THE TECHNOLOGY & COST STRUCTURE OF A NATURAL GAS PIPELINE

Olivier MASSOL Florian PERROTTON

Séminaire PSL* – 13 February 2019

OUTLINE

- The technology of a natural gas pipeline
  - Insights for cost
  - Insights for rate-of-return regulation
- Extension: application to examine the deployment of a gas pipeline in a LDC

PART 1: THE TECHNOLOGY & COST STRUCTURE OF A NATURAL GAS PIPELINE

A note on rate-of-return regulation

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LITERATURE REVIEW

- So far, two main methodological approaches have been proposed to examine the technology and cost structure of the gas pipeline industry

- **Engineering-rooted analyses**
  - Chenery (1949), Yépez (2008), Massol (2011), André & Bonnans (2011)
  - De Wolf & Smeers (2000)

+ : a rigourous representation of the technology

**- : cumbersome, case specific.
Economics?
Little used in regulatory policy debates (exception, Callen (1978))**

- **Econometric studies**
  - cross-section studies (e.g., Ellig & Giberson, 1993)
  - Time series (e.g., Gordon et al., 2003)

+ : easy to implement (when data are available)

- : atheoretical? Data availability is critical

A tribute to Hollis Chenery

- <u>Hollis B. Chenery (1918-1994)</u>

  1950 - Ph.D. (Harvard – W. Leontief).

  His career combined Academia & positions in international institutions

Interestingly, his early papers aimed at bridging engineering analysis and economic reasoning.

This approach had a considerable early influence (e.g.: V. Smith (1957, 1959))

<u>As time went by,</u> his engineering analysis has been at best oversimplified

e.g. : "the cost of a pipeline per mile, is proportional to D whereas its capacity is proportional to D^2."

and in most cases ignored…

<u>Why should we pay a tribute now ?</u>

<u>Yépez (2008):</u> a refreshing but partial revival.

<u>Midthun, Bjorndal and Tomasgard (2009):</u> it is important to model gas engineering fundamentals to analyze natural gas markets.

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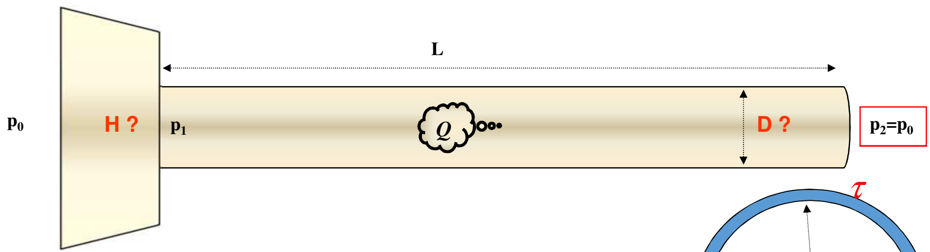
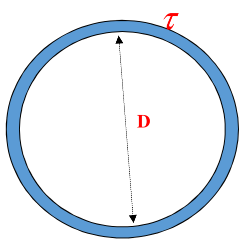
Technology: Chenery (1949) – Yepez (2008)





1 - Compressor equation

$$H = c_1 \cdot \left[\left(\frac{p_1}{p_0} \right)^b - 1 \right] Q$$

2 - A flow equation (Weymouth)

$$Q = \frac{c_2}{\sqrt{L}} D^{8/3} \sqrt{p_1^2 - p_2^2}$$

3 - Mechanical stability

$$\tau = c_3 D$$

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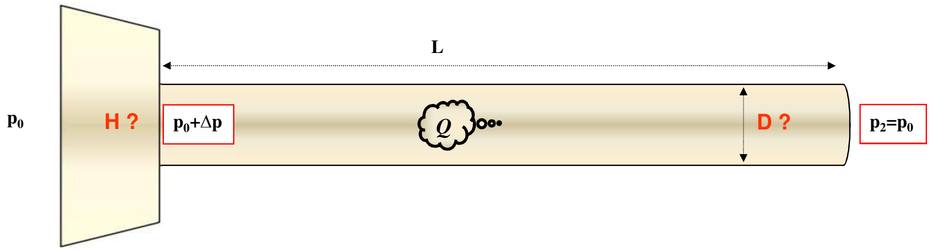
Perrotton & Massol (2018): an approximation



