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Technological and Economic Aspects of Blending Hydrogen into Natural Gas Pipeline Networks: Determination of Key Issues for a Selected Gas Pipeline in Iran

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Table of Contents

1. Background

Recently, the generation of renewable electricity was increased and the current demands for energy indicate that the further portion of this energy source will be increased [1]. For example Germany plan to generate 80% of its electricity from renewable energy sources by the year 2050 [2]. Renewable energy sources such as wind power, geothermal, photovoltaic and etc have an important role in reduction of greenhouse gas emission. The fluctuation of energy generation from renewable sources is the major challenges for applying these methods. Various methods were applied to use the renewable electricity such as storage which a reliable and safe operation [3]. The previous options to storage of electricity may be used such as pumped hydro electricity storage (PHES), compressed air energy storage (CAES) and batteries [3; 4; 5]. But, these storage techniques have some limitations like low energy density and storage potential. A novel and interesting method for storage of energy is "power to gas" (P2G) option that excess electricity converts to hydrogen by water electrolysis, which can be stored and, when needed, can be reconverted into electricity with fuel cells. Hydrogen is an important gas which can be used as a fuel in the vehicles or as a material of chemical plants. Hydrogen can be injected into the natural gas network pipeline to the later use. By this method significant amount of renewable energy can be saved and delivered to the other places of need [6].

Conversion of excess renewable electricity into hydrogen and oxygen take place in one of the power to gas process steps. The produced hydrogen could be injected to the natural gas pipeline. The second step in the power to gas process is the reaction of hydrogen and CO_2 and production of methane by the methanation process. The produced methane could be injected to the natural gas pipeline directly without any limitations [7]. Methane production by this method has a lower efficiency but could be added to the gas distribution grid with large capacity. In contrast to the methane case, the injection of hydrogen into the natural gas pipeline has volumetric fraction limitation. For example, the allowed volumetric fraction of hydrogen in the gas distribution grid in Iran is about 5% which can be varied by region to region.

It can be mentioned that power to gas technology is currently under development and limited to verify in the demo-plants [8]. Figure 1 demonstrates the application pathway of power to gas system.

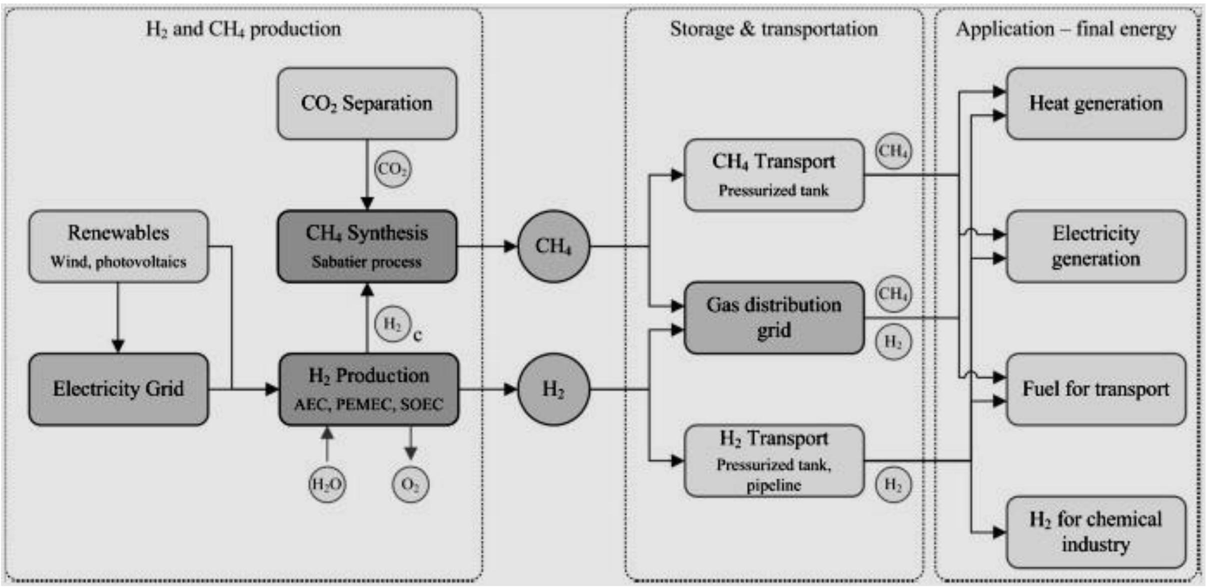

Fig. 1. Various application pathways for power to gas system [6]

