A Systematic Mapping of Natural Gas Transportation Systems’ Reliability and Risks Analysis

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***Abstract*—This paper will analyze the challenges, profits, and risks that the gas transportation systems could face. As valuable economic and industrial systems, gas transportation systems are complicated, comprehensive, and elastic. However, gas transportation systems connect different levels of customers, and gas transportation systems rely heavily on the relationship loop between gas customers and gas producers, these factors make the gas transportation systems have to face comprehensive engineering and human-related challenges. In this paper, we will analyze the natural gas transportation system together with four parts of its interaction systems. First, we will list general gas transportation challenges. Second, we will analyze the risks and interactions between each part of the system. Finally, we will bring our conclusions about the system’s construction risks.**

***Index Terms*—system engineering; natural gas transportation systems; system risks analysis; decision making; stakeholders.**

I. Introduction

The Gas Transportation Systems can transport gas and energy across the border, support thousands of residents, families, commercial agents, product institutes, as well as different industries. A natural gas transportation system is made up of compressor stations, pipelines, city gate stations, and storage facilities [9]. However, since this system has so many stakeholders and bring benefits to so many people, it is inevitable that the systems could face many transportation risks. How to target those risks and avoid these effects could be a important part to expand and maintain the system.

Current research put the concentrations on economic analysis for the transnational natural gas transportation system [12][13][15], technology assessment [2][3], and policy analysis of managing transnational natural gas transportation system [6][8][17]. One of the basic consideration is the risks and reliance of this high-level systems.

In this paper, we will list challenges and risks of transnational natural gas transportation systems’ construction in section 2, 3, 4, 5, analyze the reasons that cause these challenges and potential consequences in section 6, 7, and bring the suggestions about how to maintain target sub-systems 8. Finally, in section 9, we explain our conclusions from the research. The research of this paper is expected to bring more risk analysis options, ideas, and methods on building transnational natural gas transportation systems.

II. Natural gas production and transportation overview

First, we need to take an example to explain how normal gas transportation systems work as a whole part.

The figure below shows the example of Malaysia Peninsula Gas production and transportation systems.

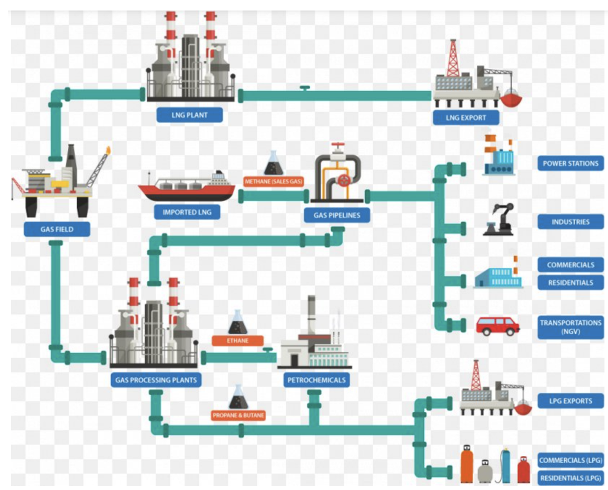

Fig. 1. Malaysia Peninsula Gas Utilisation Natural Gas Natural-gas Processing Pipeline Transportation [16]

As the figure shows here, there exits different commercial gas using, thus, there are many forms of the gas generated energy, this could cause the transportation systems to become complicated. The production, processing, transportation and selling processes make the whole systems full of uncertainty. Those uncertainty things in each step leading significant construction risks. In order to make the whole system works normally and resiliently, we have to be aware of the factors that cause those risks, how these factors work in the whole system and what decisions need to be made at the same time.

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Since the whole systems is complicated and technique comprehensive, at the beginning, we should put the list of factors in the natural gas transportation system, in this project, we focus on these main factors: Pipelines constructions, gas distribution limitations, gas distribution system's stakeholders, and the system shaping forces.

Besides those key factors, there are other defining characteristics in constructing the system:

Local environment and residents' energy-using safety and health. Commercial monopoly. The system maintains' problems. Realigned infrastructures Challenges of constructions Local benefits of the gas supplement.