1 - Compressor equation

$$H = c_1 \cdot \left[\left(\frac{p_0 + \Delta p}{p_0} \right)^b - 1 \right] Q \approx c_1 b \frac{\Delta p}{p_0} Q$$

2 - A flow equation (Weymouth)

$$Q = \frac{c_2 p_0}{\sqrt{L}} D^{8/3} \sqrt{\left(\frac{p_0 + \Delta p}{p_0} \right)^2 - 1} \approx \frac{c_2 p_0 \sqrt{2}}{\sqrt{L}} D^{8/3} \sqrt{\frac{\Delta p}{p_0}}$$

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

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Further Assumptions

H1: The amount of energy ***E*** used for the compression is proportional to ***H***

H2: The capital expenditures ***K*** is proportional to the weight of steel (i.e., to the volume of an open cylinder)

$$K = P_S L \pi \left[(D + \tau)^2 - D^2 \right] W_S$$

So, using the mechanical stability condition:

$$K = P_S L \pi D^2 \left[2 c_3 + {c_3}^2 \right] W_S$$

We obtain the **Cobb-Douglas** production function $Q = M\ K^{8/9} E^{1/3}$

$$Q^{\beta} = K^{\alpha} E^{1-\alpha} \quad \text{with} \quad \alpha = 8/11 \quad \text{and} \quad \beta = 9/11$$

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Insight #1: The long-run cost function

Long-run

$$\min_{K,E} \quad C(Q) = r\,K + e\,E$$

$$\text{s.t.} \quad Q^{\beta} = K^{\alpha} E^{1-\alpha}$$

Long-run cost function

$$C(Q) = \frac{r^{\alpha} e^{1-\alpha}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}} Q^{\beta} \text{ with } \quad \beta = 9/11 < 1$$

- A concave function => **strictly subbaditive** (Sharkey, 1982)
  - It verifies the technological condition for **a natural monopoly**

    => A need for price and entry regulation of some form!

Cost-minimizing capital $K(Q) = \left(\frac{e\alpha}{r(1-\alpha)}\right)^{1-\alpha} Q^{\beta}$

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Insight #2: The short-run

Short-run

K is fixed

E is variable

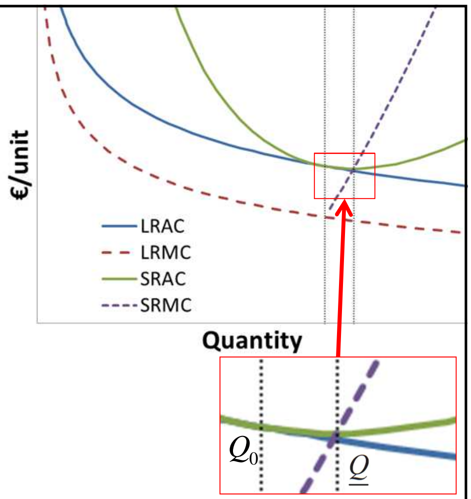
$$E(Q,K) = K^{\frac{-\alpha}{1-\alpha}} Q^{\frac{\beta}{1-\alpha}}$$

Short-run cost function

$$SRTC_K(Q) = rK + eK^{\frac{-\alpha}{1-\alpha}} Q^{\frac{\beta}{1-\alpha}}$$

With

$$\beta/(1-\alpha) = 3 > 1$$



$$\frac{Q}{Q_0} = \left[\frac{\alpha}{\beta+\alpha-1}\right]^{\frac{1-\alpha}{\beta}} = \sqrt[3]{\frac{4}{3}} \approx 1.1006$$

Insights:

- A moderate potential for economies of scale in the SR
- SR marginal cost pricing (see Hecking, 2015) can generate a cost-recovery problem

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INSIGHT #3: R-O-R REGULATION