Beside the storage of renewable electricity, P2G could be applied for transportation of energy via the natural gas distribution grid which already used anywhere. Also, production of renewable fuels for mobility and heating purposes, and production of renewable raw materials industry may be achieved by using of hydrogen. Now, hydrogen is utilized as a important feed in the various industrial processes such as petrochemical plants, chemical manufacturing, and many other applications [6]. As mentioned, by applying methanation process, P2G also can role important impact in reduction of CO_2 emitted from industrial processes and power plants.

In this research, adding hydrogen from P2G into the gas pipeline grid would be studied. It would have several advantages, may related to link the power grid with the gas distribution system. Very large storage capacity of gas infrastructure is a big advantage for storing of excess produced electricity. Despite of feeding synthetic methane into the natural gas pipeline network is not challengeable; adding hydrogen to the natural gas involves several uncertainties. What content hydrogen can be added into the natural gas system and information about the impacts and safety issue connected to do so are the main challenging topics. The limit of hydrogen content depends on pipeline and storage facilities and their tolerances. Also, hydrogen increases the heating value of the gas.

Iran has the second largest natural gas sources in the world and the gas pipeline covers almost all region of country. Also, in certain parts of Iran, from time to time, we have excess generated electricity more than customer requirements and the transportation or storage capacities are inadequate. It's a problem that will become even stricter in the future because using of new electricity lines is not an economic process and seems that this problem can be solved by applying P2G technique.

In this study, we investigate the delivering of hydrogen to the end-users aided by natural gas pipeline. Blending hydrogen into natural gas pipeline network was verified and the key barriers related to this process were determined. Depending on hydrogen blend level, the end use application of added hydrogen can be various. Blending renewable hydrogen with natural gas can improve the carbon intensity and sustainability of the final natural gas product delivered to consumers. As we know, fuel cells are an important role in the future of energy. The most important feed for fuel cells is hydrogen that must be in access anywhere for use. The other application of blending hydrogen is related to separation of hydrogen in order to apply in the industries or use in the fuel cell vehicles.

2. Aim

The excess electricity produced from renewable sources can't be stored for using later. Thus, this energy could be converted to another king of energy such as hydrogen and methane. Hydrogen can be produced by the water electrolyze and can be used in-situ as a various resources. Hydrogen can be stored in the pressurized tanks and used as a fuel in the H_2-vehicles. But in case of distance between the renewable energy generation sites and the consumption places, it is recommended to convert the produced energy to the appropriate form which can be transferred by the minimum loss of energy. Recently in Iran the photovoltaic energy generation was started in the remote and low population area, so the transportation of energy to the most demanded area may be useful. As the natural gas pipelines cover almost all populated area in the country, we can propose to convert the renewable electricity to hydrogen and then add it to the natural gas grids. According to present natural gas network conditions, the maximum threshold of hydrogen concentration added into the natural gas pipeline must be determined in the two end-uses scenarios. The impact on the end-use systems, safety, leakage and downstream extraction are also studied.

3. Methods and Results

Blending hydrogen into natural gas pipeline grids has been used in order to transfer pure hydrogen to the markets. Hydrogen can be extracted from the natural gas mixture by applying separation and purification processes. By this delivery method, the cost of building a new hydrogen pipeline and other infrastructures could be saved. This hydrogen delivery method also consists of additional costs associated with blending, extraction and modification of existing pipelines. These costs must be evaluated by the alternative methods for bringing the energy sources materials to consumers.

In this paper the following key issues related to adding hydrogen to existing natural gas pipeline networks will be discussed.