III. Natural gas transportation and pipelines construction

The natural gas transportation is a crucial activity performed by the gas industry in which the gas and other energy has to be moved from one location to another. Several types of transportation means might be applied to transport the gas, yet it is well known that pipelines represent the most economical means to transport large quantities of natural gas. In addition, the advent of metallurgical improvements and welding techniques, coupled with the exponential increase of pipeline networks during the last decades all over the world, have made the gas transportation via pipelines more economically attractive.

Currently, pipelines are used in constructions on both offshore and onshore energy transportation systems, with a remarkable difference in terms of security and construction prices. Building pipeline systems under the sea is highly costly and technically demanding, a lot more than onshore. For example, the Nord Stream2 pipeline project is expected to as long as 1,222km corresponds to the 965.7 km long onshore pipeline system on Russian and German territories, whereas the remaining is destined to the 259.4 km long offshore section of the project. However, as the consequence of Russia's recognition of the Donetsk and Luhansk republics, Nord Stream 2 AG, a consortium for construction and operation of the Nord Stream, filed for bankruptcy on 1 March 2022 and laid off all 106 employees from its headquarters in Zug, Switzerland [8]. Hence, when financial, political or environmental issues arise, gas transportation operators need to look for different alternatives to perform this task inevitably. Especially for onshore gas transportation, from which natural gas can be transported as liquefied natural gas (LNG), medium conditioned liquefied gas(MLG), or compressed natural gas(CNG), by using the tank of specially constructed seagoing vessels.

The scale of a gas network system be greatly different from one country to another. In the US, for example, a large gas network system may encompass several hundreds of pipelines (adding up to several hundreds of thousands of miles) and tens of compressors stations strategically distributed along the transmission lines. The US natural gas pipeline network has about three million miles of mainline and other pipelines that link natural gas production areas and storage facilities with consumers. This natural gas transportation network delivered more than 25 trillion cubic feet of natural gas in 2016 to about 74 million customers" (Natural Gas Pipelines, 2017). On the contrary, the natural gas transmission network in Belgium is composed of a relatively smaller number of pipelines (20–40) and compressor stations (4–8) when compared to those found in the US and Russia [10].

While the size of a gas pipeline system definitely plays an important role when solving natural gas network flow problems, it is the network topology that really defines the complexity of the model, e.g., cyclic networks are extremely more difficult to solve than its (gun-barrel and tree-shaped) network counterparts [2]. The current state of the art on natural gas transmission network problems in steady-state can efficiently handle large gas systems by applying network reduction and decomposition techniques, or hybrid-heuristic algorithms, most of them, however, with no guarantee of optimality, which enforces the scientific community to enhance the existing methods [2].

IV. Stakeholders

We list the main stakeholders that rely on the natural gas transportation systems.

1. Technical engineering institutes 2. Local residents 3. Natural gas customers' communities 4. Natural gas company and government

- 1. Technical engineering institutes
  1.1 Pipeline constructions 1.2 Pipeline operations
- 2. Safety and environment impact for residents
  2.1 Health
  2.2 Living environment
- 3. Impact on the natural gas customers' community 3.1 Stability 3.2 reliability
- 4. Economic benefits for natural gas company and government 4.1 Revenues to the government 4.2 Employment 4.3 Flexibility of transport increases industry profit margins; minimizes price instability

After listing the main stakeholders, We draw a relationship impact map and a interest map of stakeholders to discuss those stakeholders.

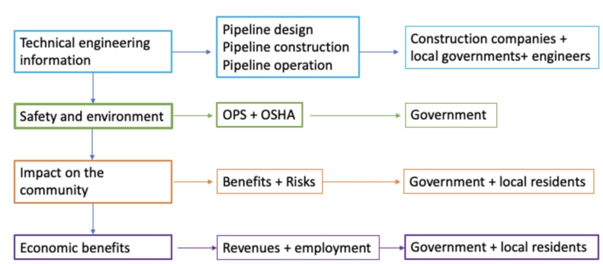

Fig. 2. Stakeholder Relationship

According to Figures 2 and 3, each of those stakeholders rely on the benefit of natural gas transportation systems. At the same time, they have interactions with each other. The negative impact between different stakeholders hurt the resilience of the whole natural gas transportation system.