- We assume a constant elasticity demand schedule

$$P(Q) = A\,Q^{-\varepsilon} \quad \text{with} \quad \varepsilon \in (1-\beta, 1)$$

and examine the behavior of the regulated monopoly

$$\underset{K,Q}{\text{Max}} \quad \Pi(Q) = P(Q)Q - r\,K - e\,E(Q,K)$$

$$\text{s.t} \quad P(Q)Q - e\,E(Q,K) \leq s\,K \qquad (1)$$

- **Solution (K*, Q*): see Klevorick (1971). We have K*> K(Q*)**

And $\frac{K^*}{K(Q^*)}$ **is determined by: the ratio s/r (and is declining with that ratio), the demand elasticity and the technology parameters**

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INSIGHT #3: R-O-R REGULATION

- The socially desirable allowed rate of return

$$\underset{s}{\text{Max}} \quad W(s) = \int_0^Q P(q)\,dq - r\,K - e\,E(Q,K)$$

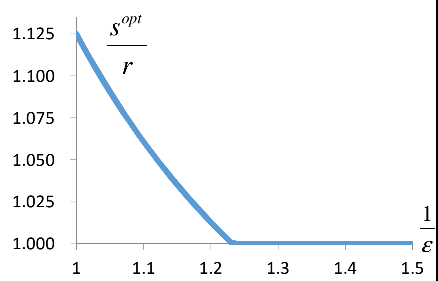
$$\text{s.t.} \quad \left[\begin{array}{l} \underset{K,Q}{\text{Max}} \quad \Pi(Q) = P(Q)Q - r\,K - e\,E(Q,K) \\ \text{s.t.} \quad P(Q)Q - e\,E(Q,K) = s\,K \\ K \geq 0 \;,\; Q \geq 0 . \end{array} \right.$$

Solution: $s^{opt} = \frac{\left[\beta-(1-\varepsilon)(1-\alpha)\right]^2 r}{\alpha\left[\beta-(1-\alpha)(1-\varepsilon)^2\right]}$ iff $r < s^{opt}$

s^{opt} is monot. decreasing with (1/ε)

and s^{opt}>r iff $\frac{1}{\varepsilon} < \frac{11}{2+4\sqrt{3}} \approx 1.23$

As ε < 1, s^{opt} is bounded: $\boxed{\frac{s^{opt}}{r} < \frac{\beta}{\alpha} = 1.125}$



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PART 2: UNLOCKING NATURAL GAS PIPELINE DEPLOYMENT IN A LDC

A note on rate-of-return regulation

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BACKGROUND: MOZAMBIQUE'S GAS BONANZA

- One of the poorest nations (W. Bank, 2015)

2015 GDP/cap:	$525.0
2015 HDI ranking:	180 *(out of 188 countries)*
2012 Electrification rate:	20.2%

- 2010: prolific gas discoveries in the North

  Reserves (Rovuma Basin): 3,700 Bcm *(i.e., 2.5 x Troll in Norway)*

- **The IOCs**

  Favor large scale, export-oriented, LNG projects

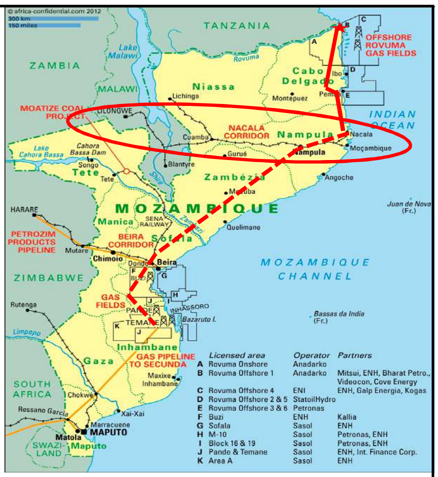
  Overlook the domestic market

- **The Government of Mozambique**

  - Obtains a share of the volumes extracted (PSA)

    Mega-project developers have applied to GoM for gas supply (e.g.: fertilizers, methanol, aluminum)

  - Ambitions the deployment of a national pipeline system



A proposal by the World Bank (2012)

- **A phased pipeline development**
- **Gas-Based Industries (GBI) can provide the "anchor" load needed for pipeline development**

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Building Ahead of Demand?

- **Chenery (1952), Manne (1961):** « build ahead of demand »

  In case of **investment irreversibility** and **pronounced economies of scale**, it is justified to **install ex ante an appropriate degree of overcapacity** to minimize the expected cost of production over time if the future output trajectory is expected to rise over time.

