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Economic Analysis on Hydrogen Pipeline Infrastructure Establishment Scenarios: Case Study of South Korea

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Abstract: South Korea has a plan to realize a hydrogen economy, and it is essential to establish a main hydrogen pipeline for hydrogen transport. This study develops a cost estimation model applicable to the construction of hydrogen pipelines and conducts an economic analysis to evaluate various scenarios for hydrogen pipeline construction. As a result, the cost of modifying an existing natural gas to a hydrogen pipeline is the lowest, however, there are issues with the safety of the modified hydrogen pipes from natural gas and the necessity of the existing natural gas pipelines. In the case of a short-distance hydrogen pipeline, the cost is about 1.8 times that of the existing natural gas pipeline modification, but it is considered a transitional scenario before the construction of the main hydrogen pipeline nationwide. Lastly, in the case of long-distance main hydrogen pipeline construction, it takes about 3.7 times as much cost as natural gas pipeline modification, however it has the advantage of being the ultimate hydrogen pipeline network. In this study, various hydrogen pipeline establishment scenarios ware compared. These results are expected to be utilized to establish plans for building hydrogen pipelines and to evaluate their economic feasibility.

Keywords: hydrogen; pipeline; economic analysis; case study; infrastructure

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1. Introduction

Because hydrogen is a sustainable energy source and does not emit greenhouse gases, it is attracting attention as an eco-friendly energy worldwide [1–5]. Global hydrogen energy demand will increase rapidly from 8 EJ in 2015 to 78 EJ in 2050 and is expected to account for 18% of the total energy demand [6]. South Korea considers hydrogen as an important energy source and is promoting the establishment of a hydrogen economy. Currently, in Korea, hydrogen is mostly used as an industrial raw material, and some of it is consumed in the power generation field. Korea is expected to depend on hydrogen energy for about 18% of the energy usage in 2050 [7]. However, because Korea has limited resources of fossil fuels and renewable energy for hydrogen production, it is challenging to build a sustainable hydrogen economy. In Korea, there is an issue that the supply of by-product hydrogen and green hydrogen is insufficient, and the hydrogen price is as high as 6000–8000 won/kg [8]. To solve this problem, a strategy of importing hydrogen from a place where the unit cost of hydrogen production is low such as Australia is being considered [9].

Hydrogen imported from overseas can be supplied to Korea through ships. Then, hydrogen arriving in Korea can be transported through a pipeline network. For this purpose, a pipeline network for large-scale hydrogen transport is essential. South Korea is promoting the construction of a hydrogen pipeline network for stable and economical hydrogen transportation [10]. However, a pipeline that can continuously supply hydrogen over a large-scale and long-distance has not yet been established in Korea. Currently, hydrogen is produced by using natural gas on a small scale near demand sites. However, there is a limitation in that it is expensive to separate pure hydrogen from natural gas [11]. Therefore, it is necessary to analyze the economic feasibility of the establishment of the hydrogen pipeline network.

Kim et al. identified potential environmental impacts through a life cycle assessment on hydrogen transport methods through pipelines [12]. The environmental impacts are analyzed for two cases: (1) hydrogen pipelines and (2) mixed transport of hydrogen and natural gas through conventional natural gas pipelines. However, only a little economic analysis research on the hydrogen pipeline establishment has been conducted. Liu et al. reported an economic analysis on hydrogen transport through natural gas pipelines [13]. Parker made a model for the cost estimation of hydrogen pipeline establishment through a statistical approach [14]. Based on the existing natural gas pipeline cost model, a modified model was developed by reflecting the difference between natural gas and hydrogen pipeline construction. In particular, the cost of building a hydrogen pipeline is estimated by multiplying the natural gas model by a multiplier that can reflect this difference. However, since the hydrogen pipeline cost modeling is performed without calculating the multiplier value based on detailed information about the pipeline construction, there is a limitation of low reliability. Fekete et al. reported a hydrogen pipeline cost factor depending on materials [15]. Penev et al. conducted an economic analysis on hydrogen pipelines for fueling stations with different pipeline diameters [16]. However, the previous studies have limitations in that they performed only environmental analyses or performed simple economic analyses with single-variable changes such as diameter or material without considering realistic pipeline establishment scenarios [12–16].

In order to build a hydrogen pipeline network in the future, it is essential to develop an accurate and reliable hydrogen pipeline establishment economic analysis model. Therefore, in this study, a new hydrogen pipe construction cost model was developed in the case of Korea as an exemplary study. The hydrogen pipeline construction cost model was developed based on the previously reported natural gas pipeline construction cost model [14]. In particular, the material cost required to construct a hydrogen pipeline was calculated by considering the diameter, length, thickness, and material of the hydrogen pipeline. Three different hydrogen pipeline establishment scenarios were proposed: (1) natural gas pipeline modification, (2) short-distance hydrogen pipelines, and (3) long-distance main hydrogen pipelines. It was believed that these three scenarios were the most reasonable and probable options for the hydrogen pipeline establishment in South Korea. Then, the economic feasibility was analyzed by estimating and comparing the cost of the hydrogen pipeline construction based on the proposed scenarios. The cost of building a hydrogen pipeline by 2056 was evaluated based on the history of natural gas pipeline construction in South Korea. Based on the analysis, implications for policy makers when constructing hydrogen pipeline infrastructure and the applicability of this work for the cases in other countries were discussed.