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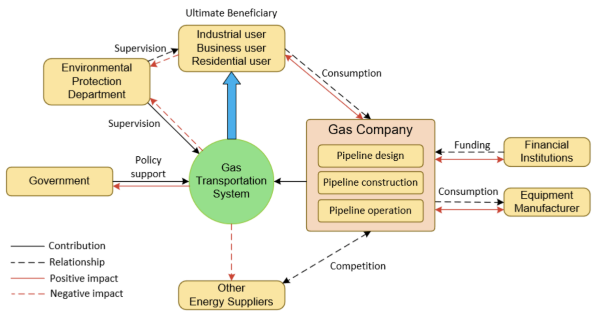

Fig. 3. Interest Map of Stakeholders

One of the general and significant case is the natural environment. The impact between natural gas providers and natural environment, as well as the impact different levels of natural gas customers and natural environment, both of those two groups have to face environment challenges and the value transformations brought by gas supply constitution. The government, as the potential stakeholder controller, have to consider some trade-off solutions and implement them as policy. This case of natural environment decides the reliability of the whole system. On the other hand, system's controllers have to face several specific and inevitable risks when they make construction decisions on different parts of gas providing facilities and gas consuming facilities.

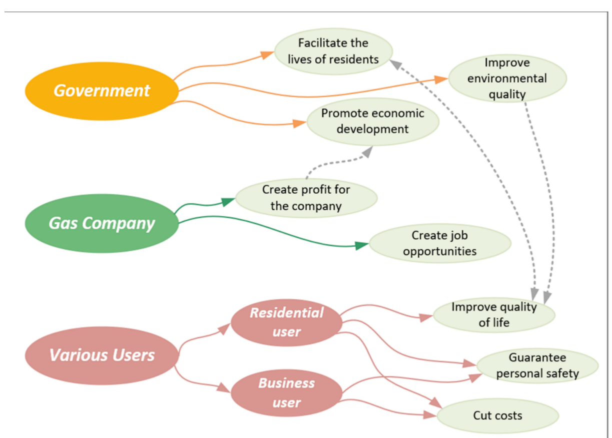

Fig. 4. Value adding process

After those construction decision settle down, as different parts of the natural gas transportation systems, those stakeholders wish to keep the values that brought by the system to be consistent, and expect to expand these values based on their needs.

V. Risks Analysis

The specific attributes of transportation and the complexity of gas pipeline networks both bring operation challenges. Natural gas producers and different levels of consumers are dominant stakeholders of the whole gas transportation system. Those parts could be the sub systems that rely on the gas transportation systems, even have inner reliance across sub systems. We have to be aware of the risks during these systems' interactions with gas transportation system, and strength the reliance in building gas transportation system.

We would first try to analyze and summarize short and long term risks exit on the natural transportation systems.

A. Short-term risks

The construction of gas transportation system require large investment. Investment costs in the natural gas transportation system would be higher due to the frequent need to invest not only in the pipelines itself, but also in the insulation of houses and additional supplementary infrastructure. Therefore, a change would often have negative financial consequences and hence potentially negative social consequences as well [5].

Natural gas transportation brings health risks aligned with natural gas producing system. Producing natural gas can contaminate air and drinking water, creating negative health impacts for citizens close to production sites. The gas-related accidents and the threat of earthquakes also named as additional threats. Studies also identified an increased human mortality rate due to shale gas (compared to conventional gas, nuclear, or renewables) [5].

B. Long-term risks

Long term risks of gas transportation systems always bring concerns about energy security. For the example from Russia, concerns from two main aspects: -The need for long-term shortage-free supply of consumers with the required energy resources, provided the energy sector operates under nominal conditions. -The creation of conditions for providing consumers with energy resources under emergency conditions [3]. For the example from Germany, the country is widely recognised as a climate leader with impressive progress in its energy transition and ambitious plans while at the same time offering strong state support to three new LNG terminals.