- **The GoM has to attract FDI in a gas pipeline system**
  - **But: foreign investors are reluctant to consider the potential future of the domestic market**

  ⇒ They solely consider the proven demand of **large X-oriented gas-based industries**

- **Joskow (1999)**: in LDCs, simple regulatory instruments should be favored to attract FDI in the infrastructure sector.

  ⇒ Mozambique has implemented a simple form of **rate of return regulation**

Can planners/regulators leverage on the A-J effect to adequately build "ahead of demand"?

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Research Questions

How should the allowed rate of return be determined?

- to attract investment
- to achieve the installation of an "adequate" degree of overcapacity
- to protect society from monopoly prices

- Roadmap

  1 – Examine and characterize the ***ex ante*** behavior of the regulated firm

  2 – Characterize the ***ex post*** behavior of the regulated firm in case of an *ex-post* expansion of the demand

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2: The *Ex Ante* behavior of the regulated firm

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A Regulated Monopoly

- We assume a constant elasticity demand schedule

$$P(Q) = A\,Q^{-\varepsilon} \quad \text{with} \quad \varepsilon \in (1-\beta, 1)$$

and examine the behavior of the regulated monopoly

$$\underset{K,Q}{\text{Max}} \quad \Pi(Q) = P(Q)Q - r\,K - e\,E(Q,K)$$

$$\text{s.t} \quad P(Q)Q - e\,E(Q,K) = s\,K \qquad (1)$$

- Solution: see Klevorick (1971).

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STATIC COMPARISONS

- We compare the solution (*) with two benchmarks:
  - (M) Monopoly
  - (a) Average cost pricing
- Comparing metrics: output, capital, and cost ratios

	$\frac{Q^*}{Q^M}$	$\frac{K^*}{K(Q^*)}$	$\frac{C^*}{C(Q^*)}$
gradient w.r.t. s/r	<0	<0	<0

These ratios are determined by: the ratio s/r, the demand elasticity and the technology parameters.

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3: THE CASE OF AN EX-POST EXPANSION OF THE DEMAND

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The ex-post behavior of the regulated firm

- *Ex ante:*

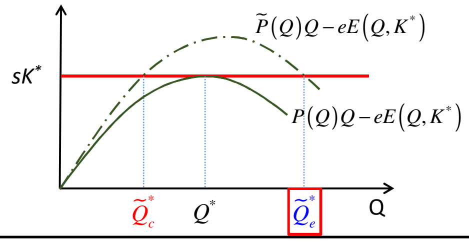
  The regulator has set ***s*** that will remain fixed after the construction

  The regulated firm decides its investment and thus ***K****

- *Ex post:*

  A larger demand: $\tilde{P}(Q) = (1+\lambda)P(Q)$ with $\lambda > 0$

  Lemma: The regulated firm must adjust its output, and there are exactly two candidates: $\tilde{Q}_c^* < Q^* < \tilde{Q}_e^*$



We focus on the case of the expanded output $\tilde{Q}_e^*$

This output is monotonically increasing with λ

A cost efficient Ex Post Output level

- We now consider a cost-efficient capital-output combination (K_{ce}, Q_{ce}) …

$$K_{ce} = K(Q_{ce})$$

where $K(Q)$ is the LR cost minimizing capital

… that also verifies the ***ex post*** rate-of-return constraint:

$$(1+\lambda)P(Q_{ce})Q_{ce} - eE(Q_{ce}, K_{ce}) = sK_{ce}$$

- Solving, we obtain a closed form expression of (K_{ce}, Q_{ce})

QUESTION

- **Can we set s so that the *ex post* capital-output combination is cost efficient?**

Proposition: *For any* $\lambda \in \left(0, \bar{\lambda}\right)$ *with* $\bar{\lambda} \equiv \left[\frac{\beta-(1-\varepsilon)(1-\alpha)}{(1-\varepsilon)\alpha}\right]^{\frac{\eta}{\beta}}\left[\frac{1-\varepsilon}{\beta}\right]-1$

there exists a unique rate of return $s_{\lambda} \in \left(r, s^{M}\right)$ *such that:* $K^{*} = K\left(\widetilde{Q}_{e}^{*}\right)$

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3: POLICY DISCUSSION

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Discussion

- Setting s to optimally build ahead of demand is a desirable objective but…

… if **λ** is small achieving *ex post* cost efficiency requires to set **s at a high level**

i.e., close to the rate of return obtained by an unregulated monopoly if **λ** is close to zero.

