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Economic analysis of storage systems for renewable energy generated hydrogen

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ABSTRACT

Renewable energy is going to be the main energy source because of the limited petroleum reservoir on earth. But many renewable energy sources are highly fluctuant and difficult to forecast. Storing excess renewable energy is a challenge. In this work, hydrogen is produced by electrolyzing water with excess renewable energy. When reacting with hydrogen, carbon dioxide becomes a carbon source for chemical products that diminishes the negative effects of carbon dioxide on the environment. To minimize the system cost and simplify the technical complexity, optimal hydrogen temporary storage systems must be chosen. Different hydrogen storage systems are studied in this work, including liquid hydrogen tank, high pressure tank system, pipeline system and salt cavity system. These systems are analyzed and compared considering their storage capacity, system costs, advantages and disadvantages. To analyze capital and operational expenditure of the hydrogen storage systems, an analysis mechanism is developed.

KEYWORDS: cost analysis, hydrogen storage, storage capacity, system comparison

1. INTRODUCTION

Fossil fuel-based power plants produces large amount of carbon dioxide and this aggravates the greenhouse effect and speeds up global climate change. The usage of exhausted carbon dioxide is one solution to diminish the negative effects on the environment. On the other hand, renewable energy is going to be the main energy resource instead of petroleum in the future. But storing the excess renewable energy is a challenge because of its high fluctuance. In the study, the excess renewable energy is used to electrolyze water to produce hydrogen. The hydrogen reacts with carbon dioxide to produce raw materials for the chemical industry, such as carbon monoxide and formic acid. Because of the variability of renewable energy a hydrogen storage system is necessary for the surplus hydrogen.

For hydrogen storage, there are many different methods: physical storage, adsorption storage and chemical storage. In physical storage systems, hydrogen is either cooled down through heat exchanger to be stored in liquid hydrogen tanks (LH_2) [1-4], or compressed by high pressure to be stored in compressed gaseous hydrogen tanks (CGH_2) [1-7] or salt cavities [8-10]. Cryo-compressed hydrogen (CcH_2) storage system is a combination of liquid hydrogen and compressed gaseous hydrogen storage systems [11]. In CcH_2 storage system, under high pressure hydrogen doesn’t need to be cooled down to -252.8 °C to achieve the liquid state. Taking full advantage of low temperature and high pressure, CcH_2 can store hydrogen under a lower pressure than compressed gaseous hydrogen storage and at the same time at a higher temperature than liquid hydrogen storage (-252.8 °C). This helps to reduce the technical difficulty both for liquefaction and compression. By adsorption hydrogen is bound on the surface of the adsorbent by high pressure: carbon Nano fiber (CNF) [12-13], metal organic frameworks (MOFs) [14-17] and zeolite [18-19]. In chemical storage system hydrogen is bound with materials through chemical bonding. The technologies include mainly metal hydride storage (MH_2) [1-2] and chemical hydride storage [2-3]. Cryo-compressed hydrogen storage, adsorption storage and chemical storage are still in development and unsuitable for large-scale hydrogen storage in the range of tons. Therefore, in this work only liquid hydrogen storage and compressed gaseous hydrogen storage are studied. Besides the hydrogen storage the peripherals are also taken into account in this work for the cost analysis including purification plant, liquefier, compressor, buffer storage, etc.

Many projects and activities are undergoing in Europe for hydrogen that is considered to be the future fuel and energy storage medium [20-21]. Cost comparison of different storage systems, such as hydrogen, pumped hydro, CAES and different batteries is done by Meiwes for the purpose of stabilizing the grid and to maximize the utilization factors for renewable power generators [22]. But the cost analysis is for hydrogen as energy storage itself, and not the storage for hydrogen. Similar to this work, Bruggink and Roesler [23] also analyzed the cost of hydrogen as fuel in vehicles against oil and electricity. In the work of Tillmentz [24], cost for hydrogen transport and distribution is estimated, which only includes the transport of liquid and compressed hydrogen by trailer and by pipeline. There is almost no systematic cost analysis for large-scale hydrogen storage systems. So in this study, a cost analysis mechanism is developed and costs of hydrogen storage systems mentioned above are estimated and compared.

Firstly, boundary conditions for hydrogen storage systems are set up. Then the hydrogen storage systems (see Fig. 1) are designed with the given boundary conditions according to the characteristics of different hydrogen storages. Finally, capital expenditure and operational expenditure of different hydrogen storage systems are analyzed and compared based on the cost analysis mechanism.