2. Scenario Modeling for Economic Analysis

2.1. Hydrogen Pipeline Establishment Scenarios

In this study, three scenarios were proposed for hydrogen pipeline establishment, and the cost of building a hydrogen pipe was estimated and compared.

2.1.1. Scenario 1: Conventional Natural Gas Pipeline Modification

Scenario 1 is the case of constructing a hydrogen pipeline by modifying existing natural gas pipelines. This is the fastest way to build an infrastructure for hydrogen transportation [17]. There are two methods of transporting hydrogen using existing gas pipelines. The first method is to mix hydrogen gas with natural gas and transport the mixed gas through the existing natural gas pipelines. The other method is the modification of the existing natural gas pipelines to hydrogen pipelines.

In the case of the hydrogen and natural gas mixture, the existing natural gas pipelines can be used without modification, so the cost required is only the hydrogen mixing and reforming facility construction cost, which does not need a large cost. However, there is a limitation in that it is suitable only for a low capacity of hydrogen transport, and there is the potential safety issue of hydrogen embrittlement. In the case of modifying natural gas pipelines to hydrogen gas pipelines, there is the advantage that a larger amount of hydrogen can be transported. However, there is the limitation of the cost to modify the existing natural gas pipelines.

For these reasons, in this study, the scenario was set for the second case, an existing natural gas pipeline modification.

2.1.2. Scenario 2: Short-Distance Hydrogen Pipeline

Scenario 2 is the case of building a short-distance pipeline, which has been used to transport by-product hydrogen near chemical plants. In this case, small-scale and short-distance hydrogen transport is possible. However, it is considered a technology suitable for the transitional stage before the establishment of hydrogen economy.

Currently, a short-distance hydrogen pipeline of about 200 km has been built in the petrochemical industrial complex and pilot hydrogen city of Korea [10]. More than half of the currently constructed hydrogen pipeline is composed of A106 Gr. B materials. Therefore, Scenario 2 is assumed to utilize an A106 Gr. B pipeline with a size of SCH 80.

2.1.3. Scenario 3: Long-Distance Main Hydrogen Pipeline

Scenario 3 is the case of finally constructing a long-distance main hydrogen pipeline for large-scale hydrogen transport for a hydrogen economy society. The main hydrogen pipeline network is assumed to be constructed along the same path as the current natural gas main pipeline network.

A hydrogen pipeline is recommended to have a diameter of 0.3–1.5 m at a pressure of 2–10 MPa, and API 5L X42 and X52, which are low-grade steel pipes, are suitable. Therefore, Scenario 3 was assumed to use API 5L X52- and API 5L X42-grade materials according to the pipe diameters.

2.2. Hydrogen Pipeline Establishment Cost Modeling

In this study, an economic analysis of hydrogen pipeline establishment was performed by applying a modified hydrogen pipe construction cost model that was modified in this study based on the previous model proposed by Parker [14]. The model of this study estimated the pipeline construction cost, labor cost, right-of-way, and other costs according to pipe diameters and distances. The hydrogen pipe construction cost estimation model is shown in Equation (1).

The basic specifications for all pipes followed the KOGAS safety code of the Korea Gas Corporation [18]. In the case of South Korea, the standard for hydrogen piping has not yet been established. For this reason, API RP 941, the international standard specified in the safety code, was followed for the undefined specifications [19]. The cost of the pipeline according to the standard was estimated based on the price list provided by the company that manufactures and sells the pipes [20].

$$H_2\ \mathrm{PCC}\ (\mathrm{dia[inch]}, \mathrm{len[mile]}) = x * \mathrm{NG\ Material}\ (\mathrm{dia},\ \mathrm{len}) + y * \mathrm{NG\ Labor}\ (\mathrm{dia},\ \mathrm{len}) + 1 * \mathrm{NG\ Misc}\ (\mathrm{dia},\ \mathrm{len}) \quad (1)$$

2.2.1. Hydrogen Pipeline Material Cost Modeling

In Equation (1), x is a multiplier for the material cost. In this study, an appropriate value of x was estimated through a comparison with the material cost for natural gas pipelines. Most of the natural gas piping in South Korea is a high-pressure piping for 6.86 MPa and uses API 5L X65 and X42 grades. Table 1 shows the current status of the natural gas main pipeline by pipe diameters. Although pipe diameters and thicknesses vary, 30″ diameter pipes accounted for the most at 63.7% [21]. The maximum pressure is 0.98–6.86 MPa. For pipelines with a diameter of 24″ or larger, use API 5L X65, and for pipelines with a smaller diameter than 24″, use API 5L X42. In the case of natural gas piping, SCH 40 and 80 are most commonly used. According to the national standard certification standard of Korea, the maximum allowable pressure of SCH 80 is 8 MPa. The natural gas main pipeline specifications used for this study are shown in Table 2.

