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The Gas Transportation Network as a ‘Lego’ Game: How to Play with It?

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Working paper series : REFGOV-IFM - 68

THE GAS TRANSPORTATION NETWORK AS A ‘LEGO’ GAME: HOW TO PLAY WITH IT?

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Abstract:

Gas transportation networks exhibit a quite substantial variety of technical and economical properties ranges roughly from an entrenched natural monopoly to near to an open competition platform. This empirical fact is widely known and accepted. However the corresponding frame of network analysis is lacking or quite fuzzy. As an infrastructure, can a gas network evolve or not from a natural monopoly (an essential facility) to an open infrastructure (a “highway” facility)? How can it be done with the same transportation infrastructure components within the same physical gas laws?

Our paper provides a unified analytical frame for all types of gas transportation networks. It shows that gas transport networks are made of several components which can be combined in different ways. This very “lego property” of gas networks permits different designs with different economic properties while a certain infrastructural base and set of gas laws is common to all transportation networks. Therefore the notion of “*gas transportation network*” as a general and abstract concept does not have robust economic properties.

The variety and modularity of gas networks come from the diversity of components, the variety of components combinations and the historical inclusion of components in the network. First, a gas network can combine different types of network components (primary or secondary ones). Second, the same components can be combined in different ways (notably regarding actual connections and flow paths). Third, as a capital-intensive infrastructure combining various specific assets, gas transportation networks show strong “path dependency” properties as they evolve slowly over time by moving from an already existing base.

The heterogeneity of gas networks as sets of components comes firstly from the heterogeneity of the network components themselves, secondly from the different possibilities to combine these components and thirdly from the ‘path dependence’ character of gas network constructions. These three characteristics of gas networks explain the diversity of economic proprieties of the existent gas networks going from natural monopoly to competitive markets.

KEYWORDS: gas transport networks, regulatory economics, network regulation

JEL Codes: L5, L29, D42, D61, D62

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Introduction: Gas networks are not "Single Size" Tools but a Set of Pieces as in a Lego Game

There is huge diversity among gas transportation networks. They vary from a straight single pipeline linking a few points (IEA 1994) to interconnected networks with more than 200 pipelines linking thousands of points (EIA 2009). Besides the number of pipelines and entry and exit points, the gas networks can also be differentiated by their other components such as "*compression stations*" (always necessary for transport and with various effects on transportation capacity), "*storages*" or "*physical hubs*" (which are optional and do not exist in all gas networks). Moreover certain combinations between compression stations and pipelines allow the gas flow to take only one and a single direction while other combinations permit opposite directions (upstream or downstream) creating a totally new architecture of gas networks (IEA 1994, CIEP 2009, Mokhatab et al 2006).

This paper shows that the characteristics of gas networks result in three features: 1) networks are made with different network components, 2) these components can be combined in different ways and 3) the various possible combinations are "path dependent" of long series of sequential decisions to add components. As a result the gas networks can exhibit different designs having different economic proprieties. It explains why we cannot determine natural gas networks in general as having a single homogeneous economic nature. It also explains the difficulty of defining the actual 'core' proprieties of gas transportation when constructing general techno-economic models of gas flows as shown by Midthun, K. T et al. (2006) or by the traditional industrial economic tools of monopoly theory as discussed by Kahn (1989): "*The local distribution of gas is generally recognized as a natural monopoly of the familiar type, with the same justification: economies of scale with increasing intensity of use of given distribution facilities. But with respect to the pipeline network that carries natural gas from the field to the city gate of the local distribution system, the question of the proper role of the competition has come into increasingly intense contention in recent years*" (Kahn, 1989, page 152).

The determination of the network economic features is a key issue in order to understand and delimitate the potential of competition of a gas network. As underlined by Moselle and Harris, (2007) the determination of pipeline features and potential of competition is essential in order to define the appropriate regulation; however the methodologies applied should be mostly based on a 'case by case' analysis to take in account the network specificities.

In order to identify the origins or rational foundations of gas networks heterogeneity, we apply a technical-economic approach. First we define the primary components of the gas transportation network: the tube itself and its compression stations. Second, we analyze the properties coming from different combinations between pipes and compressors. It covers several changes of key economic properties of gas transportation: the economies of scale of transport capacity, the short term tradeoffs between transport capacity and line-pack capacity, and the externality effects resulting in transport congestion. We also introduce the interconnections among various pipelines and sets of compressors. As a result, the diversity of network designs grows with the number of pipelines and compressors being co-operated through interconnections.

In the third part we introduce a new group of network components being the "secondary components". There are a range of secondary components: storages and physical hubs, plus LNG terminals being a special kind of storage and physical hub. It introduces a broader heterogeneity generated by the sequential insertion of primary and secondary components in existing gas transmission networks. We study the strong interaction between secondary and primary components. The "secondary components" are not necessarily present in all gas networks, however when present these secondary components interact strongly with the primary components enough even to change the network architecture and the network properties entirely.

1) The Primary Components of Gas Transport Network: a Kind of 'Lego' Box

The primary components of the gas transportation network, being the tube itself and its compression stations, are present in any gas pipeline. They are the basic components of very simple networks composed of one single pipeline but also those of more complex networks. These two components are basic because it is their interaction that makes gas flow. However these two components show some heterogeneities which may change the flow characteristics. The physics of gas flow consequently impacts the economic uses of this flow. So the choice of the basic components, being done to answer different needs, can result in different transportation features. A pipeline can transmit a reference quantity which is defined according to the pipeline material, the pipe diameter, the distance and topology between the different entry and exit points connected to this pipe. The compressors can themselves differ in technologies, power and location along the pipe. Therefore it is the actual definition of these two components (pipe and compressors) which sets the basic characteristics of every transport system: its transport capacity, its storage capacity through line-pack, and its congestion constraints.