2. Boundary conditions for hydrogen storage system

An ideal hydrogen production/consumption profile is set up in Fig. 2. This graphic illustrates the capacity of hydrogen production (dash line), hydrogen consumption (dot dash line) and hydrogen storage status (solid line). Hydrogen is produced by electrolyser 2 t/h continually for 12 hours, and then the electrolyser takes 12-hour break. Meanwhile the hydrogen consumption is 1 t/h continually for 24 hours. Therefore, a capacity of 12 t and a flow rate of 1 t/h both for charging and the discharging are required for the system. System fluctuations such as electrolysis disruption and consumption interruption are not taken into account in this work. If the storage tolerance should be considered, hydrogen storage volume can be increased according to specific requirement. In addition, after electrolysis the hydrogen is under a pressure of 50 bars at a temperature of 80 °C. But the customer needed conditions for hydrogen is 20 bars and at room temperature. These conditions are also considered for system design.

3. Hydrogen purification

In order to avoid the possible disruption and corrosion in hydrogen storage system led by the contamination in hydrogen (in this case water and oxygen), hydrogen must be purified before its transportation to hydrogen storage or directly to chemical processing plant (consumer). As the

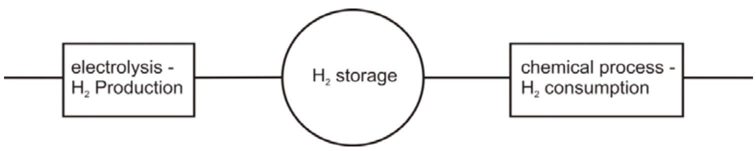

Fig. 1. System for hydrogen production, storage and consumption.

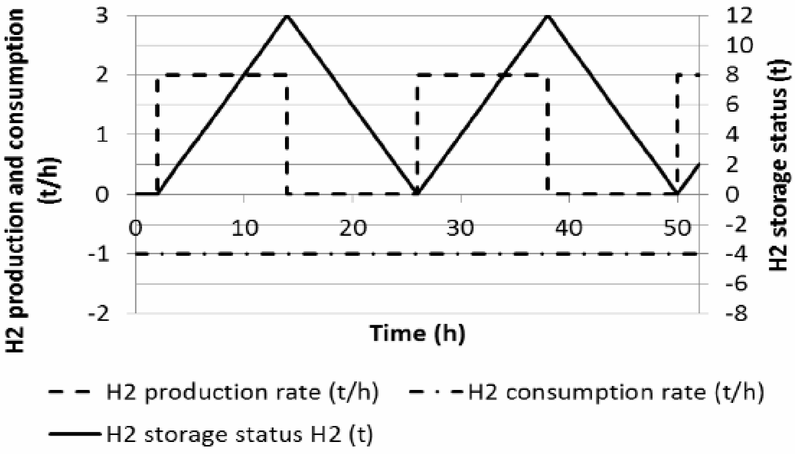

Fig. 2. Boundary conditions for hydrogen storage system.

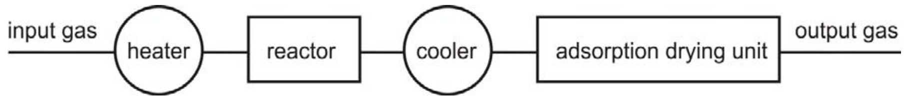

Fig. 3. Structure of catalytic purification plant.

hydrogen from electrolyser is 80 °C which already exceeds the general allowable temperature of compressed gaseous hydrogen tanks (50 °C), a cooler is necessary. In this case, the purification plant works not only as liquefier, but also as cooler and drier. The structure of a catalytic purification plant is shown in Fig. 3 that consists of a heater, reactor, cooler and a drying unit. In the purification plant the input gas is heated at first to a reaction needed temperature before the reactor converts oxygen and hydrogen into water. The highly exothermic reaction causes high gas temperature. Through the cooler the purified gas is cooled down and the reaction produced water is condensed from the purified gas. The content of the water is reduced further through the drying unit. This kind of purification plant costs 3 to 4 million euros [25]. In this work, the purification plant is used for all the hydrogen storage systems.