Table 1. Current status of natural gas main pipelines by diameter in Korea [21].

Dia (″)	Length (km)	Rate (%)
4	1.09	0.02
10	2.4	0.05
12	10.49	0.21
16	2.8	0.06
20	1337.61	26.91
24	48.39	0.97
26	374.9	7.54
30	3165.8	63.69
36	27.5	0.55

Table 2. Specifications of natural gas main pipelines by diameter in Korea.

Dia (″)	Material	SCH	Thickness (mm)	Weight (kg/km)	Cost (USD/km)
4	API 5L X42	SCH 80	8.56	22,300	25,422
10	API 5L X42	SCH 80	15.10	96,000	109,440
12	API 5L X42	SCH 80	17.40	132,000	170,280
16	API 5L X42	SCH 80	21.44	203,000	284,200
20	API 5L X42	SCH 80	26.20	311,000	528,700
24	API 5L X65	SCH 80	30.90	442,000	1,502,800
26	API 5L X65	SCH 80	32.91	477,302	1,783,428
30	API 5L X65	SCH 80	37.36	604,540	2,700,327
36	API 5L X65	SCH 80	44.03	816,930	4,729,372

For Scenario 1, the modification cost for natural gas pipelines is required. However, because it is not a case of constructing a new pipeline, the total construction cost was estimated excepting pipe material cost.

For Scenario 2, the hydrogen piping information is listed in Table 3. Based on the standard of natural gas and hydrogen pipelines, the material cost per unit length of piping was compared. The material cost of hydrogen pipelines is 0.93 times that of natural gas pipelines. Therefore, the hydrogen pipeline material cost model was derived as in Equation (2).

Table 3. Specifications of hydrogen pipelines based on Scenario 2.

Dia (″)	Material	SCH	Thickness (mm)	Weight (kg/km)	Cost (USD/km)
4	A106 Gr. B	SCH 80	8.08	18,630	22,069
10	A106 Gr. B	SCH 80	14.82	84,817	107,718
12	A106 Gr. B	SCH 80	17.10	118,486	154,032
16	A106 Gr. B	SCH 80	21.40	203,170	268,184
20	A106 Gr. B	SCH 80	26.20	311,290	419,095
24	A106 Gr. B	SCH 80	31.00	442,320	604,197
26	A106 Gr. B	SCH 80	33.09	516,639	710,221
30	A106 Gr. B	SCH 80	37.66	682,619	949,128
36	A106 Gr. B	SCH 80	44.51	975,106	1,375,604

For Scenario 3, hydrogen piping information is listed in Table 4. The material cost per a unit pipe length was compared based on the standard of natural gas and hydrogen pipelines. Depending on the pipe diameters, two material cost models were derived because the pipeline materials were different for pipes more than and less than 24″. For pipeline diameters over 24″, the material cost of hydrogen pipelines was 0.49 times that of natural gas pipelines. The material cost of hydrogen pipelines with a diameter of less than 24″ was 0.58 times that of natural gas pipelines. Therefore, the hydrogen pipeline material cost models were derived as in Equation (3).

Table 4. Specifications of hydrogen pipelines based on Scenario 3.

Dia (″)	Material	SCH	Thickness (mm)	Weight (kg/km)	Cost (USD/km)
4	API 5L X42	SCH 40	5.74	13,570	15,470
10	API 5L X42	SCH 40	9.82	54,969	62,665
12	API 5L X42	SCH 40	11.07	74,677	85,131
16	API 5L X42	SCH 40	12.70	123,000	172,200
20	API 5L X42	SCH 40	15.10	183,000	311,100
24	API 5L X52	SCH 40	17.40	255,000	673,200
26	API 5L X52	SCH 40	17.34	295,352	861,710
30	API 5L X52	SCH 40	18.35	384,991	1,353,949
36	API 5L X52	SCH 40	19.10	541,609	2,497,558

Scenario 2

$$H_2\ \text{Material}(\text{dia}, \text{len}) = 0.93 * \text{NG Material}\ (\text{dia},\ \text{len}) \tag{2}$$

Scenario 3

$$\begin{aligned} &\text{For dia} \geq 24'',\ H_2\ \text{Material}(\text{dia}, \text{len}) = 0.49 * \text{NG Material}\ (\text{dia}, \text{len}) \\ &\text{For dia} < 24'',\ H_2\ \text{Material}(\text{dia}, \text{len}) = 0.58 * \text{NG Material}\ (\text{dia},\ \text{len}) \end{aligned} \tag{3}$$

2.2.2. Hydrogen Pipeline Total Establishment Cost Modeling

When constructing a new pipeline, it is common to build along the existing pipeline. In this study, it is assumed in the modeling that there is no right-of-way cost of the hydrogen piping. Other costs also accounted for a very small proportion of the total cost and were set at the same rate as in the natural gas pipelines because there is no significant difference in construction depending on the type of pipeline. However, in the case of labor cost which accounts for a large proportion of the cost, the y value of Equation (1) was set using different assumptions for each scenario in consideration of the maturity of the technology.