Gas transport networks differentiate primarily by their tubes themselves and then with their architecture ranking from trunk lines to grids. A gas transport system is initially and voluntarily designed as a grid or as a trunk line system. The latter is usually a long-distance, wide-diameter pipeline system that links a major supply source with a market area (or with a large pipeline / LDC serving a market area). Trunk lines tend to have fewer entry points (usually they are at the very beginning of its route: "Upstream"). They also have fewer exit points, fewer connections with other pipelines and associated lateral lines. A typical grid transmission system is made of a number of lateral branches exiting from the mainline. It results in a network of integrated receipts (entry) and deliveries (exit) that operate in, and serve many market areas. This grid transmission system is then similar to a set of "trunk and branches" (like in a typical local distribution company network configuration but on a much larger scale).

The second differentiation concerns the compressors. The choice of compressors defines the range of pressure and so the range of volume and velocity at which gas can flow inside the pipes. All along the route between the gas producing area, or supply source, and the consumption market area, a certain number of compressor stations are inserted into the transmission system. These stations contain one or more compressor units whose purpose is to receive at an intake point the gas flow (which has decreased in pressure since the previous compressor station) then to increase the pressure and rate of flow which keeps the gas moving along the pipeline.

1.1 The Gas Pipe: Techno-Economic Properties

Even in the simplest case of one single tube gas network, there are many choices that need to be made 'ex ante' to design the pipeline according to the expectation of its future use. The relevant choices when designing an investment in gas transport are related to three dimensions: economical, technical and locational.

The actual flow of gas in a pipeline depends on the gas' physical properties and of the transport infrastructure. The interrelation between economical, technical and locational dimensions will determine the actual properties of gas flow[3], and consequently the pipeline economic potential for transport. The choices framing the pipeline investment 'ex ante' determine the range of possible uses of pipeline 'ex post'. The actual ex ante

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[3] The variables defining the amount of gas flow can be seen in the general flow equation: Qsc= C(Tb/Pb)*D0,25[(P_{in} – P_{out})/($FY_GT_aZ_aL$)]0,5E (Mokhatab S. et all, 2006). Where: Qsc is the standard gas flow rate, measured at base temperature and pressure; T_b is gas temperature, (base conditions 519,6° R); P_b is base pressure, (base conditions, 14,7 Psia); P_{in} is inlet gas pressure psia; P_{out} is outlet gas pressure; D is the inside diameter (in inches); F is the Moody friction factor; E is flow efficiency factor (correcting some assumptions); Y_G is gas specific gravity; T_a is the average absolute temperature of pipeline; Z_a is the average compressibility factor; L is the pipeline length in miles; C is 77,54 (a constant for the specific units used).

choice depends on the expectation of pipeline use concerning the global transportation volume, the localization of supply and demand and the transport spikes frequency.

a. The Economic Choices: Pipe Size Diameter and Length

The pipeline transport capacity depends on the volume created by the internal diameter and the length of the pipe. The choice of these two parameters is based on the desired transport flow features being how quickly the gas molecules will be transported by time unit and how far. It covers the acceptable pressure drop, compression ratio, and allowable gas velocity. An acceptable pressure drop in gas transmission pipelines is the one that minimizes the size of required facilities and the related expenses such as the construction cost of the pipe, the power of the compressors to be installed, the size and number of these compressors, and the compressor fuel consumption, as will be seen in the next sections.

The size of the pressure drop depends on the length of the pipeline segment (between two compressor stations) because longer pipeline segments need more pressure to move gas[4]. Consequently it is one of the main concerns for long pipelines. For some short pipelines (as short pipeline segments), on the contrary, the pressure drop is of secondary importance. Then the pipe can be designed with the demand spikes size and frequency as the main variable in determining how much gas one can transport in a given period.

b. The Technical Choices: The Friction Factor, Withstanding of Internal Pressure and the Temperature Isolation

The choice of pipeline material has a strong influence on two key variables of the gas flow being the friction factor and the temperature of gas. Firstly the choice of material determines the efficiency of the gas flow as related to its friction with the tube and the change of gas temperature. The friction factor and temperature change influence the gas flow when it faces pressure differential. Then the consequences of the material choice differ for a “big” and a “small” pipe. In a small pipe, a cheap and less effective material is less consequential to the gas flow than in a big pipe. It is one more ‘ex ante’ decision which will determine possibilities of economic uses and variable costs of network.

The pipeline material changes the frictional factor through the pipe roughness (ε). “*Fluid flow is characterized by dimensionless value known as the Reynolds number roughness (ε), which is often correlated with the pipe material and, it is divided by inside diameter*.” (Mokhatab S. et al, 2006 page 256)

The roughness of the pipeline determines how much the pressure will drop when the gas is flowing in the pipe. If the friction factor increases, and if everything else is constant, it results in higher pressure drops, which reduce the efficiency of gas transport. A higher friction factor increases the need of pressure which is an energy consumption factor (as energy consumed by compressors) and a cost of gas transportation.

The amount of energy being lost in friction depends on the material of the pipeline and of the precise interaction between the gas and the pipe. So besides the proper characteristics of the material of the pipe it depends on the chemical and physical characteristics of the gas being transported and of the size of the pipe internal surface with which the gas will be in contact.

As a result, the friction factor comes from a complex interaction of variables and the ex ante calculation of (ε) is not trivial. In most cases, pipeline operators customize the flow equations of their particular pipeline by measuring the actual flow, pressure, and temperature in operation and then calculating back the pipeline

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[4] A large pressure drop between stations will result in a large compression ratio and might introduce poor compressor station performance.

efficiency or “actual pipe roughness”.

Regarding now the second major variable, the inside temperature of gas, it is influenced by the material of the pipe and the pipe wall thickness. It works through two mechanisms. One is the frictional loss described above and the other is the capacity of heat transfer with the outside environment.