4. Liquid hydrogen storage system

For storing hydrogen in liquid form, it must be cooled down to -252.8 °C (20.4 K) at first. Through liquefaction the volume of the gas can be reduced enormously. Cryo tank must be thermally insulated to store the liquid hydrogen as long as possible. In general, cryo tank consists of two vacuum separated steel containers. In the vacuum area heat reflecting coating is used to avoid heat conduction and heat radiation. Even with this tank structure the temperature in cryo tank increases. After-cooling-process or evaporation-process of hydrogen in tank is used to keep the tank temperature at an allowable level. Regarding the second method, the evaporated hydrogen gas causes high pressure in the tank. The gas must be discharged to keep the tank pressure at a safe level, this is the so called boil off. The boil off rate is in general between 0.3% and 3%, and this percentage depends on the system size [1]. Larger systems have higher boil off rate than smaller systems because of more heat exchange with ambience environment and more hydrogen losses. One serious problem of liquid hydrogen storage is the large energy requirement for liquefaction, up to 30% of its energy content [1]. In addition, the purity of hydrogen gas must be higher than 99.999% for liquefaction. Joule-Thomson cycle, Claude cycle, Haylandt cycle, Linde cycle, dual-pressure-Linde process and dual-pressure Claude cycle are available for liquefaction process [13].

A. Liquefier

Liquefier is a core component for hydrogen liquefaction. The largest liquefier in the world has a liquefaction capacity of 2.25 t/h (Union Carbide, Linde Div. in USA) [26]. According to the study from LBST, a liquefier with possible capacity up to 6.5 t/h costs ca. 140 million euros and requires a floor space of 10,000 m^2 [26].

B. Cryo tank and its system

Cryo tank with a volume of 300 m^3 costs about one million euros (3,330 €/$m^3_{geom.}$) [25]. It costs 7.5 €/nm^3 for storing 12 tons of hydrogen using one tank. 100 m^3 are needed to install the cryo tank if it has a spherical shape. The tank life time is between 20 and 30 years. But the input flow rate is limited to ca. 3 t/h [25]. The liquefier and cryo tank described in [26] and [25] can satisfy the system set up listed in section 2: 1 t/h flow rate. But what should be mentioned is if the required flow rates are higher than the allowable values of liquefier and cryo tank, buffer storage is needed to insure the system stability. In Fig. 4 buffer storage is introduced into the system between the purification plant and the liquefier.

Because of the small pressure difference between the electrolyser produced hydrogen and storage pressure, pressure tank is one of the optimal buffer storages, since compressor is unnecessary. For system cost analysis all possible costs are taken into account.

In Fig. 4 part of the purified hydrogen is transported directly to the chemical processing plant (consumer), and the decreased temperature caused by expansion can be compensated with heater (like ambient air or water). The excess hydrogen is liquefied and stored in cryo tank. When needed, the liquid hydrogen can be discharged through a thin cable and heated up by ambient air (heater) to room temperature. The heated hydrogen gas must be compressed from 2.5 bars to 20 bars according to the set up in section 2. The compressed hydrogen is cooled down by the cooler back to room temperature before it is transported to the consumer. In general, a compression plant has already been equipped with a cooler. All the main components are counted in the system cost.

Liquid hydrogen storage system is low cost, but the additional cost for liquefier is very high. Flow rate of liquefier and cryo tank are limited. Besides this, energy loss in liquefaction process is very high. Compressor also increases the total investment. To sum up, liquid hydrogen storage system is very expensive.

5. Compressed gaseous hydrogen storage system with buffer and compressor

Compressed gas hydrogen storage is the most common technique. Hydrogen can be stored in pressure tank under a pressure up to 700 bars. This technique is relatively mature and simple compared to other techniques, but the weight and the cost of the system must be further decreased in the future.

In the system with buffer field (note: buffer field is not buffer storage mentioned before to insure the cryo tank system stability) and salt cavity, hydrogen must be compressed to the storage pressure at first. If the flow rate of the compressor cannot meet the requirement, buffer storage is needed, like in liquid hydrogen storage system (see Fig. 5). Hydrogen must be cooled down before charging into the storage because of the