In the case of piping construction in Scenario 2, short-distance hydrogen pipelines have already been established in Korea. Therefore, it was assumed that the labor cost required for the construction of a short-distance hydrogen pipeline would not be much different from that of the natural gas pipeline. Through this, Equation (5) was derived. On the other hand, in the case of Scenario 3's long-distance main hydrogen pipeline, there has not been many construction cases yet, and it is considered a relatively new technology with low technological maturity. Therefore, Equation (6) was derived by setting y to 1.5. For Scenario 1, according to the IEA, the cost of modifying a natural gas pipeline to a hydrogen pipeline is estimated to be 21–33% of the cost of building a new hydrogen pipeline [22]. Therefore, Equation (4) for Scenario 1 was derived by multiplying the model of Scenario 3 by 27%.

Scenario 1

$$\begin{aligned} \text{For dia} \geq 24'',\quad & H_2PCC\ (\text{dia[inch]}, \text{len[mile]}) \\ & = 0.27 * \left[0.49\left[\left\{330.5\ (\text{dia})^2 + 687\ (\text{dia}) + 26,960\right\}\ (\text{len}) + 35,000\right]\right. \\ & +1.5\left[\left\{343\ (\text{dia})^2 + 2074\ (\text{dia}) + 170,013\right\}\ (\text{len}) + 185,000\right] \\ & \left.+\{8417\ (\text{dia}) + 7324\}\ (\text{len}) + 95,000\right] \\ \text{For dia} < 24'',\quad & H_2PCC\ (\text{dia[inch]}, \text{len[mile]}) \\ & = 0.27 * \left[0.58\left[\left\{330.5\ (\text{dia})^2 + 687\ (\text{dia}) + 26,960\right\}\ (\text{len}) + 35,000\right]\right. \\ & +1.5\left[\left\{343\ (\text{dia})^2 + 2074\ (\text{dia}) + 170,013\right\}\ (\text{len}) + 185,000\right] \\ & \left.+\{8417\ (\text{dia}) + 7324\}\ (\text{len}) + 95,000\right] \end{aligned} \tag{4}$$

Scenario 2

$$\begin{aligned} H_2PCC\ (dia[inch],\ len[mile]) &= 0.93\left[\left\{330.5\ (dia)^2 + 687\ (dia) + 26,960\right\}(len) + 35,000\right] \\ &+1.25\left[\left\{343\ (dia)^2 + 2074\ (dia) + 170,013\right\}(len) + 185,000\right] \\ &+\{8417\ (dia) + 7324\}(len) + 95,000 \end{aligned} \tag{5}$$

Scenario 3

$$\begin{aligned} &\text{For dia} \geq 24'',\quad H_2PCC\ (dia[inch], len[mile]) \\ &= 0.49\left[\left\{330.5\ (dia)^2 + 687\ (dia) + 26,960\right\}(len) + 35,000\right] \\ &+1.5\left[\left\{343\ (dia)^2 + 2074\ (dia) + 170,013\right\}(len) + 185,000\right] + \{8417\ (dia) + 7324\}(len) + 95,000 \\ &\text{For dia} < 24'',\quad H_2PCC\ (dia[inch], len[mile]) \\ &= 0.58\left[\left\{330.5\ (dia)^2 + 687\ (dia) + 26,960\right\}(len) + 35,000\right] \\ &+1.5\left[\left\{343\ (dia)^2 + 2074\ (dia) + 170,013\right\}(len) + 185,000\right] + \{8417\ (dia) + 7324\}(len) + 95,000 \end{aligned} \tag{6}$$

3. Results and Discussion

3.1. Hydrogen Pipeline Establishment Cost

The hydrogen pipeline construction cost was calculated for each scenario. It was assumed that the hydrogen pipeline network was built nationwide in the same way as the existing natural gas pipeline network. Table 5 shows the construction cost of Scenario 1. It was confirmed that the pipeline with a diameter of 30”, which was widely used as the main pipeline, was built the longest, accounting for about 71.2% of the total cost.

Table 5. Expected cost of hydrogen pipeline construction based on Scenario 1.

Dia (”)	Length (km)	Expected Cost (USD)	Expected Cost (Million Won)
4	1.10	163,000	179
10	2.40	266,076	338
12	10.50	878,257	1114
16	2.80	358,262	455
20	1337.60	147,797,658	187,526
24	48.40	6,454,900	8190
26	374.90	54,156,015	68,713
30	3165.79	547,350,768	694,479
36	27.50	6,229,543	7904
Total	4970.99	763,654,479	968,897

USD = 1100 won.