3.1. Impact on End-Use Systems

The maximum threshold of mixing hydrogen to the natural gas is very important issue in transportation of hydrogen via the natural gas pipeline networks. The extent of hydrogen in the natural gas impacts on end-use systems such as household, industrial or power generation appliances. The type and age of end-use facilities determine a maximum hydrogen blend threshold which does not significantly effect on their operations and safety. Hydrogen can impact on industrial facilities case by case and may be need modifying on their operating and control systems. We found that within 4%-20% hydrogen, the end-use systems can operate without a large modification. Higher than this hydrogen extent, the adaption of end-use facilities and modifications of operation must be required. Material compatibility of end-use appliances in long term duration is unknown. The cost of upgrade the pipelines is the other issue which vary from country to country. For example, in case of adding 4% hydrogen, the cost of required modification in the sensors is about $ 500,000 in Iran.

3.2. Material Durability

Adding hydrogen on the natural gas has the physical and chemical effects on the pipeline. Hydrogen damage is a well-known damage in the metal pipe lines. Hydrogen content, operating conditions and material type are the important parameters in the hydrogen damage. Small hydrogen molecules cause the high tendency of it to leak from valves, gaskets and other facilities. Durability of metallic pipeline also depends on the line pressure which at higher pressure the hydrogen degradation increases. Our study indicated that hydrogen effects on the initiation of defects in the natural gas pipeline. Also, we found that hydrogen permeation trough the poly ethylene pipelines are about 4-6 times faster than methane. However, hydrogen permeation is too small and no more safety consideration may be need. In addition, the following issues relative to material durability and hydrogen impact may be addressed: hydrogen embrittlement in the steel pipelines and hydrogen fatigue.

3.3. Safety

There are various safety factors for consideration in case of blending hydrogen into natural gas pipeline. Due to high tendency of hydrogen to ignite, a main concern is the high potential of ignition in the system with blending hydrogen relative to pure natural gas (methane). The other researchers evaluated the risk factors for blending hydrogen in various concentrations (e.g. 5%, 10%, 20%, 25%) [9]. In this study, risk assessment scale ranked in the range of 0-50 which the zero scale represented no significant hazard while in 50 scale showed the severe hazard. Our finding represented that in the blending of low hydrogen concentration (less than 20 V%) the risk of ignition was in minor level (up to 10 scale) and can be ignored. Also, in case of safety zones in explosion for natural gas leakage, 20 V% or less hydrogen would result minor increases in the severity of the explosion. In higher hydrogen contents in the main natural gas pipeline presented a minor increase in overall risk, but in the other lines the risk was different. In the lines that gas leakage more tendencies to accumulate, surely the risk was so high. For reduction of overall risk, installation of monitoring devices is proposed. However, the overall risk in blending more than 50 V% of hydrogen into any kind of pipelines significantly increases.

Up to 50 V% of blending hydrogen, the failure frequency is almost unchanged compared to the natural gas pipeline. According to minimum energy required for ignition of hydrogen, the probability of ignition for mixture of natural gas and hydrogen is higher relative to pure natural gas. The changes of natural gas properties and the effects on hazard by adding hydrogen is presented in Table 1. Based on this assessment, adding hydrogen up to 20% increases the explosion risk in a confined room and the probability of a fire. It is concluded in this study that the use of hydrogen blended natural gas under well regulated circumstances should not increase the risk of explosions in comparison to those with unblended natural gas and this results is in agree with the previous studies [9].

Table 1. Effects of blending hydrogen to natural gas on gas properties and hazard

Property	Effect of hydrogen addition	Hazards		
		Explosion	Fire	Suffocation
Density	Low			✓
Velocity of Dispersion	The same	✓	✓	✓
Household Gas Pipe Leak Rate	Higher	✓	+	✓
Lower flammability limit	The same level	✓	✓	
Higher Flammability Limit	Higher	+		
Minimum Energy for Ignition	Lower	✓	✓	
Auto Ignition Temperature	Lower	✓	+	

✓ Hazards exists without change up to 15% hydrogen content
\+ Hazard increases by presence of hydrogen

In the natural gas distribution pipelines, the potential risks are evaluated by the probability of pipeline failure and the consequence of the failure:

$$Risk = \text{probability of the failure} \times \text{consequence of the failure}$$

The major failure in the natural gas pipelines was addressed by leak, and eight failure types are categorized as: corrosion, material defect, natural force, other outside forces, excavation damage, equipment malfunction, operation and the others. Figure 2 shows the leak incidences reported in the main distribution lines as the major failure percentage.