- Hence, can the two public policy objectives of:

(1) **protecting consumers** from excessive prices *ex ante*

(2) « **building ahead of demand** »

be jointly achieved?

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The *Ex Ante* socially desirable *s*

$$\underset{s}{\text{Max}} \quad W(s) = \int_0^Q P(q)\,dq \;-\; r\,K \;-\; e\,E(Q,K)$$

$$\text{s.t.} \quad \left[\begin{array}{l} \underset{K,Q}{\text{Max}} \quad \Pi(Q) = P(Q)Q \;-\; r\,K \;-\; e\,E(Q,K) \\ \text{s.t.} \quad P(Q)Q \;-\; e\,E(Q,K) \;=\; s\,K \\ \qquad K \geq 0 \;,\; Q \geq 0\,. \end{array} \right.$$

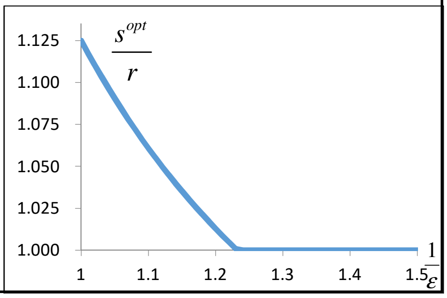
<u>Solution:</u> $s^{opt} = \dfrac{\left[\beta-(1-\varepsilon)(1-\alpha)\right]^2 r}{\alpha\left[\beta-(1-\alpha)(1-\varepsilon)^2\right]}$ valid if $s^{opt} > r$

s^{opt} is monot. decreasing with (1/ε)

and s^{opt}>r iff $\frac{1}{\varepsilon} < \frac{11}{2+4\sqrt{3}} \approx 1.23$

As ε < 1, s^{opt} is bounded:

$$\boxed{\frac{s^{opt}}{r} < \frac{\beta}{\alpha} = 1.125}$$



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Application and Discussion

$\frac{1}{\varepsilon}$	$\underline{\lambda}$	$\overline{\lambda}$	$\frac{\tilde{Q}_e^*}{Q^*}(\underline{\lambda})$	$\frac{\tilde{Q}_e^*}{Q^*}(\overline{\lambda})$	$\mathrm{Min}\left\{\frac{\Delta W^*}{\Delta W^a}(1), \frac{\Delta W^*}{\Delta W^a}\left(\frac{\beta}{\alpha}\right)\right\}$	$\frac{\Delta \tilde{W}^I}{\Delta \tilde{W}^a}\left(\frac{\beta}{\alpha}\right)$
1.05	0.251	0.287	2.053	2.498	0.723	0.990
1.15	0.170	0.200	1.547	1.757	0.727	0.980
1.30	0.106	0.131	1.337	1.440	0.738	0.964
1.50	0.063	0.082	1.223	1.274	0.748	0.937

This table details the range of ***λ*** for which it is possible to: (i) build ahead of demand while (ii) maintaining a fair rate of return ***s*** lower than the threshold **βr/α**.

For $\lambda < \underline{\lambda}$, one has to follow Joskow (1999) who points that regulators in developing economies often face possibly conflicting public policy goals and have to clearly define and prioritize these goals

Conclusions

- The technology of a natural gas pipeline can be approximated by a Cobb-Douglas production function that has two inputs ***K*** and ***E.***
- **Case λ=0:** the socially desirable fair rate of return ***s*** can be larger than ***r*** the market price of capital in the gas pipeline industry.

  Note: welfare maximization suggests that the ratio s/r has to be lower than β/α = 1.125
- **Case λ>0:** It is possible to use the A-J effect to "build ahead of demand"

  BUT: the range of λ for which this strategy does not hamper the social welfare obtained ex ante is quite narrow.

  => It will be needed to prioritize the public policty objectives…

Thank you!