In the case of Scenario 2, a short-distance hydrogen pipeline with a small diameter is installed near the nationwide hydrogen production bases. Accordingly, as shown in Table 6, it was assumed that pipelines with diameters of 12” or less were built.

Table 6. Expected cost of hydrogen pipeline construction based on Scenario 2.

Dia (”)	Length (km)	Expected Cost (USD)	Expected Cost (Million Won)
4	1.10	546,735	601
10	2.40	902,621	993
12	4967.49	1,254,713,741	1,380,185
Total	4970.99	1,256,163,097	1,381,779

USD = 1100 won.

Table 7 shows the construction cost of Scenario 3. As in Scenario 1, it was assumed that the hydrogen pipeline network was constructed in the same way as the existing natural gas pipeline network.

Table 7. Expected cost of hydrogen pipeline construction based on Scenario 3.

Dia (″)	Length (km)	Expected Cost (USD)	Expected Cost (Million Won)
4	1.10	603,704	664
10	2.40	985,468	1084
12	10.50	3,252,804	3578
16	2.80	1,326,896	1460
20	1337.60	547,398,735	602,139
24	48.40	23,907,037	26,298
26	374.90	200,577,832	220,636
30	3165.79	2,027,225,067	2,229,948
36	27.50	23,072,380	25,380
Total	4970.99	2,828,349,924	3,111,185

USD = 1100 won.

In this study, it was assumed that the construction of a hydrogen pipeline network would be similar to that of natural gas. Based on the total pipeline extension data of the natural gas main pipeline by year, the length of pipeline construction by pipe diameter and the cumulative construction cost were estimated as presented in Tables 8 and 9, respectively. For the calculations, it was assumed that the pipeline construction will start from 2023 and hydrogen pipelines will be built as much as the current natural gas pipelines in 33 years.

Table 8. Total hydrogen pipeline length for each diameter by year.

Year	36″	30″	26″	24″	20″	16″	12″	10″	4″
2023	0.60	62.43	7.35	0.98	26.36	0.10	0.19	0.05	0.02
2024	1.27	135.68	15.98	2.12	57.29	0.21	0.42	0.11	0.05
2025	1.35	142.68	16.80	2.24	60.25	0.23	0.45	0.11	0.05
2026	1.35	142.68	16.80	2.24	60.25	0.23	0.45	0.11	0.05
2027	1.35	142.68	16.80	2.24	60.25	0.23	0.45	0.11	0.05
2028	1.45	154.16	18.15	2.41	65.10	0.24	0.48	0.13	0.05
2029	2.04	216.58	25.49	3.40	91.46	0.34	0.68	0.18	0.06
2030	3.48	369.46	43.50	5.79	156.03	0.58	1.16	0.29	0.11
2031	3.59	381.56	44.93	5.99	161.13	0.60	1.19	0.31	0.11
2032	6.34	672.67	79.20	10.56	284.06	1.06	2.11	0.53	0.21
2033	7.85	834.47	98.25	13.10	352.38	1.30	2.62	0.66	0.26
2034	7.97	845.93	99.60	13.28	357.23	1.34	2.66	0.66	0.27
2035	8.90	944.04	111.16	14.82	398.65	1.48	2.96	0.74	0.29
2036	11.73	1245.58	146.66	19.55	526.00	1.96	3.91	0.98	0.39
2037	12.39	1315.84	154.93	20.66	555.67	2.06	4.14	1.03	0.42
2038	12.81	1360.63	160.19	21.36	574.58	2.14	4.26	1.06	0.43
2039	14.66	1556.18	183.22	24.43	657.16	2.45	4.89	1.22	0.48
2040	14.61	1551.10	182.63	24.35	655.02	2.43	4.88	1.22	0.48
2041	14.71	1561.29	183.82	24.51	659.31	2.45	4.91	1.22	0.48
2042	15.06	1599.51	188.32	25.11	675.46	2.51	5.02	1.26	0.50
2043	15.13	1605.24	189.00	25.20	677.87	2.53	5.04	1.26	0.50
2044	16.32	1733.28	204.08	27.21	731.94	2.72	5.44	1.37	0.55
2045	16.43	1744.73	205.43	27.39	736.79	2.74	5.47	1.37	0.55
2046	16.66	1768.94	208.28	27.78	747.01	2.78	5.55	1.38	0.56
2047	17.27	1833.92	215.93	28.79	774.45	2.88	5.76	1.43	0.58

Table 8. *Cont.*

Year	36″	30″	26″	24″	20″	16″	12″	10″	4″
2048	18.14	1925.64	226.72	30.22	813.18	3.03	6.05	1.51	0.61
2049	21.36	2266.43	266.84	35.58	957.11	3.56	7.11	1.79	0.71
2050	24.40	2589.40	304.87	40.65	1093.48	4.07	8.13	2.03	0.82
2051	25.44	2700.87	318.01	42.41	1140.56	4.23	8.48	2.12	0.85
2052	26.63	2827.64	332.92	44.39	1194.08	4.44	8.88	2.22	0.89
2053	28.03	2976.06	350.40	46.72	1256.77	4.67	9.35	2.33	0.93
2054	28.74	3051.23	359.25	47.89	1288.50	4.80	9.58	2.40	0.97
2055	29.13	3091.99	364.05	48.54	1305.72	4.86	9.70	2.43	0.97
2056	29.45	3126.38	368.10	49.08	1320.25	4.91	9.82	2.45	0.98

Unit: km.