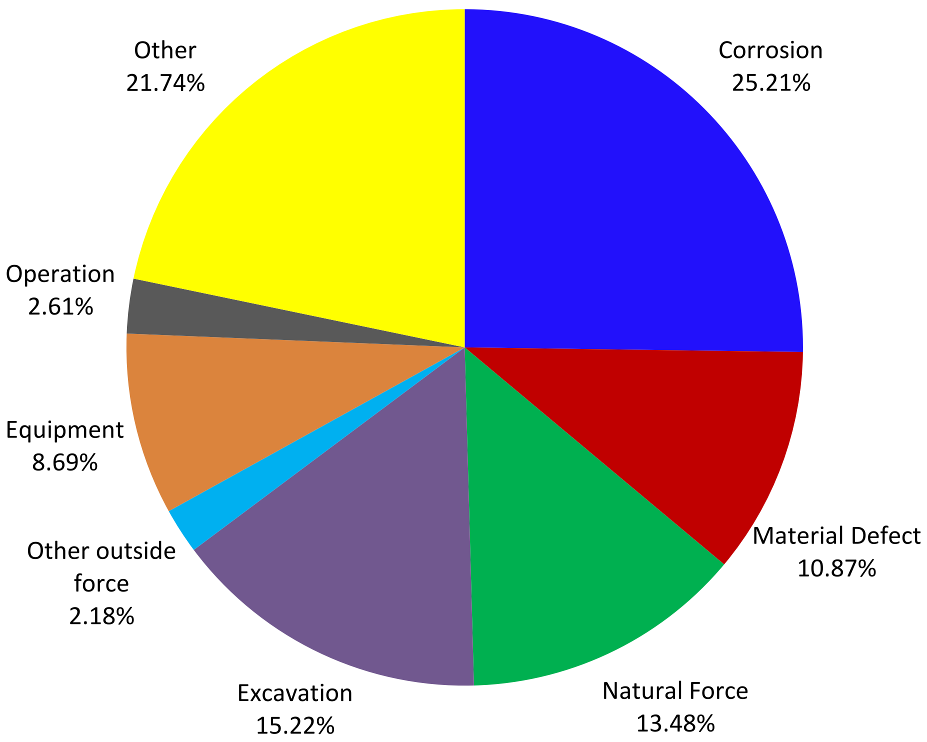

Fig. 2. Leak incidents in main distribution lines

From Figure 2, the two frequent leak incidents in the main pipeline are corrosion and excavation. By adding the hydrogen into natural gas pipelines, the effects of each failure would not be mainly changed. But, it can be mentioned that the severity and possibility of a fire or explosion may be increased by the presence of hydrogen in the line.

3.4. End-Use Extraction

In this section the main methods which can be used to separate the hydrogen are presented. Membranes and pressure swing adsorption (PSA) are the most appropriate methods to separate hydrogen from the mixture of natural gas and hydrogen.

In the membrane technology, separation of a gas from the mixture base on selective permeation of one species molecules across a permeable membrane. Most industrial application of membrane technology recovers hydrogen by 95-99% purity. There are special membranes that can separate the gases by larger purity. For example, Palladium (Pd) membrane technologies can achieve hydrogen at 99.9999999% purity [9].

By increasing the gas pressure, the fraction of adsorbed components on the porous surface mostly increase. For separation of hydrogen, the adsorption materials are carefully chosen to adsorb non-hydrogen components at the lower pressure.