The friction factor and the temperature have strong interaction. With everything else constant, the increase/decrease of the friction loss also means increase/decrease of temperature. While a temperature change can modify the physical proprieties of gas, it also can modify its frictional factor also. For example, a lower gas temperature can increase the liquefaction of gas in the pipe and directly increase the friction losses in the transport system[5].

The temperature and the frictional factor have complex interactions and can change along the pipeline. It is why the “*ex ante*” prediction of temperature is a difficult task which needs numerous measurements to be made all along the pipeline. To predict the temperature profile and calculate the pressure drop it is necessary to divide the pipeline into several smaller segments interacting with more homogeneous outside environment characteristics. These environment characteristics can be more or less influential depending on the pipe wall material and thickness. As this allows more or less heat transfer between the outside and the inside of the pipeline.

The kind of pipe wall material and wall thickness also determines the maximum pressure to be exerted in a pipeline. It works as the pipe wall resistance to local over pressure of gas[6]. The current practices are based on experimental cases plus safety margins. (Sotberg and Bruschi, 1992). One limits the maximal pressure because if “*the internal pressure in a pipe causes the pipe wall to be stressed, and if allowed to reach the yield strength of the pipe material, it could cause permanent deformation of the pipe and ultimate failure*.” (Tabkhi F. 2007, page 22)

c. The Location Constraints: Environmental Characteristics as Temperature, Soil and Elevation

The choice of the pipeline path is also a key choice to design networks. On the one hand it determines the distance between the potential consumers and the pipe branches; on the other hand it is a key parameter of network costs.

The pipeline environment characteristics such as soil and temperatures are influential in determining the physical and chemical properties inside the pipe. It inevitably varies from region to region and along a given pipeline route. The costs of pipelines are then quite different from region to region. The external physical environment plays a key role in influencing the temperature profile and the overall heat transfer coefficient.

The other crucial external factor which influences the gas flow is the pipeline topology. Pipelines are usually not strictly horizontal, and their slope affects the gas flow.[7]

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[5] “Flowing gas temperature at any point in a pipeline may be calculated from known data in order to determine (1) location of line heaters for hydrate prevention, (2) inlet gas temperature at each compressor station, and (3) minimum gas flow rate required to maintain a specific gas temperature at a downstream point.” (Mokhatab S. et al, 2006 page 43)

[6] “After selecting the appropriate outside diameter for a pipe, it is necessary to determine a suitable wall thickness that can withstand the internal pressure. For a given outside pipe diameter, the pipe wall thickness is calculated to withstand different loads (e.g., lateral loading, external pressure collapse, installation stresses).” (Bay, 2001).

[7] If the elevation is not negligible a correction for the static head of fluid Hc may be taken into account: $Qsc= C(T_b/P_b)*D0,25[(P_{in}– P_{out}-H_c)/(FY_GT_aZ_aL)]0,5E$ $Hc = [0,0375g (H_2-H_1) Pa_2]/ (Z_aT_a)$ (Mokhatab S. et al, 2006)

To summarize, investing in a pipeline involves choices. These choices affect different variables which can be grouped into three bunches: the pipeline technical characteristics (notably the pipe material), the pipeline economic characteristics (here the pipe size and length) and its geographical location (giving the environmental constraints). These three types of variables are in interaction to determine the gas flow. However the gas flow also depends on other network components as the set of compressors.

1.2 The Compressors

A gas transmission network being made of high pressure pipelines utilizes a set of compressor stations to move gas over distances. Actually gas compression is utilized in all aspects of the natural gas industry to move the gas between two points.[8] The gas transport is actually based on pressure differential. It is why the compressor stations besides the pipe itself are basic elements of gas transport[9].

The choice of compressors is also a key feature to design any network. When the network is designed, the choice of compressor technology, localization, number and timing of insertion define with the pipeline itself the three main features of a single pipe: the range of flow volume that can be transported, the frequency that the transported gas volume can increase and decrease and also the sites of gas injections and withdraws.

Nowadays, it has been a trend toward increasing pipeline operating pressure. The benefits of operating at higher pressure include the ability to transmit larger volumes of gas through a given size of pipeline, to lower transmission losses due to friction, and the capability to transmit gas over long distances without additional boosting stations.

There are two main technologies applied to compressors: the reciprocating compressors, which are a displacement machine[10] and the centrifugal compressors which work by centrifugal force.

On the one hand the reciprocating compression process impels undesired fluctuations. Therefore, pulsation dampeners have to be installed upstream and downstream of the compressor to avoid damages to other equipment, however these dampers carry pressure losses (several percent of the static flow pressure). On the other hand reciprocating compressors are flexible in throughput and discharge pressure range; it is why they are widely utilized in the gas processing industries and in other uses which demand flexible throughput and discharges.[11]

The gas centrifugal compressor[12] "*speeds up and compresses gas via a rotor with blades. Centrifugal force is*

Where: H2 is the out elevation and H1 is the inlet elevation. In other words, the increase of elevation between two inlet and outlet are equivalent in a decrease of outlet gas pressure. So if everything else is constant, the increase of Hc means that the inlet pressure P1 should be bigger.

[8] Compressors are used for gas flow in any process including gas lift, gas gathering, gas processing operations (circulation of gas through the process or system), transmission and distribution systems, and reducing the gas volume for shipment by tankers or for storage.

[9] "The pressure drop in a gas pipeline, i.e., the essential parameter to determine the required compression power for the transmission is derived from the differential momentum balance. Friction between fluid boundary layer and interior surface of the tube induces energy losses and, consequently, reduces the gas pressure." (Tabkhi F. 2007, page 16)

[10] "A reciprocating compressor is a positive displacement machine in which the compressing and displacing element is a piston moving linearly within a cylinder. As the piston moves forward it compresses gas into smaller space, thus raising its pressure. (Ohama et all, 2006, page 90). Moreover we can differentiate the two types of reciprocating compressors, called "lube" with oil injection and "non lube" the oil-free. (Bloch H. P., 2006).