Table 9. Expected cumulative construction cost of hydrogen pipelines by year based on scenarios.

Year	Scenario 1	Scenario 2	Scenario 3
2023	17,675	31,623	65,462
2024	37,460	67,430	138,742
2025	39,353	70,856	145,751
2026	39,353	70,856	145,751
2027	39,353	70,856	145,751
2028	42,450	76,460	157,221
2029	59,311	106,974	219,669
2030	100,602	181,703	372,601
2031	103,871	187,619	384,708
2032	182,498	329,915	675,917
2033	226,198	409,003	837,771
2034	229,295	414,608	849,241
2035	255,791	462,559	947,373
2036	337,239	609,961	1,249,032
2037	356,216	644,305	1,319,318
2038	368,311	666,195	1,364,114
2039	421,130	761,785	1,559,740
2040	419,754	759,294	1,554,643
2041	422,506	764,276	1,564,838
2042	432,829	782,958	1,603,071
2043	434,378	785,761	1,608,806
2044	468,959	848,346	1,736,887
2045	472,056	853,951	1,748,357
2046	478,594	865,783	1,772,572
2047	496,143	897,542	1,837,568
2048	520,918	942,380	1,929,327
2049	612,965	1,108,963	2,270,240
2050	700,194	1,266,827	2,593,310
2051	730,302	1,321,317	2,704,823
2052	764,540	1,383,279	2,831,630
2053	804,628	1,455,829	2,980,102
2054	824,929	1,492,570	3,055,293
2055	835,941	1,512,498	3,096,076
2056	845,231	1,529,312	3,130,485

Unit: million won.

3.2. Discussion of the Scenarios

The total hydrogen pipe construction cost according to each scenario and the construction cost by year are shown in Figures 1 and 2, respectively. Scenario 1 was the case of modifying existing natural gas pipelines, and it was confirmed that the cost was lower than Scenario 2 and 3, which were the cases of building new hydrogen pipelines. Scenario 2, which built a short-distance hydrogen pipeline, and Scenario 3, which built a long-distance main hydrogen pipeline, cost about 1.8 times and 3.7 times as much as Scenario 1, respectively.

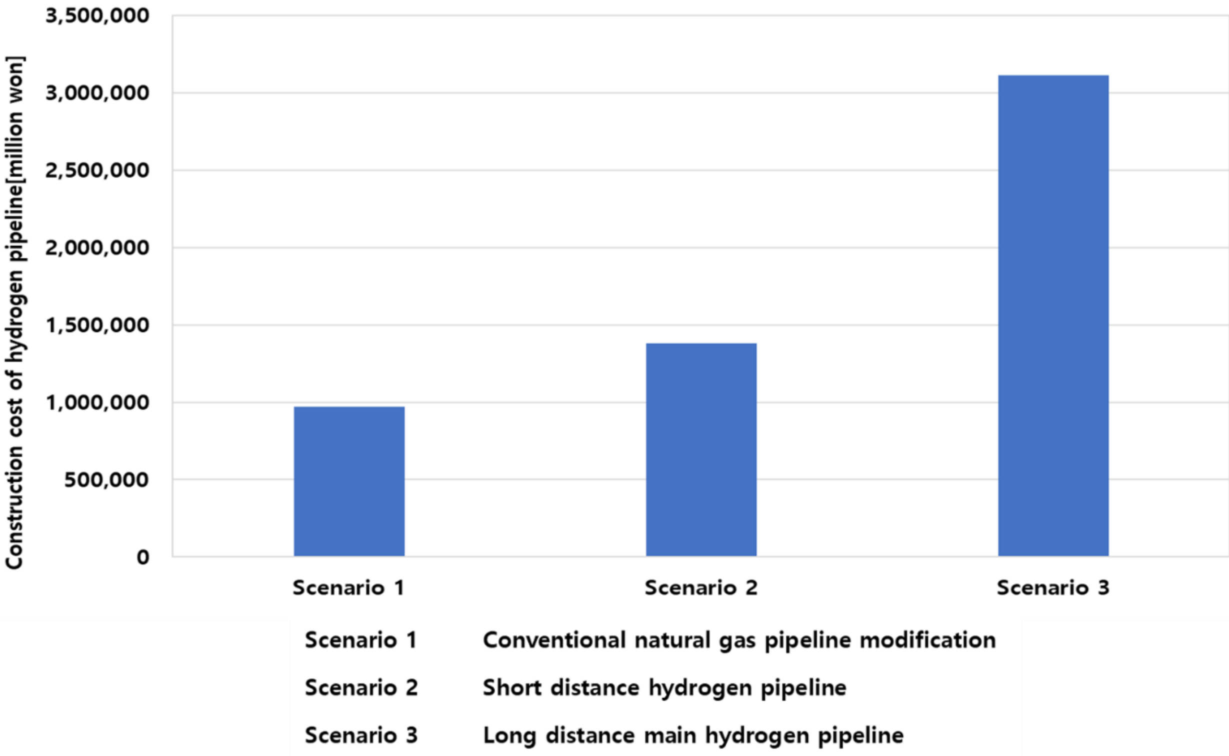

Figure 1. Construction cost of hydrogen pipelines based on case scenarios.