Consideration of the energy security calls for identification of critical facilities, i.e. energy transportation systems which, in case of partial or complete failure to operate, can cause severe damage to the country through the energy sector [3].

Some health risks, especially invisible ones (such as risks that occur underground such as the contamination of aquifers or seismic activity), are beyond the direct perception of lay people. Moreover, those risks are spatially diffuse, uncertainty exists about which region will be affected to what extent, and the effects are often temporally delayed [6].

VI. Shaping Forces

Compared with other systems that high related with natural transportation systems. Gas export system could be sensitive and sometimes vulnerable when facing shaping forces. In this project, it is the diplomatic situation.

In most cases, gas, oil, electricity, and other energy systems have huge transportation costs. The values that exist in these

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huge transportation systems could be a vital remedy and, probably benefits for these transportation systems.

But in general, those transportation systems cover huge areas, even across countries. When gas transportation work across the border, the export system could be the sub-component of this system. The export system of gas transportation systems could bring interests from political, commercial, and economic values to gas transportation systems. Sometimes, those benefits could be affected and even dominated by political forces.

In EU, many countries are small and failed to accomplish energy producing-consuming balance. They rely heavily on energy import from Russia. As the chart shows, some countries rely on almost totally energy import from Russia. Actually, until 2022, Russia supplies about 40% of the natural gas European Union overall [18].

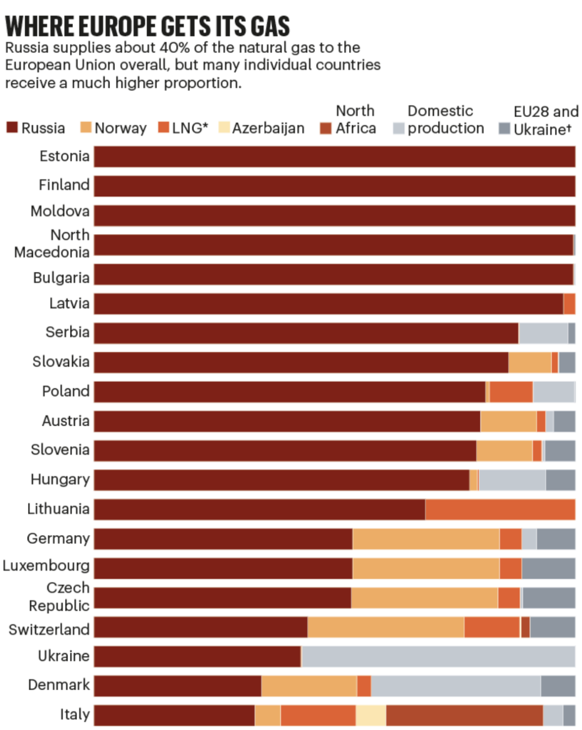

Fig. 5. Europe gas import percentage chart (Sources: Bruegel/European Network of Transmission System Operators for Gas/Eurostat/UK Government/Government of Ukraine)

The diplomatic relationship between many countries could shape and determine the export systems, transnational system constructions, international energy transportation, and different levels of stakeholders, as Figure 8 shows, all of these essential components can't work and add other values without stable diplomatic agreement. Considering current Ukraine War, the shaping force are definitely reshaping the energy map of the EU.

Besides, the diplomatic activities could force the gas providing and transportation in a economic way, the price fluctuations of energy market. This cause the stakeholders, such as energy company and the government may face deficits. This