In the following, we evaluate the cost of hydrogen separation by PSA technique. The other costs such as injection cost, capital cost, hydrogen loss, etc. are not considered. The recovery cost of hydrogen applying this method is shown in Figure 3. In this system the recovery of hydrogen is equal to 80%. For a pipeline with 10% concentration of hydrogen, the separation cost is about $3.4-$9.0/kg of extracted hydrogen, varying by recovery rate of hydrogen per day (Figure 3). For a 20% hydrogen concentration, the separation cost decreases to $2.5-$8.1/kg of extracted hydrogen.

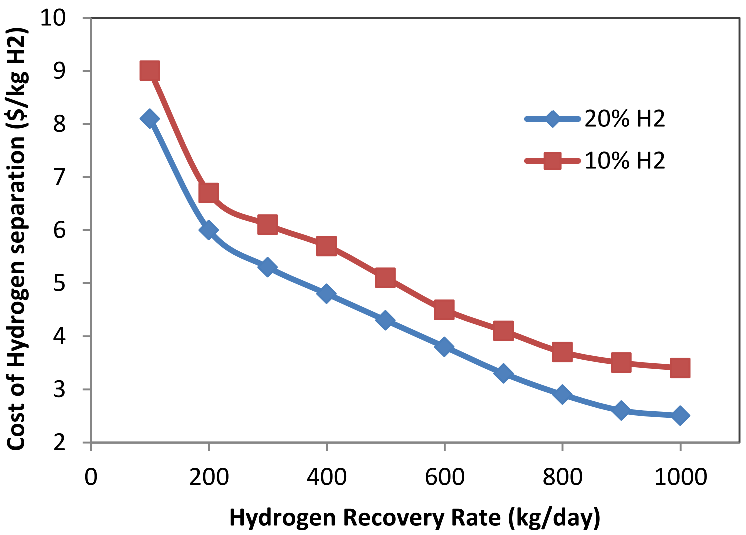

Fig. 3. Cost estimation of hydrogen separation by PSA unit from 300 psi natural gas distribution pipeline

3.5. Leakage

The leakage rate of hydrogen through the pipe walls and connections is greater than methane, because hydrogen is a much smaller molecule than methane. So, it need to more safety and economy consideration in case of presence of hydrogen in pipeline. By testing of the pipelines in the various conditions the following are obtained:

- Hydrogen permeation is 4-5 times greater than that of methane
- The permeation rate increases with pressure for both of methane and hydrogen
- The aging of pipeline has no significant effects on the leakage from pipeline

For example, the leakage rates for hydrogen and methane from a 20% hydrogen mixture at 5 bar are 2.3 and 1.1 L/(km.day), respectively [10]. Under the same conditions, the permeability of pure methane is 1.4 L/(km.day).

4. Conclusions

We found that up to 20% hydrogen, the end-use systems can operate without a large modification. Higher than this hydrogen extent, the adaption of end-use facilities and modifications of operation must be required.

Adding hydrogen up to 20% into the pipelines increases the explosion risk in a confined room and the probability of a fire. We obtained that corrosion and excavation are two frequent leak incidents in the main pipeline which equal to 25.21% and 15.22%, respectively.

Our investigation indicated that membranes and pressure swing adsorption (PSA) are the most appropriate methods to separate hydrogen from the mixture of natural gas and hydrogen. By applying PSA technique for end-use separation, for a pipeline with 20% concentration of hydrogen, the separation cost is about $2.5-$8.1/kg of extracted hydrogen. This cost would be decreased in case of using higher concentration of hydrogen and increased in lower hydrogen content.

The leakage rates for hydrogen and methane from a 20% hydrogen mixture at 5 bar are 2.3 and 1.1 L/(km.day), respectively.

By considering all parameters, we conclude that for about 5 V% concentration of hydrogen for apply to end-user without extraction, no modification would be needed in the present pipeline conditions. In the starting of power to gas technique in the country, blending hydrogen into the natural gas pipelines in order to promote the heating value of the gas is suggested. By developing the fuel cells and also H_2-vehicles in the country, the using of the other P2G applications will be considered.

5. References

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