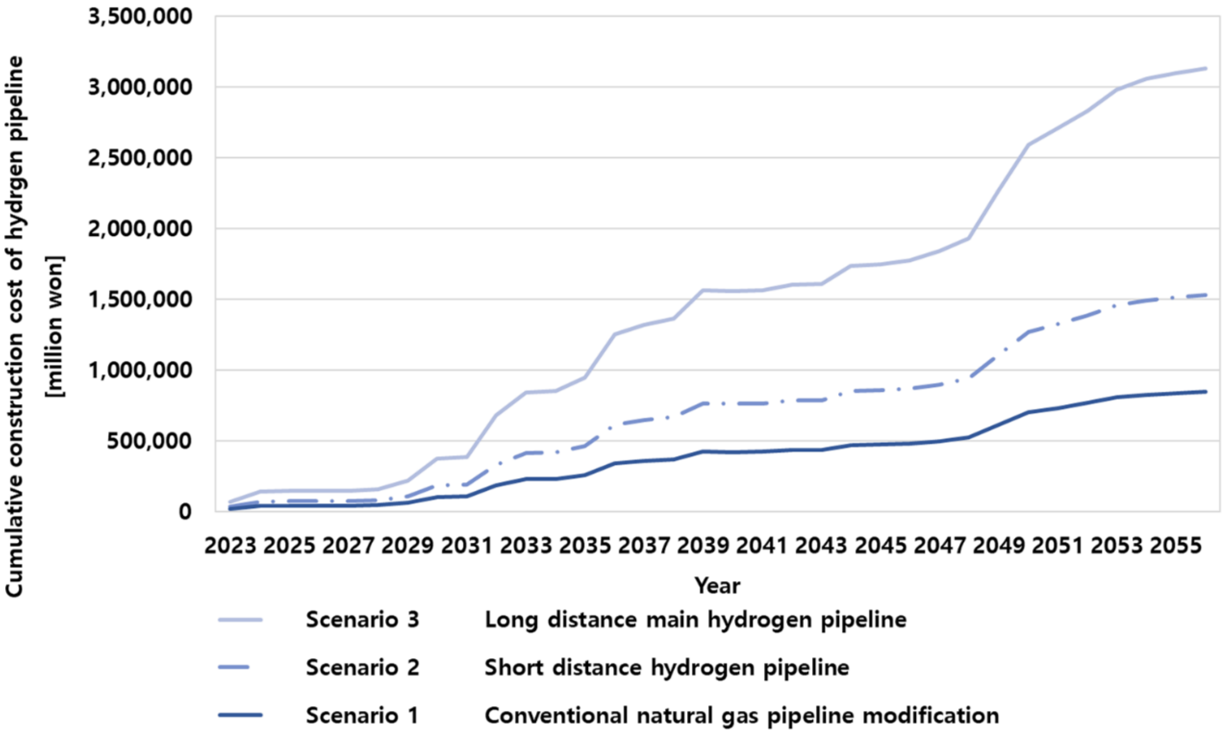

Figure 2. Accumulative construction cost of hydrogen pipelines by year based on case scenarios.

It was confirmed through this study that it is the most economical method to modify the natural gas pipeline at the present time according to Scenario 1. However, if natural gas pipelines are modified to hydrogen pipelines, there may be a risk of insufficient natural gas infrastructure. Natural gas is widely used for heating and hot water at home, and it is also an energy source that can be used in a transitional period to secure the power supply stability during the expansion of renewable energy, which is an intermittent power source with large output variability. Until stable power generation and the supply of hydrogen or renewable energy is realized, natural gas with fast responsiveness is essential for a stable energy supply. Considering this, Scenario 1 has a limitation in that it is difficult to be considered a good strategy of building a hydrogen pipeline network.

In the case of the transitional short-distance hydrogen pipelines of Scenario 2, the pipe diameters and the transport capacity are small. For this reason, it is difficult to build a nationwide pipeline network through Scenario 2. However, because the short-distance hydrogen pipeline technology is relatively mature and it is already being used for the transportation of by-product hydrogen, it can be used as a transitional hydrogen transportation technology.

In the case of Scenario 3, there is the advantage that ultimately stable hydrogen transport through the long-distance main hydrogen pipeline is possible. However, many technologies for building long-distance main hydrogen pipelines have not been demonstrated, and there is an issue that requires a large cost, as shown in the results of this study.

