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Research note

The technology and cost structure of a natural gas pipeline: Insights for costs and rate-of-return regulation

Florian Perrotton[a,b], Olivier Massol[a,c,d,*]

[a] IFP Énergies Nouvelles, 1-4 av. de Bois Préau, F-92852, Rueil-Malmaison, France
[b] EconomiX, Université Paris Nanterre, 200 av. de la République, F-92000, Nanterre, France
[c] Center for Economics and Management, IFP School, 228-232 av. Napoléon Bonaparte, F-92852, Rueil-Malmaison, France
[d] Department of Economics, City, University of London, Northampton Square, London, EC1V 0HB, UK

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ABSTRACT

This note details a complete microeconomic characterization of the physical relationships between input use and the level of output of a simple point-to-point gas pipeline system and uses it to contribute to the public policy discussions pertaining to the economic regulation of natural gas pipelines. We show that the engineering equations governing the design and operations of that infrastructure can be approximated by a single production equation of the Cobb-Douglas type. We use that result to inform three public policy debates. First, we prove that the long-run cost function of the infrastructure formally verifies the condition for a natural monopoly, thereby justifying the need of regulatory intervention in that industry. Second, we examine the conditions for cost-recovery in the short-run and contribute to the emerging European discussions on the implementation of short-run marginal cost pricing on interconnector pipelines. Lastly, we analyze the performance of rate-of-return regulation in that industry and inform the regulatory policy debates on the selection of an appropriate authorized rate of return. We highlight that, contrary to popular belief, the socially desirable rate of return can be larger than the market price of capital for that industry.

1. Introduction

The last 30 years have seen an enduring interest in the construction of large-scale natural gas pipelines across the globe. Though an emerging literature has studied the market effects of a new pipeline project,[1] the examination of the technology and costs of these capital-intensive infrastructures has attracted less attention. Yet, that analysis is critically needed to inform policy development and decisions. Even in countries where liberalization reforms have been implemented, natural gas pipelines remain regulated (von Hirschhausen, 2008) and authorities must frequently deal with project-specific requests for adjustments within the regulatory framework.[2]

So far, two different methodological approaches have been considered to investigate the technology. The first is rooted in engineering and can be traced back to Chenery (1949). It aims at numerically determining the least-cost design of a given infrastructure using optimization techniques (Kabirian and Hemmati, 2007; Ruan et al., 2009; André and Bonnans, 2011). This approach is widely applied by planners and development agencies to assess the cost of a specific project (Yépez, 2008). Yet, because of its sophistication and its numerical nature, it is seldom considered in regulatory policy debates (Massol, 2011). The second approach involves the econometric estimation of a flexible functional form – usually a translog specification – to obtain an approximate cost function. This method has become popular in Northern America either to estimate the industry cost function using cross-section datasets (Ellig and Giberson, 1993) or to model the cost function of a single firm using a time series approach (Gordon et al., 2003). So far, data availability issues have hampered the application of this empirical approach in Continental Europe and Asia.

This research note develops a third approach: it proves that a production function of the Cobb-Douglas type captures the physical relationship between input use and the level of output of a simple point-

* Corresponding author. IFP Énergies Nouvelles, 1-4 av. de Bois Préau, F-92852, Rueil-Malmaison, France.
E-mail address: olivier.massol@ifpen.fr (O. Massol).

[1] Among others, Newbery (1987) assesses the trade opportunities generated by a new pipeline, Hubert and Ikonnikova (2011) evaluate the impacts on the relative bargaining powers of exporting and transit countries, and Rupérez Micola and Bunn (2007) and Massol and Banal-Estañol (2016) investigated the relation between pipeline utilization and the degree of spatial market integration between interconnected markets.

[2] For example, the augmented rate-of-return that was allocated to two new pipeline projects in France during the years 2009–16: the pipeline connecting the new Dunkerque LNG terminal to the national transportation network and the North-South Eridan project (CRE, 2012).

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to-point pipeline infrastructure. More precisely, we show how that micro-founded model of the technology naturally emerges from the engineering equations governing the design of that infrastructure. One of the great merits of that approach is that it greatly facilitates the application of the standard theory of production to characterize the microeconomics of a natural gas pipeline system.

To explore the policy implications, we use that production function to successively examine the properties of the cost function in the long and in the short run. We also compare the market outcomes obtained under three alternative conditions of industrial organization (unregulated private monopoly, average-cost pricing, and rate-of-return regulation). Our results: (i) indicate the presence of pronounced increasing returns to scale in the long run; (ii) confirm the natural monopolistic nature of a gas pipeline system and the need for regulatory intervention; (iii) clarify the conditions for cost-recovery if short-run marginal cost pricing is imposed on such infrastructure; (iv) quantify the performance of rate-of-return regulation in that industry, and (v) reveal that the socially desirable rate of return is not necessarily equal to the market price of capital in this case.

2. Theoretical model of the technology

We consider a simple point-to-point pipeline infrastructure that consists of a compressor station injecting a pressurized flow of natural gas Q into a pipeline to transport it across a given distance l.

Following Chenery (1949) and Yépez (2008), designing such a system imposes to determine the value of three engineering variables: the compressor horsepower H, the inside diameter of the pipe D and τ the pipe thickness. These variables must verify three engineering equations presented in Table 1 (first column). The compressor equation gives the power required to compress the gas flow from a given inlet pressure p_0 to a predefined outlet pressure $p_0 + \Delta p$ where Δp is the net pressure rise. The Weymouth equation models the pressure drop between the inlet pressure $p_0 + \Delta p$ measured after the compressor station, and the outlet one p_1, which is assumed to be equal to p_0. Lastly, concerns about the mechanical stability of the pipe impose a relation between the thickness τ and the inside diameter D.