[11] It can be classified as "high speed" or "slow speed". Typically, high-speed compressors operate at speeds of 900 to 1200 rpm and slow-speed units at speeds of 200 to 600 rpm. High-speed units are normally "separable," i.e., the compressor frame and driver are separated by a coupling or gearbox. For an "integral" unit, power cylinders are mounted on the same frame as the compressor cylinders, and power pistons are attached to the same drive shaft as the compressor cylinders. Low-speed units are typically bundled in design.

[12] In the centrifugal compressors the gas entering the inlet nozzle of the compressor is guided to the inlet of the impeller. An impeller

used to force the air or gas to an outer chamber under higher pressure; they are designed to operate above 75-80% speed. Surging can occur below these speeds. This makes the centrifugal compressor ideal for continuous high duty operation". (Yaskawa, 2009, page 1) Therefore this type of compressor is able to have quite important output but it is not as flexible as the reciprocating compressors concerning the range of discharge pressures.

The different working principles cause differences in the operating characteristics of the centrifugal compressors compared to those of the reciprocating unit. The key variables for equipment selections are their cost and also their efficiency according to the actual gas demands' profile served by the gas pipes. According to Ohama et all (2006), to define the more efficient technology designers must take into account the pressure ratio, the maximum discharge, the inlet volume, the need to control the variations of the gas speed, the constraints from the gas quality, and the need to control the compressing power of a station (comparative table in annex- table 1). The expectation of demand fluctuations plays an important role in choosing the compressor technology. While both gas engines and gas turbines can use the pipeline gas as a fuel, an electric motor has to rely on the availability of electric power. Due to the number of variables involved, the task of choosing the optimum driver can be quite demanding. Any comparison has to take into account the different possible compressor types and whether or not the compression task should be divided into multiple compressor trains, operating in series or in parallel to one another.

All these technological choices are constrained by the physical proprieties of gas: the interactions between temperature, gas density and pressure. In a few words, the efficient technological choice actually depends on the site localization, the gas quality, and the ratio of pressure expected, the pressure range and the volume rate. As in the pipeline choice, the efficient choice for compressors investment depends on the expected demand characteristics; which is not only the amount of gas demand but the kind of usages to be served.

2. Pipe Plus Compressor Shape the Gas Flow Dynamics: A Couple of Techno-Economic Choices over Site Constraints

Optimum design of gas transmission pipelines comes from the interaction between pipeline and compressor features that were presented in last section. The network optimum design depends on the forecasted use of the pipeline: the expected demand features. The typical design of a gas pipe involves a compromise between the pipe diameter, the compressor stations' spacing, the fuel usage, and the maximum operating pressure. This compromise between the compressor and pipeline features simultaneous generates a transport capacity, a line-pack capacity and (presumably) some negative externality (i.e. some congestion constraint). All these features are the "economic products" characterizing the transport services offered by the network.

2.1 The Transport Capacity: The Main Economic Product of Gas Networks

The physical transport capacity is the main product offered by a pipeline. It is the result of the association of the two basic elements of network (compressors and pipeline). However, transport capacity can change along the pipeline if exogenous variables change. According to EIA (1994) the capacity of a pipeline in uniform environment is determined by pressure between its ends, and its diameter. To the same pressure differential, a bigger diameter means an increase of capacity of transport more than proportionally. As diameter increases, capacity rises faster than the cross-sectional area of the pipe, since gas moving in a larger line suffers proportionally less frictional drag from the wall. The increase of diameter means bigger increase in the pipeline

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consists of a number of rotating vanes that impart mechanical energy to the gas. The gas will leave the impeller with an increased velocity and increased static pressure. In the diffuser, part of the velocity is converted into static pressure. A compressor stage is defined as one impeller, with the subsequent diffuser and (if applicable) return channel. A compressor body may hold one or several (up to 8 or 10) stages. A compressor train may consist of one or multiple compressor bodies. Pipeline compressors are typically single body trains, with one or two stages.

volume. If the pipeline size is constant, the maximum transport capacity is determined by the maximum differential of pressure between the extreme points. It is also limited by the pipe wall features, as already described.

The transport capacity can be seen as the capacity to transport a certain number of molecules of gas or a quantity of energy. The two concepts become equivalent if a constant and equivalent gas quality is supposed. The capacity of transport is also measured for a determined period. It is the quantity of gas or energy that can be transported in that period. So besides the gas volume, the velocity at which gas can be transported is another important variable in the determination of the transport capacity. However the gas velocity has its own limitations. It needs to be kept below maximum allowable velocity in order to prevent pipe erosion (because of friction), noise or other variation problems. In most pipelines the recommended value for the gas velocity is 40 to 50% of the erosion velocity[13]. According to Menon (2005 page 37): "*The velocity of gas flow in a pipeline represents the speed at which the gas molecules move from one point to another. Unlike a liquid pipeline, due to compressibility, the gas velocity depends upon the pressure and, hence, will vary along the pipeline even if the pipe diameter is constant. The highest velocity will be at the downstream end, where the pressure is the least. Correspondingly, the least velocity will be at the upstream, where the pressure is higher*." ().

It should be remembered that the maximum transport capacity of a pipeline is not the same like the maximum efficient transport capacity of a pipeline, because there is a cost for energy lost from friction. Therefore what is called "congestion of the gas transport" can be seen either as an inefficient transportation zone or as the actual incapability to transport as it will be seen in the next sub-section (in the annex table 2 summarizes the tradeoffs concerning capacity increase).

2.2 The Gas under or over Pressure in the Pipeline: Congestion Constraint and Line-Pack

According to Shaw (1994) the pipeline system optimization has two physical constraints and one economic constraint. The physical constraints can be explicit or implicit. Constraints are explicit when felt directly by the user, like maximum and minimum pressure and flows at a certain point in the system[14]. Constraints are implicit when originated in the modeling of compressor and pipe control data[15] to define the range of safety network operation. The economic constraint relates to the cost of transporting gas, specially the cost of compression, as pressure increase can be technically possible while economically inefficient.