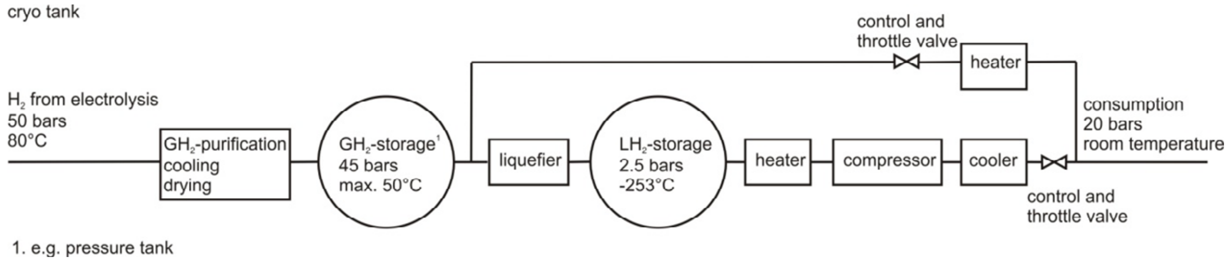

Fig. 4. Liquid hydrogen storage system with buffer storage and liquefier.

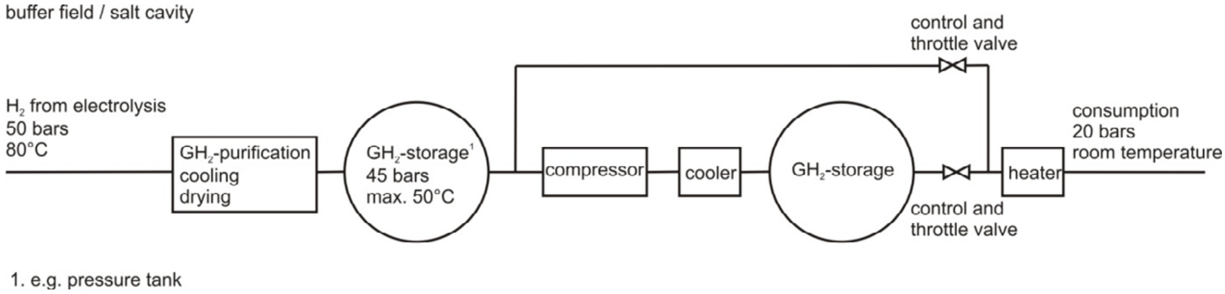

Fig. 5. Compressed gaseous hydrogen storage system with buffer and compressor.

temperature increase caused by compression. During discharge, expansion leads to a temperature decrease. Hydrogen must be heated up back to room temperature by a heater (like ambient air or water) when needed before it is transported to the customer. All the main components are counted in the system cost.

A. Compressor

One core component for high pressure hydrogen storage system is the compressor. A reciprocating compressor with a flow rate of 4 t/h bars costs around 3 million euros to compress gas from 50 bars to 300 bars. This price is doubled if it also includes planning, foundation and control system installation besides the costs for oil plant, pulsation damper, drive system, cooler and instrumentation [25]. For the installation 600 m^2 is required.

B. Buffer field

A buffer field system stores hydrogen under a pressure of 300 bars and consists of many bundles; every bundle has 16 compressed gas bottles with 80 liters volume each. For 12 tons hydrogen, 580 m^3 storage volume i.e. 460 bundles are needed. This costs ca. 4.8 million euros (36 €/nm^3, 8,300 €/$m^3_{geom.}$) [25], and cover an area of 640 m^2. The compressed gas bottles can achieve up to 35,000 cycles.

The storage volume, 580 m^3 is realizable only when the storage output pressure can reach 0 bars. But in this case the output pressure is 20 bars which means the tanks cannot be discharged down to a pressure below 20 bars. On one hand, it causes an additional investment for hydrogen to keep the tank pressure at 20 bars. This additional hydrogen gas, which always stays in the tank to hold the tank pressure at 20 bars, is called cushion gas. On the other hand, the installation volume must be increased for the usable storage volume for 12 tons of hydrogen. Total installation volume of the storage should be calculated according to the DOD (depth of discharge: dischargeable hydrogen/total stored hydrogen) of the storage. The DOD of buffer field is 90%. Cushion gas is the remaining hydrogen in the tanks under 20 bars: 1.2 tons. For the calculation of cushion gas, total thermal energy content of cushion gas is calculated according to the lower heating value of hydrogen at first. The efficiency of electrolyser at 60% for hydrogen production must also be taken into account. Then the 1.2 tons cushion gas costs 6,000 € based on an estimated price of wind energy generated electricity, which is 9 €ct/kWh (euro cent per kWh) (see Table 3). For the cost analysis the cushion gas cost is converted to €ct/nm^3 which means the cost of cushion gas per normal cubic meter stored hydrogen. This calculated price will not be affected by the changing of installation volume.