We now combine these equations to construct an approximate production function. To our knowledge, the pressure rise Δp usually ranges between 1% and 30% of p_0, which leads to the first-order approximations detailed in Table 1 (second column). Combining them, one can eliminate the relative pressure rise $\Delta p/p_0$ and obtain the following relation between the output Q and two engineering variables H and D:

$$Q = \sqrt[3]{\frac{2(c_2 p_0)^2}{c_1 b l}} D^{16/9} H^{1/3}. \quad (1)$$

Table 1
Engineering equations.

Exact engineering equations	Approximate engineering equations
Compressor equation: [(a)] $H = c_1 . \left[\left(\frac{p_0+\Delta p}{p_0}\right)^b - 1\right] Q$	Approximate compressor equation: [(a)] $H = c_1 b \frac{\Delta p}{p_0} Q$
Weymouth flow equation: [(b)] $Q = \frac{c_2}{\sqrt{l}} D^{8/3} \sqrt{(p_0 + \Delta p)^2 - p_1^2}$	Approximate flow equation: [(b)] $Q = \frac{c_2 p_0 \sqrt{2}}{\sqrt{l}} D^{8/3} \sqrt{\frac{\Delta p}{p_0}}$
Mechanical stability equation: [(c)] $\tau = c_3 D$	Mechanical stability equation: [(c)] $\tau = c_3 D$

Notes: [(a)] [(b)] the positive constant parameters c_1, c_2 and b (with $b < 1$) are detailed in Yépez (2008) for the USCS unit system. Elevation changes along the pipeline are neglected in the flow equation. [(c)] This equation follows the industry-standard practice and assumes that the pipe thickness equals a predetermined fraction c_3 of the inside diameter (e.g., $c_3 = 0.9\%$ in Ruan et al. (2009 – p. 3044)).

This relation can be reformulated as a production function that gives the output as a function of two inputs: energy and capital. First, we let E denote the total amount of energy consumed by the infrastructure to power the compressor. By definition, the total amount of energy E is directly proportional to the horsepower H. Second, we let K denote the replacement value of the pipeline. We assume that the capital stock K is directly proportional to the pipeline total weight of steel S and let P_S denote the unit cost of steel per unit of weight. Hence, $K = P_S \times S$. The total weight of steel S required to build that pipeline is obtained by multiplying the volume of steel in an open cylinder by the weight of steel per unit of volume W_S:

$$S = l\pi \left[\left(\frac{D}{2} + \tau\right)^2 - \left(\frac{D}{2}\right)^2\right] W_S, \quad (2)$$

where $\pi \approx 3.1416$ is the mathematical constant. Combining that equation with the mechanical stability equation in Table 1, the amount of capital expenditure related to the pipeline is as follows:

$$K = P_S l \pi D^2 [c_3 + c_3^2] W_S. \quad (3)$$

This equation shows that the pipeline diameter is directly proportional to the square root of K, the amount of capital invested in the pipeline. So, the engineering equation (1) can readily be rewritten as a production function: $Q = B\ K^{8/9} E^{1/3}$, where B is a constant. To simplify, we rescale the output by dividing it by B and use this rescaled output thereafter. So, the Cobb-Douglas production function of a gas pipeline is:

$$Q^\beta = K^\alpha E^{1-\alpha}, \quad (4)$$

where the capital exponent parameter is $\alpha = 8/11$ and $\beta = 9/11$ is the inverse of the degree to which output is homogeneous in capital and energy. As $\beta < 1$, the technology exhibits increasing returns to scale.

3. Results and policy implications

In this section, we show how the technological model above can be applied to derive several policy-relevant insights. Since natural gas pipelines are deemed as natural monopolies, we first examine whether that reputation is supported by the properties of the long-run cost function. We then examine the short-run cost function to assess the performance of short-run marginal cost pricing. Lastly, we assess the performance of rate-of-return regulation for that industry.

3.1. Long-run cost

We let e denote the market price of the energy input and r the market price of capital faced by the firm. From the cost-minimizing combination of inputs needed to transport the output Q, one can derive the long-run total cost function (Cf., Appendix A):

$$C(Q) = \frac{r^\alpha e^{1-\alpha}}{\alpha^\alpha (1-\alpha)^{1-\alpha}} Q^\beta. \quad (5)$$

Three insights can be drawn from that specification. Firstly, the elasticity of the long-run cost with respect to output is $\beta = 9/11$ and lower than one. The cost function (5) also validates the empirical remarks in Chenery (1952) and Massol (2011) who suggested that this elasticity is almost constant over most of the output range. Secondly, the ratio of the long-run marginal cost to the long-run average cost is constant and also equals β. As $\beta < 1$, setting the price equal to the long-run marginal cost systematically yields a negative profit. Lastly, one can note that the univariate cost function (5) is concave and thus strictly subadditive (Sharkey, 1982 - Proposition 4.1). The cost subadditivity property has important policy implications: it attests that a point-to-point gas pipeline system verifies the technological condition for a natural monopoly. As this particular industry structure may lead to a variety of economic performance problems (such as excessive prices,

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