Under any of these constraints, when the pipeline does not work properly to minimize gas transportation cost, that constraint is said to generate a congestion problem. The first and easier kind of gas transport congestion is a demand of gas transport bigger than the gas transport capacity. It occurs when an increase of gas flow in the system conflicts with safety conditions because the maximum possible pressure has already been reached. It happens if an increase of gas injection into the pipeline decreases the pressure differential (upstream vis-à-vis downstream) to a lower level being smaller than the frictional factor. It comes from the fact that it is not enough to inject gas to make it flow in the pipe given the resulting pressure differential. It happens when it is no longer possible to further increase that pressure at the injection point. However transport congestion can also be as a less extreme problem, when the decrease of pressure differential does not lead to stopping the gas flow while actually decreasing the delivery flow or increasing the delivery pressure.

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[13] As a rule of thumb, pipe erosion begins to occur when the velocity of flow exceeds the value given by Equation: Ve= C/ρG0,5. (Salama M. M., 2000), where: V_e is the flow velocity; C is a empirical constant; ρG is the mixture (gas) density.

[14] Examples are maximum supply pressure or minimum contracted delivery flow.

[15] Examples are: thickness wall and maximum compression, maximum and minimum compressor flow, maximum and minimum compression ratio and etc. These implicit constraints are derived from the pipeline and compressor proprieties as treated in section 1.

Congestion can also be seen as a typical kind of economic inefficiency. It is the case when one can technically increase the gas flow but at a cost not being optimal (being bigger than the increase of benefits) as explained by Menon S. (2005 page 180) "*there is a limit to the number of compression stations that can be installed in a given pipeline system, since the HorsePower required continues to increase with flow rate and, hence, the capital cost and operating costs as well. At some point, the costs increase at very high rate compared to the increase inflow rate. Each pipe size has a particular volume that can be economically transported based upon cost*." One of the costs is the cost of corrosion of the pipeline, as the increase of flow rate increases velocity, and therefore increases the corrosion of the pipeline conflicting with the need to stay below the erosion velocity.

The decrease of pressure ratio at inlet and outlet points can be undesired as negative congestion effects. It may carry inefficiencies or even block the transport system. However decreased pressure ratio of a pipeline also can bring value to the transport system because it brings a storage capacity service inside the pipeline. It is the "line packing service": storing gas inside the pipeline network by boosting the line pressure, employing the flexibility allowed by the range of possibilities to use the same network.

Moreover a pipeline company can use interconnected pipelines segments to store gas. These new segments of pipes are called loops[16]. The line-pack is a storage tool characterized by a fast process of injections and withdraws, and is often used to balance the system in the short-term. However it has a limited capacity and is a costly type of long-term storage resource as line-pack capacity is constrained by the pipeline diameters and the limits of pipeline pressure[17].

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[16] "The purpose of a pipe loop that is installed in a segment of a pipeline is to essentially reduce the amount of pressure drop in that section of the pipe. By doing so, the overall pressure drop in the pipeline will be reduced. This in turn, will result in an increased pipeline flow rate at the same inlet pressure. Alternatively if the flow rate is kept constant, reduction in total pressure required will cause reduction in pumping horsepower." (Menon 2005, page 177)

[17] The actual line-pack capacity, as it emphasized by IEA (2002), depends on the design of the gas transmission system. "Some designs are based on the principle that transmission capacity and supply capacity are matched, and the transmission system cannot be used to diurnal storage. In other designs, the transmission system can be used not only for transporting gas from the supply sources to the end-users but also a mean to balance the fluctuation in demand that occurs during the day." (IEA, 2002, page 68). Moreover as showed by Keyarts et all (2009) the line-pack has in one hand an economic value but in the other hand it has also a economic cost, as its employment can decrease transport capacity.

2.3) The Game Box Being Transformed by Multiplying Its Pieces: The Interconnection of Pipelines

As shown, the transport of gas between two points (inlet and outlet) takes place trough the combination of two basic components: pipes and compressors. Even in the simplest case, being only two points and a pipeline between them, the actual design depends on different variables; notably: where, how much and how often the gas is expected to flow. One can then easily understand that the connection of several networks actually changes the expected and the real uses of pipelines. As a result, connecting has an important impact on the previous 'ex ante' network designs and on the future 'ex post' uses of these networks. Each former single pipe gets the possibility to quickly increase its number of inlet and outlet points by addressing the other pipe as an added set of basic components.

The interconnection between pipelines brings a "core change" in gas transportation, as it multiplies the number of entry and exit points and increases the variety of alternative gas paths. With several pipelines interconnected, gas can flow between many points if there is enough pressure differential between them. This way more complex gas networks are created by sequential additions of components over time. In networks where many pipes are interlinked, the gas coming from one point can be delivered too many points through different pipes[18].

In the simplest example of transport (only one pipe linking two points) the gas commodity and the transport are inseparable products. As if all the components (compressors, pipeline, gas) were actually a unique and big component. There the components are inseparable in order to work properly.

However when there is a connection of pipes and compressors, with many entry and exit points, the transport infrastructure can be used to carry gas from alternative entry points to alternative exit points. In this case one can distinguish two different activities, being complementary but separable. The gas is itself a certain commodity transacted between buyers and suppliers. Apart from that commodity trade there also exists alternative services of gas transportation that can be transacted between entry and exit points.

The potential differentiation between the two complementary products, gas and transport, becomes actual in a network with alternative transportation routes between points of entry and exit. It then becomes possible to separate the gas commodity trade from the transport trade. With different transport paths the gas molecule trade is more easily distinguished from the transportation related services[19].