Buffer field is quite flexible for rebuilding and repositioning. But additional investment and floor space for compressor and additional energy requirement for compression are needed.

C. Salt cavity

In general, a salt cavity has a volume of about 500,000 m^3, and it is economically inefficient if the volume is smaller than 150,000 m^3 [25]. In this section a salt cavity with a volume of 500,000 m^3 is considered. This salt cavity works between two different pressures, 60 bars and 180 bars, and costs about 25 million euros [25]. In general, the usable volume of the cavity is 70%

and the remaining 30% volume is for cushion gas. If this 70% volume of salt cavity is completely used, the storage price is 0.5 € per nm^3/71 €/m^3_{geom}. To put the salt cavity into operation, 2,000 tons of cushion gas (ca. 10 million euros, for the calculations, refer to section buffer field) is needed for keeping the pressure in salt cavity at least at 60 bars. In this work, salt cavity is used only for storing12 tons of hydrogen, the cost is 187 €/nm^3 which is much more expensive than the price when the cavity volume is completely used.

Salt cavity is the cheapest storage because of the large storage volume, but only if the volume usage rate is high enough. It is worthy to use salt cavity only if the cavity is shared with other hydrogen storage. At the same time, the salt cavity is geology dependent and requires a long construction period. It takes about 10 years, from planning to implementation. Besides the cost for cushion gas, the cost for pipeline system is also very high, when the salt cavity and hydrogen consumers are at different locations. Salt cavity shows outstanding life time despite its relatively high capital cost. The first salt cavity in Germany has worked for more than 40 years.

6. Compressed gaseous hydrogen storage system without buffer and compressor

In the system with hydrogen storage under 45 bars, compressor is unnecessary. The system shown in Fig. 6 is much simpler than the systems introduced in the above sections. After purification process hydrogen is charged into storage and transported to the consumers. A heater is needed to compensate the temperature drop caused by hydrogen expansion.

A. Pressure tank

Pressure tanks store hydrogen under a pressure of 45 bars. 3,330 m^3 storage volumes are needed for 12 tons of hydrogen which is 29 pressure tanks with 115 m^3 volume each. This costs 4.5 million euros in total (33.7 €/nm^3, 1,350 €/$m^3_{geom.}$) [25]. Horizontal tank system covers an area of 1,600 m^2 and vertical tank system 260 m^2. Up to 155.000 cycles the pressure tanks can be used when the loading condition is between 42 bars and 22 bars [25]. Similar to the buffer field, the total storage volume must be calculated with the DOD of the pressure tank, here it is 45%. Cushion gas costs 33,000 euros in this case.

In pressure tank storage system, no compressor is necessary, the cycle life is long and the floor space of vertical tank system is small.

B. Pipe container

There are already some existing pipe container systems for natural gas storage. This system can also be used for hydrogen storage. Pipe container is similar to pipeline, but built underground in a serpentine shape with larger diameter than pipeline. To store 12 tons of hydrogen, for example under the pressure of 45 bars, 3,330 m^3 storage volumes is needed, and the length of the pipe container is 2.1 km with a diameter of 1.42 m and a wall thickness of 23.5 mm. It costs 1,400 €/m for material [25], 1,000 €/m for pipework and 500 €/m for underground mining [27]. In total, a pipe container system costs above 6 million euros (45.6 €/nm^3, 1,830 €/$m^3_{geom.}$). As for the pressure tank, the total storage volume must also be calculated according to DOD 45%, and the cushion gas costs 33,000 euros.

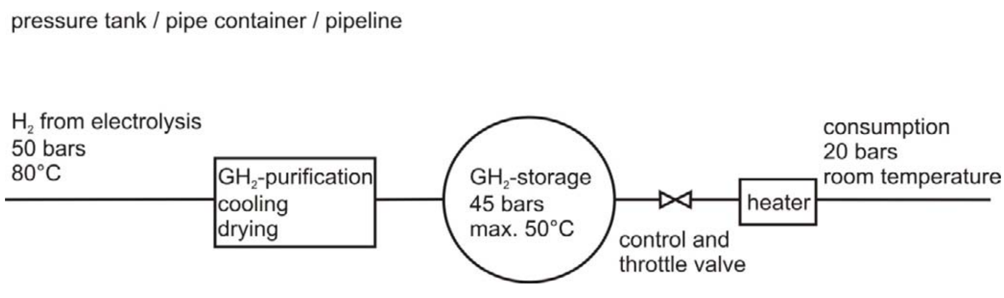

Fig. 6. Compressed gaseous hydrogen storage system without buffer and compressor.