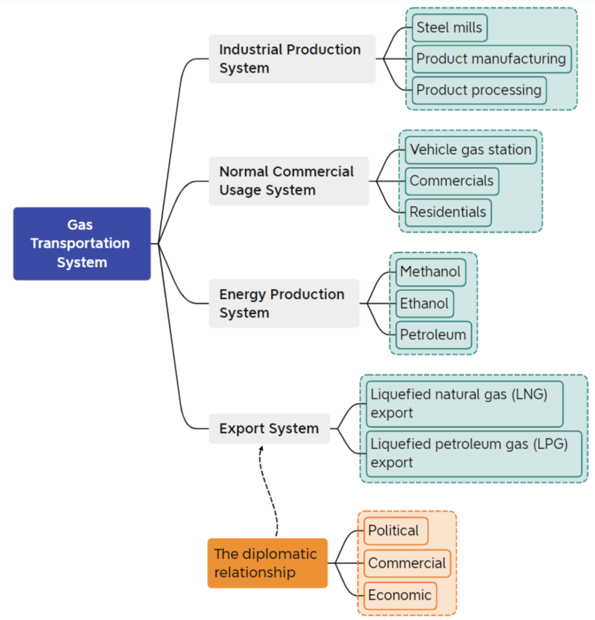

Fig. 6. Shaping Forces

deficits consequence, again, decrease the fund that used for transportation facilities and security remediations.

VII. Reliance Analysis

Many energy consumers rely on gas transportation systems. Figure 9 shows the reliance among gas transportation systems and other 4 main gas-using systems.

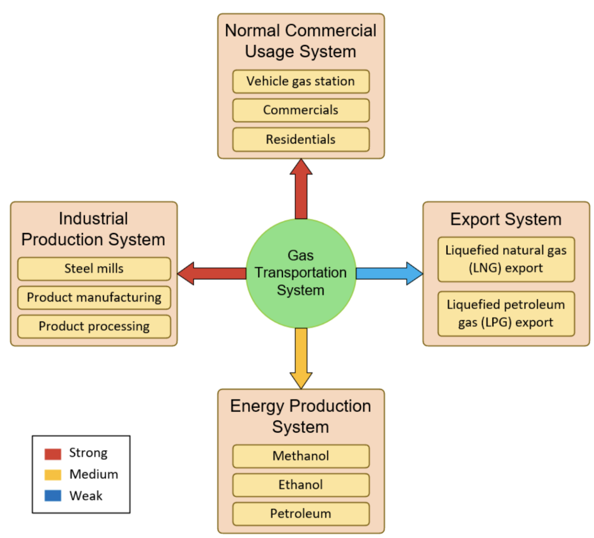

Fig. 7. Reliability between systems

Figure 10 shows the whole map of risks, reliance from stakeholders, related gas using subsystems to the gas transportation system, in most of cases, those different circle parts in this graph shows bi-direction relationship. Those relationship put risks, and the reliability of gas transportation could decrease and avoid these risks.

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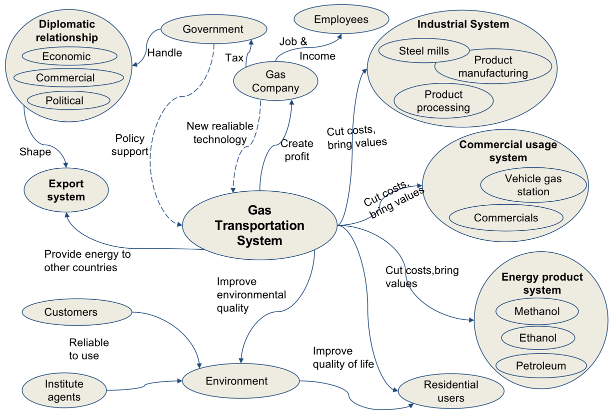

Fig. 8. Risk and reliance relationship graph of gas transportation system

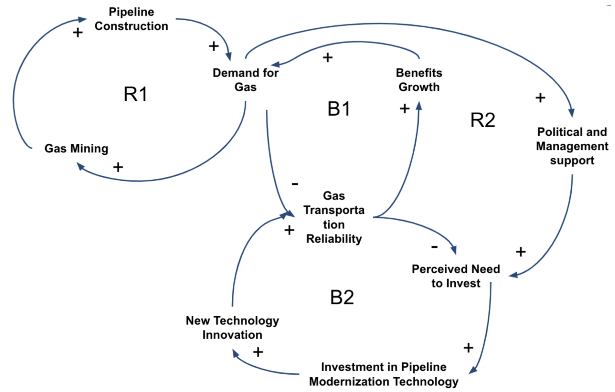

Fig. 9. Casual Loop analysis for gas providers

Those reliance above need a operational gas transportation system. They revealed how a stable gas transportation can link those consuming systems together tightly.