2.4) Changing the Network Design

Collections of pipelines and compressors can exhibit different designs offering different opportunity for further network design changes and opening different paths for the future of gas transportation. In a gas network, new investments into interconnections need to take into account certain interactions. Firstly the interaction between demands on the two sets of lines and second the interaction between the two sets of gas flows. 'Ex ante' (before the interconnection), one can already expect that the future transportation demand in the new unified set of lines will depart from the former demand of transport in the old two separated sets of lines. It is because a gas inlet in one line may become a new exit point for the other line. Even with only two lines in a

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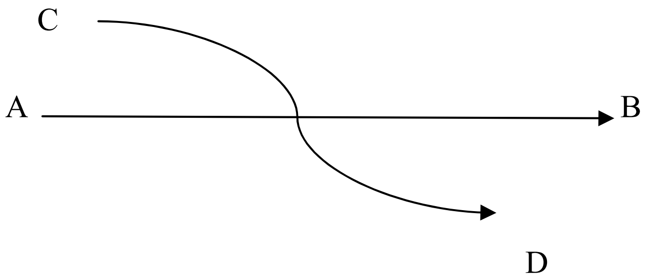
[18] "Usually, several pipelines meet at transportation nodes in the network. The natural gas is mixed, and a homogeneous gas leaves the transportation node through one or several other pipelines." (Midthun, et al., 2006 page 4).

[19] In other words, it can be called 'module' according to the definition propose by Glachant J. M. and Perez Y. (2008). A module would define independent task blocks and would build clean impermeable interfaces.

newly connected network such new demand interaction may be already very consequential. In a simple example (figure 1) the gas transported inside an AB line may not be the gas going from A to B but the gas going from C to B or from A to D.

Figure 1: A simple example with 2 pipes



Considering now the 'ex post' side of line interactions, new interconnections can change the pipeline inlet and outlet pressures and so it can also alter the transport capacity. *"In a natural gas network, the practical capacities that can be utilized in one part of the network depend on the pressures and flows elsewhere in the system. For a node with more than one pipeline connected, the chosen pressure level in the node influences the capacity in all pipelines connected to the node" (Midthun et all., 2006, page 6).* So such 'ex post' interactions need to be considered. These are kinds of external effects (externality) which have to be evaluated and controlled.

Furthermore changing the pressure ratio in a given pipeline can push the gas in the opposite direction. If the original flow direction is A to B, as indicated in the figure 1, and if the pressure ratio changes enough, increasing further the pressure ratio B/A can make the gas flow from B to A. In order to exploit and control the capability to reverse flows in gas networks, a certain ex ante coordination of designs of the sets of compressor stations and of metering stations is required in the whole interconnected system as underlined by GIE (2009).

Afterwards the 'ex ante' redesign of networks and the 'ex post' actual transport operation interact to define the operative transport capacity, the possibilities of flow redirections, the likely congestions and the line-pack capacities.

3) The Inclusion of Secondary Components: Increasing Flow Mobility

The two components already presented (compressors and pipeline) are essential to any gas transport network. In this third section new boxes of components will be added. These new pieces, even if not present in all networks, are able to introduce strong changes of gas transport flow, network design[20] and, as a result, of economic uses of networks.

These new components are hubs and storage. They are key pieces influencing the transport capacity and the other network features. They can increase the mobility of gas flows[21] against former site and time asset

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[20] The insertion of these new components is strongly related with the higher maturity of the gas industry as detailed by Honore (2009). and Estrada et all (1995).

[21] As underlined by IEA (2002), the flexibility provided by the gas pipelines and compressors are limited by the pipe diameter, the maximum design pressure and the compressors configuration.

specificity “à la Wiliamson[22]”. Storages and hubs are bi-directional components. They can work as entry points as well as exit points in the network. Along with hubs and storages this section will introduce the “Liquefied Natural Gas” (LNG) infrastructures as another kind of hub and storage.

3.1) The Hub: An Infrastructure’s Interface

A physical hub is an interconnection of many pipes at the same point, from which several gas flows can be delivered to and taken from. Therefore a hub is a place to actually trade gas. According to IEA (2002) the precise infrastructure of gas hubs can vary. However they are currently described as a pipeline working as a header system linking pipelines with relatively short distances between their transfer points. This is often interconnected to other facilities as storages or LNG facilities. Hubs usually have bilateral compressors and pressure changes in hubs according to the actual gas demand flows between the pipes, allowing reverse flows according to demands and offers[23].

Hubs are connected with others pipes through gateways with compressor stations and metering stations. As a hub is a connecting point, where gas is let in and out, the pressure with which the gas is withdrawn and injected needs to be under operators control in order to not generate too much negative externalities in the connected pipelines. Besides of their transmission capacity, hubs also need to have some extra capacity to store gas in order to cover temporary imbalances between supply and demand without disturbing the whole system. It means that hubs have, as a practical rule, some storage capacity. It can be line-pack capacity or other kind of storage infrastructures. Frequently hubs are developed attached to some underground storage. However, according to EIA (2003), a hub can have easy access to distant storage, even if they are not directly interconnected. Today, in the new ‘LNG era’, LNG infrastructures and LNG storages can also play that role of distant storages in order to serve certain hubs.

In summary, a hub is a component able to connect a larger number of other components and to interface their economic and technical operations. A physical hub is a unique interfacing piece in the gas Lego game. It allows a bigger number of components to interact in a single place and it permits control of the external effects that could be generated.

3.2) The Storage

There are three current ways of storing gas: a- compression inside the transport facility[24], b- underground facility, and c- liquefaction facility. The first way is the line-pack process described in the former section. The third, liquefaction storage, is a special kind of storage particular to LNG facilities. The second type, the underground storage referred to in this subsection is the most conventional type of storage.