3.3. Implications

The following implications for policy makers could be obtained from the above analysis of results. (1) Hydrogen pipeline construction step-by-step scenario: considering the economic feasibility and characteristics of each scenario, it is essential to build a main hydrogen pipeline as in Scenario 3 in the long term. However, it is difficult to prepare a large amount of budget in a short time for Scenario 3. Plus, it is also challenging to develop mature hydrogen main pipeline technology. Therefore, it is necessary to combine the transitional scenarios such as Scenario 1 and 2 in the initial stage of hydrogen pipeline construction. (2) Hydrogen pipeline construction cost estimation: in order to establish a hydrogen pipeline construction plan and receive budget allocation from the National Assemble, it is necessary to analyze the approximate budget size and benefits. This study was able to present quantitative values for policy making by proposing the total budget for each scenario.

The results of this study can be used not only in Korea, but also in the case of building hydrogen pipelines in other countries. Unlike other countries, the characteristic of South Korea's infrastructure is that it is a peninsula and has an independent network due to its complete disconnection from North Korea. Therefore, the scenario analysis for the hydrogen pipeline construction of this study can be used for the island countries such as Japan and the United Kingdom, which generally have independent networks. In addition, in the cases of Europe and the United States with more extensive and dependent networks, alternative models can be developed through modifications based on this study.

3.4. Limitations

This study developed a hydrogen pipeline network construction cost model based on the past and present natural gas pipeline network construction. However, the construction of a hydrogen pipeline network is intended to respond to climate change and the construction trend can differ from that of the existing natural gas pipeline network.

In addition, the long-distance hydrogen pipeline network technology is a technology that has not been proven much yet, and the detailed hydrogen pipeline network standard has not been determined yet. Therefore, a more accurate economic analysis must be carried out considering developing a thin-film coating material that minimizes hydrogen embrittlement, establishing a steel composition standard suitable for a new piping infrastructure to transport high-pressure hydrogen, estimating the cost of new piping construction, and deriving a cost-saving plan.

Plus, there are various technologies for hydrogen transport such as compressed hydrogen gas, liquefied hydrogen, ammonia, liquid organic hydrogen carrier (LOHC), and hydrogen pipeline networks [23]. Therefore, comparative economic and environmental analysis studies for various hydrogen transport technologies are required.

This study only considered the materials and construction costs derived from the hydrogen pipeline diameter and length for economic analysis. However, the flow rate of hydrogen through the pipeline should be also considered in further studies. In addition, landforms for the pipeline establishment should be considered for a more comprehensive economic analysis.

In spite of the above limitations, this study performed a basic economic analysis for the construction of a hydrogen pipeline network infrastructure in Korea, thereby suggesting various scenarios for future hydrogen pipeline network construction and developing a model for estimating the cost of each. The economic analysis for a nationwide hydrogen pipeline network establishment has rarely been reported yet, and it is expected that it can be used for subsequent research on the development of scenarios for building hydrogen pipelines in various countries in the future.

4. Conclusions

In this study, the cost of building a hydrogen pipeline for realizing a hydrogen economy in Korea was estimated and analyzed based on the modified economic analysis model. Three scenarios were assumed to analyze the economic feasibility of constructing a hydrogen pipeline network, and the hydrogen pipeline construction cost was estimated based on the current status of the natural gas main pipeline. As a result of the analysis, it was confirmed that Scenario 1, which modifies the currently built natural gas main pipeline into a hydrogen pipeline network, requires the least cost. However, if the existing natural gas pipelines are modified, there can be a limitation that the existing natural gas infrastructure disappears. In the case of Scenario 2, which constructs a short-distance hydrogen pipeline, and Scenario 3, which constructs a long-distance main hydrogen pipeline, it was confirmed that the costs were 1.8 times and 3.7 times that of Scenario 1, respectively. Scenario 2 was cheaper than Scenario 3, but Scenario 2 had a limitation in that it was difficult to build a large-capacity hydrogen pipeline network nationwide with only a short-distance hydrogen pipeline. In the case of Scenario 3, although it was the ultimate hydrogen pipeline network construction scenario, it was confirmed that there was an issue that required a lot of cost. Therefore, it was concluded that the various scenarios above should be considered and combined for each stage of hydrogen pipeline construction. This study was able to develop a model for estimating the cost of each pipe diameter by year by proposing three scenarios. Through this, it was expected to be used in follow-up research on the development of scenarios for building hydrogen pipelines in various countries.

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Abbreviations

API	American Petroleum Institute
API RP	American Petroleum Institute Recommended Practice
API 5L	API code for pipelines for oil and natural gas transportation
A106 Gr. B	American Society of Mechanical Engineers(ASME) code for seamless steel pipe for high temperature service
SCH	Schedule number that indicates the thickness of a pipe
Symbols	
NG	Natural gas
dia	Diameter of pipe
len	Length of pipeline
PCC	Pipeline construction cost
Material	Material cost
Labor	Labor cost
Misc	Miscellaneous cost

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