Consider the complex of gas transportation, such as Nord Stream1 and Nord Stream2 built though comprehensive geographic situations, offshore gas transportation and onshore gas transportation bring more options for gas transportation. For example, the onshore transportation can finish by using either vessel with tanks or undersea pipelines. The latter always face huge costs and uncertain risks, financial crisis, diplomatic shaping forces, geographic limitations and benefits for stakeholders could could the decision to be complicated. In order to minimize the technical uncertainty and stabilize the benefits, the gas transportation systems should be built to be reliable at the early time.

Transporting energy by pipeline is safe and environmentally friendly. Furthermore, pipeline transportation is safer than transportation by road, rail, or vessel, as measured by incidents, injuries, and fatalities even though more road and rail incidents go unreported [17]. This means the pipelines based gas transportation are more reliable compared to other transportation methods.

A. *Cost saving and safety improvement for energy providers*

In Figure 11, the causal loop of the natural gas providers shows the factors' relationship with reinforcement (R in Figure 11) and balance forces' explanations (B in Figure 11), positive (+) and negative consequent effects (-) among these factors. In this graph, one factor is among the causes of another factor.

According to this graph, the reliable gas provider could inform a positive feedback loop, the factors in this loop all receive potential benefits: The reliable gas transportation system decrease the perceived need to adding new investment. The gas company could use saved money to invest in the improvement of natural gas pipelines' modernization technology, this motivate would accelerate the new technology's innovation. All of these could reinhence the gas transportation reliability, strengthen the positive loop and keep benefits, and save cost for gas providers.

B. *Price fluctuation and Monopoly*

Figure 12 shows the natural gas price' fluctuation in these years. To avoid huge fluctuations, the whole gas transportation system have to be built in a control organization, this organization generally consists of several gas producers, they aim to stabilize the gas supply, to avoid the gas supply shortage when one of the gas producers halt its gas providing, and protect the reliable gas supply system.

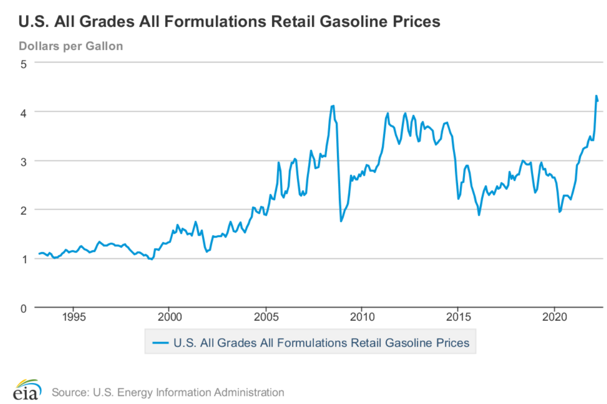

Fig. 10. Gas price fluctuation chart in U.S

After the year of 2021, in 2022, with the influence of Russia-Ukraine War, the U.S banned Russia energy, cause the significant price increase over past 25 years.

If one country's gas transportation systems not working for providing gas, especially for the main gas export country like Russia, this could cause chaois for the whole gas transportation network, even cause the transportation halting. To avoid this situation, the related stakeholders need a third party organization to guarantee the price of the gas. The organization, such as OPEC, could aim to stabilize the international energy supply and price could make decisions to avoid energy price's huge fluctuations. During Iraq War time, this measure could even flat the price fluctuations [5].

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VIII. Conclusions

The transnational natural gas transportation systems brings benefits for thousands of consumers. Stakeholders of natural gas transportation systems rely heavily not on each other, but also the natural gas transportation systems.

At same time, the complicated benefits groups may face more specific risks from engineering challenges, making the trade-off between system construction and environment, customers living experience and gas benefits. Those considerations bring more implementation uncertainty and risks. Concerns from those challenges and issues need the natural gas transportation system to be built reliability and durable.

In the end, try to identify risks and avoid related severe consequences in early system-building stage, these measures would lead the whole system become more stable and robust, and the system could benefit more stakeholders in a very long term. The controllers and decision makers of the system could make the improvement of current system to be reality and with low economic and environment cost.

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