega(\omega,2)$. When $\beta = 0$ the future does not matter, and $\Omega(\omega,2) = \Omega(\omega,1)$, and the production plan that solves (14) chooses one pipeline in the first period. Finally, when $\beta = 1$ problem (14) reduces to:

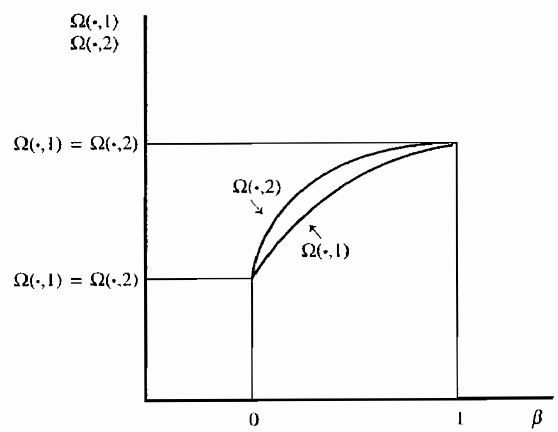
$$\Omega(\omega,2) = Max_{\{d,Y_0,Y_{01},Y_1 \ge 0\}} \int_0^{Y_0} P_0(q)dq + \int_0^{Y_1} P_1(q)dq - VC(\omega, Y_{01}; d) - \omega_d d + C(\omega, Y_1 - Y_{01})$$

But with increasing returns to scale we have that:

$$C(\omega, Y_1) \le C(\omega, Y_1 - Y_{01}) + VC(\omega, Y_{01}; d) + \omega_d d$$

So is optimum to serve both markets with one gas pipeline, i.e., $\Omega(\omega,2) = \Omega(\omega,1)$. Thus, when there are no financial benefits from postponing investments, the social planner takes full advantage of the increasing returns in the technology and builds one pipeline. In Figure 6 we see a graph of $\Omega(\omega,1)$ and $\Omega(\omega,2)$ against b, by the envelope theorem that gives that $\Omega(\omega,2)$ is non-decreasing in b, and up to parameter values, is easy to see that the graph of $\Omega(\omega,1)$ is below the graph of $\Omega(\omega,2)$, and for $\beta = 0$, and $\beta = 1$ they are equal. These results extend also to other cost structures, for example see the environments such as those proposed by Eaton and Lipsey (1980) and Eaton and Ware (1987).

FIGURE 6



Notes

1 The first ideas of this paper were born in late 1993, when I was invited to comment on the writing of the new by-law that applies to the industry. The drafts of the by-law considered concessions that granted up to fifteen years of exclusivity and other privileges. In a shy reaction, newspapers denounced some suspicious of corruption in the process to introduce natural gas in the central zone of the country. At the time, the state oil company, ENAP, owned 10% of Transgas, the leading gas pipeline project.

2 Although, there are some alternative technologies to transport natural gas, here I only consider gas transportation through a pipeline. An alternative transportation mean is a Gas Ship. However, now for Chile this alternative is not economically feasible.

3 For a classification of entry possibilities see Bain (1956). For a nice introduction into strategic entry deterrence see Salop (1979).

4 See Dixit (1979,1980); Eaton and Lipsey (1980,1981); Eaton and Ware (1987); Ware (1984).

5 With the exception of Colbún, a large generating state own company. Notwithstanding, in 1996 the government sold 37.5% of Colbún to private investors.

6 Yet, today the lack of information about the efficiency of the operation of the system by the independent operator has become a barrier to a deeper analysis on this issue.

7 This new body of law complemented a 1931 regulatory regime that applies to the industry. The code was inserted in the government energy policy, whose main objectives are: assure sufficient energy supply for an economy that is open to the rest of the world, and that face increasing levels of competition; promote a wide participation of the private sector as the major engine of growth; create long run conditions to sustain economic growth; promote conditions that allow for the development of clean and competitive markets; set and maintain rules that are precise and stable; promote free prices, and if there is any monopolistic threat, the authority must have the freedom to regulate prices; and finally, satisfy the energy requirements of the isolated neighborhoods.

8 Here I am not including those elements that raise cost of production such as operation and/or maintenance cost.

9 With these simplifying assumptions I can focus the analysis in the most distinct characteristics of the technology.

10 See Baumol et al. (1982).

11 See Lévy-Lambert and Dupuit (1975), and Katz et al. (1959).

12 Parameters of $\alpha = 8/3$, and $\gamma = 1/2$ are reported by Lévy-Lambert and Dupuit (1975).

13 Here I define a natural monopoly as an industry where the production technology is homogeneous of a degree larger than one.

14 To keep what is essential to the discussion I assume that maintenance and operation costs are zero. However, the analysis wouldn't change that much if we include them as a part of the variable costs.

15 For simplicity, to discount flows within different periods I assume a zero interest rate. Thus, the present and the future value of a project is just the sum of flows.

16 $\kappa(\omega) = A^{\frac{-1}{\alpha+\gamma}} (\omega_d (\frac{\alpha \omega_n}{\gamma \omega_l})^{\frac{\gamma}{\alpha+\gamma}} + \omega_n (\frac{\gamma \omega_l}{\alpha \omega_n})^{\frac{\alpha}{\alpha+\gamma}})$.

17 Ware builds a three-stage model where the incumbent and the entrant firm have linear costs. He finds that equilibria in the three stage game are qualitatively similar to equilibria in the two stage game. However, they differ in that in the three-stage game the strategic advantage available to the first mover is lessened.

18 This follow Bain (1956).

19 If we care about the future, and if the discount rate is not zero, then is not clear that the optimum is to build only one gas pipeline. In fact, there is a trade-off between the cost of capital and scale economies.

20 For this I have discretized the pipeline diameter choice set. First, for each feasible pair of firms pipes diameter I solve the third period Nash Equilibria. Second, given the incumbent pipe diameter and the third period Nash Equilibria I look for the entrant best response, i.e., the entrant pipe. And