The basic principle of underground storage is in fact the same as for line-pack gas under high pressure. However the gas pipe providing line-pack service has strong constraints to resist to higher pressure. With underground storage these pressure limits are much higher. The most common kinds of underground storage are depleted gas or oil fields, salt caverns or aquifer reservoirs. All these types of storage demand particular geological characteristics being not widely spread. As underlined by Bourjas (1996) the actual investment choice among alternative storage types is rather restricted.

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[22] Williamson O. E.,1981.

[23] The contract functions of a hub are also quite important and underlined by EIA (2002) “the hub operator must provide the following services: interconnections between the pipelines to allow the gas to be interchanged between the system, and ideally, storage facilities; easy transportation to and from the hub; and several associated services, such as balancing and recording transfers. An important prerequisite for successful short-term trading at a hub is the speed at which contracts can be concluded.” (EIA 2002, page 78)

[24] The line-pack is described in the second section.

The most important parameters to define the capacity of a given storage are the working capacity and the withdraw rate. The working capacity is the maximum volume of gas that can be withdrawn during a season of operation. Actually it is said to be the difference between the total capacity and the volume of cushion gas (the gas being used to push the working gas outside). The withdraw rate, or the maximum 'send out' capacity, is the maximum volume that can be withdrawn during a given time, usually a day or an hour[25]. These two parameters summarize the characteristics of the storage facility "*on the one hand its size and on the other the maximum and minimum pressure authorized during the operation. It is crucial not to go below a specified pressure, compliance can cause storage reservoir to collapse and destabilize the subsoil" (Bourjas 1996 page 199).*

To invest in gas storage, a key issue is to consider the characteristics of the demand for storage. It can go up to build a portfolio of different storages to combine different profiles of costs and of services as underlined by Commission Staff Working Document (2009). When it is useful to withdraw very fast from the storage (like to answer quickly to a fast increase of gas demand), then the salt caverns provide the best technological choice. However, to face big seasonal variations of demand, bigger storages are needed, and the aquifer and depleted fields fit better (big storage units can also be "strategic storages" as indicated by the Commission Staff Working Document, 2009). Geological and geographical restrictions are also keys for storage. A geological niche is first needed to build and then a good location to easily respond to the demand needs. Of course storage can be linked to demand through appropriate transport infrastructures, incurring then additional costs, NPC, (2003). Investing into new storages is therefore submitted to strong geological constraints and economic constraints.

3.3) The LNG facilities

The liquefied natural gas is a physical form of gas which permits the transportation of a big amount of energy in a reduced volume offered by a dedicated ship. Besides the traditional areas of the gas industry (exploration, production, transport, storage, distribution), a LNG facility chain brings a new set of facilities being those of gas liquefaction, gas shipping, gas regasification and gas storage. However in the frame of our paper, the LNG chain is only seen as a component of the gas transport network being both an exit point (where the gas is liquefied) and an entry point (where it is regasified). In theory some terminals could be both exit and entry points, while it has not been economically feasible until now[26].

As entry and exit points, the LNG facilities are new and very special pieces in a gas network. They are always modular, meaning that they can operate in separation from the rest of the gas network and that they can be plug into different places or on different gas ways. A given LNG ship, under some technical restrictions, can go to take gas at different exit points and come back to deliver to different entry points. The LNG chain provides a gigantic interconnection service among numerous networks having no other connection node and no other common infrastructure (like the two sides of an ocean). Then LNG facilities are components of interconnection creating new hub effects among previously connected or non-connected networks. The ship fleet flexibility substitutes for the site immobility of the other facilities. LNG terminals bring to networks a kind of hub. However the way they plug a 'hub' in a given network is less complex and less costly than the traditional physical hubs, operating many interconnected pipelines.

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[25] Table 3 in the annex summarizes the three main characteristics of the storage: the lead time of development, the cushion gas needed, and the deliverability and the work capacity.

26 As described by Jensen 2004 the liquefaction depends on the refrigeration of natural gas to cryogenic temperatures (approximately minus 260°F) where it becomes a liquid at atmospheric pressure and occupies a volume that is 1/600th that of the fuel in gaseous form. The product can be stored in heavily-insulated tanks or moved overseas in special cryogenic tankers. (EIA 2009b)

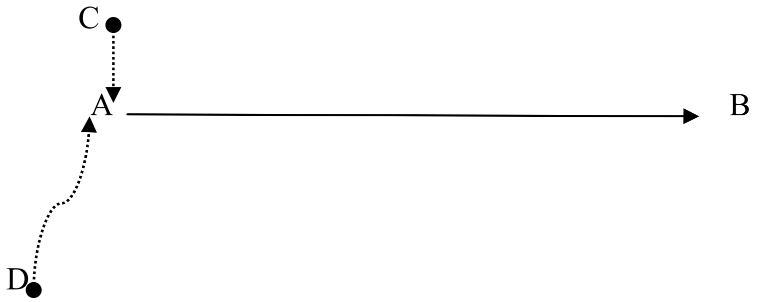
As described by IEA (1994) the receiving terminals are less costly and consume less energy than the liquefaction plants, the liquefaction plants consist of processing modules called 'trains'. In these modules there is a process to warm the LNG by heat exchange, usually with vast quantities of seawater. The LNG storage usually has the same infrastructure as the regasification plants however they demand bigger compressors to meet the peck demands. The trains' sizes tend to be limited by the size of the available compressors.

a) If the LNG facility is connected to a single pipe with only one entry and one exit point, it directly transforms the nature and operation of the network. Before the opening of the LNG facility, the infrastructure service and the gas commodity operated as a single product otherwise they did not properly operate. With the connection of a LNG facility, gas and the pipe infrastructure of transport start to be economically and technically separated, as the gas coming from LNG can go to different places, and the infrastructure is also receiving different gas inflows as commodity.

b) If the LNG facility is inserted in an already interconnected network, it adds new possibilities of gas paths and storage. LNG is frequently associated to a physical hub, since LNG facilities by themselves are potential interconnectors between different gas fields upstream.

Being the LNG a special kind of physical hub, it allows the interaction of a certain point (inlet or outlet) with a set of others points (inlet or outlet). As seen in figure 2, the gas sold at the point B, and transported through the line AB can come from different places including D or C. Even in the presence of only one line with one outlet and inlet point, it is technologically possible that the pipe transports gases coming from different sources, creating a visible separation between the gas trade and the pipeline trade.

Figure 2: The addition of LNG in a pipeline



The liquefaction decreasing the volume of gas also allows a new kind of storage being the ship. That storage has no strong geological restrictions and permits very fast withdrawal (as fast as the power of pipe compressors allow). It therefore permits a high degree of controllability of withdrawal and input. However this technology is much more expensive, because of the addition of LNG reservoirs to more powerful pipe compressors on top of the costs of the regasification infrastructure.

We have then seen in this section three new boxes of components which can dramatically change the network characteristics. Such changes increase the number of alternative gas flows, gas paths and economic choices. Hubs, storages and LNG facilities do not exist in every transport system. However when they appear, they strongly increase the gas flow mobility to the point of changing all the economic proprieties of the gas transmission network.

3.4) The Sequential Addition of Components: Understanding the Heterogeneous Nature of Gas Networks

The network is the outcome of an accumulation of components made through successive decisions. However, in each period of investment decisions, the existing network already has a set of constraints restricting the technical or economical addition of new components. As new components are rarely cut out of the system, the new components become themselves new constraints framing the future decisions relative to further network development.

To take such successive decisions models of networks have to be conceived. However the modeling conceived to optimize network designs faces strong difficulties to rationally combine this past and future set of constraints characteristic of gas infrastructure development. Decisions of the past are already constraining the decisions set today while actual decisions today will constrain the set of feasible options in the future. In order to simplify this, most of the economic models conceive of network design as a pure optimization of the existing gas flows, whatever the actual network is, as the model developed by Tabkhi F. (2007). Other models have started to incorporate the existing pipelines as parameters in the development of gas networks as Babu et al (2003)[27]. However, as showed by Midthum and all (2006), most of the physical characteristics, interfaces and interactions resulting from the introduction of new modules still have to be better taken into account to understand the real effects of new components in the existing networks.

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[27] Babu et al (2003) utilizes differential genetic evolution algorithmic which have been applied to solve complex problems in many areas. In order to develop the model some scenarios are done supposing the level of pipeline capacity demand and the incentives to investment in a new pipeline in the offer side, as well the capital costs. By evaluating different scenarios the models try to calculate the probable optimum new investment in gas transports.

Conclusion: Gas Networks Are Not One of a Kind but Vary, Resulting in a Wide Gas Network Heterogeneity

This paper shows that gas networks are heterogeneous by their very nature. Firstly because the transport network can be made with different sets of compressors and pipes. Besides the elementary box of gas network building (the compressors and pipes), we did find a set of secondary components, which can strongly increase the mobility of gas flows in the network. They are storage, hubs and LNG facilities.

Secondly, the insertion of these various components is sequential, while each introduction directly affects the transport capacity and operation. These components also affect the transport economic characteristics, and change the nature of transportation offer and demand. Eventually each new component entering the network becomes a new parameter which constrains the set of choices open to future investment.

Thirdly, the economic proprieties of gas transport actually change along the development of the transport network. Limited investments in a gas network can dramatically increase the number of possible combinations between the existing network pieces, notably the points of injection and of withdrawal of gas. As a result new possibilities of services and of trade arise here or there.

These three characteristics being inherent to gas network evolution, there is a potentially enormous heterogeneity of actual network designs and of their economic properties. Gas networks go notably from enduring natural monopoly of transport to nearly purely competitive “open gas highways”. Existing gas networks belong to many different technical and economical worlds. They are not homogenous networks. There is only very little economic sense to determine the “true economic proprieties” of gas transportation networks in general.

The heterogeneity of network designs and of components also implies that gas networks can actually offer a different set of transport services among various architectures of entry / exit points; resulting in very different kinds of markets and sets of transactions. However the scope of services and the transactional frame offered on the transport infrastructures do not depend only on the network design, while it is a key factor in the analysis of the economic proprieties of a given gas transport. That heterogeneous nature of gas transportation questions the way the European Union can conceive the access, operation and development of the existing networks in order to get a single EU gas market operating within a “seamless” transportation space. The last capacity and congestion principles elaborated by the European regulatory advisor (ERGEG) offer a remarkable key to enter into this long standing heterogeneity.

It is now obvious that the gas transportation network has a very typical “Lego game” nature. The development of gas networks is actually a successive addition of components to an existing particular base. The new components are able to change the proprieties of already installed infrastructures as to already shape the future capability of adding other components. In that Lego game however not all new pieces added or connected can be easily removed. It is a Lego game with a strong “path-dependency”: players play looking backward and forward.

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Annexes:

Table 1: Compressor features comparative table

	Reciprocating	Centrifugal
		Lube
Maximum Discharge Pressure	300barG	100barG
Maximum Pressure Ratio/Stage	3:1	3:1
Maximum Volume Inlet	15000m3/h	15000m3/h
Speed control	High	High
Dirty gas	Possible	Difficult
MW Change	Possible	Possible

Source: different sources and own elaboration

Table 2: The trade offs of gas capacity

Everything else Constant	Capacity of transport	The friction lost	The velocity
Bigger Diameter	Increase	Decrease	Increase
Increase Pressure	Increase	Increase	Decrease

Source: different sources and own elaboration

Table 3: Comparative table of the main mean features of gas storage

	Depleted field	Aquifer	Salt Cavern
Lead Time	Medium	High	Low
Cushion Gas	Medium	High	Low
Deliverability	Medium	Medium	High
Working Capacity	High	High	Low

Source: different sources and own elaboration