Table 1. Hydrogen pipelines in the world [26].

Country and location	Pipeline length [km]	Operating pressure [MPa]
Gulf Coast, Texas (USA)	217	0.34-5.5
Texas (USA)	21	12.1-12.8
Houston, Texas (USA)	62	3.5-4
Mississipi River Corridor (USA)	48	3.5
Iowa (USA)	3.2	2.8
Florida (USA)	1.6-2	4.2
Montreal East (Canada)	16	
British Columbia (Canada)	6	>30
Alberta (Canada)	3.7	3.8
Sarnia (Canada)	~3	
Europoort (Netherlands)	48	
Belgium, France, Netherlands	330	6.48-10
Rhein-Ruhr-Pipeline (Germany)	225	0.1/1.1-1.9/2.3/3
Leuna Pipeline (Germany)	100	2-2.5
Teeside (UK)	16	5
Sweden (Several smaller pipelines)	7.2	0.01-2.8
South Africa	80	

In this system, no compressor is needed. Pipe container is installed underground, and then the above-ground surface is free for agricultural use. But the costs for pipework and underground mining are very high.

C. Pipeline

Hydrogen pipeline is also a possibility for storing hydrogen. Table 1 shows the existent hydrogen pipelines until 2001 [26]. In Germany the Rhein-Ruhr-Pipeline is 225 km long with a maximal pressure of 30 bars and in operation since 1938. The second hydrogen pipeline in Germany is the Leuna Pipeline (belong to The Linde Group), which is 100 km long and the allowable maximal pressure is 25 bars.

Pipeline cost consists of material cost, working related cost, costs for rights of way and damage, and other costs like inspection, engineering, building supervision, etc. [26]. It can be estimated based on natural gas pipeline cost, 400 €/m with a diameter of 400 mm [28]. In order to minimize hydrogen losses, the working related cost for the connection sealing for hydrogen pipeline is higher than for natural gas pipeline. And also because of the usage of special steel against the embrittlement effect of hydrogen [13], the material of hydrogen pipeline is also more expensive than for natural gas pipeline. If the working related cost is 25% more expensive and material cost 50% more expensive than for natural gas pipeline, the hydrogen pipeline costs up to 480 €/m [28]. For 12 tons hydrogen storage, the storage volume is 3,330 m^3 with 26.5 km length and 400 mm diameter under a maximal working pressure of 45 bars. The total cost is around 12.72 million euros (95.3 €/nm^3, 3,820 €/$m^3_{geom.}$). Besides this, cushion gas costs 33,000 euros. Same as pressure tank and pipe container, the total storage volume must also be calculated according to DOD 45%. The land scope of the system is about 14,000 m^2.

Many experiences with natural gas pipeline systems are good references for hydrogen pipeline systems. And an alternative way is to rent the existent hydrogen pipeline from pipeline owners, which is much cheaper than to build new pipeline systems. But intermediate compression stations are needed for every 100 km pipeline to compensate the pressure losses.

7. Hydrogen system costs analysis, estimation and comparison

In this work, an analysis mechanism is developed to analyze the cost of different hydrogen storage systems. All the hydrogen amounts are related to the volume of hydrogen (nm^3), and the energy losses for liquefaction and compression are also related to the volume of hydrogen (nm^3). That means the energy loss is converted to the thermal energy content of hydrogen (nm^3). This will help to simplify the calculation of the system cost.

A. Hydrogen system costs analysis and estimation

Table 2 shows some basic parameters for system analysis. In Table 3 the input parameters for hydrogen storage systems are given. According to the boundary conditions in section 2, the peak stream for charging and discharging is 1 t/h, that is 11,100 nm^3. Total storage requirement for 12 tons of hydrogen is 133,500 nm^3. Application period is set to 30 years. Hydrogen price is calculated as the cost calculation of cushion gas according to the lower heating value of hydrogen and the efficiency of the electrolyser (60%) for hydrogen production based on an estimated price of wind energy generated electricity, which is 9 €ct/kWh.

Input data varies in different hydrogen storage systems. Therefore, these data are listed separately in Table 4. For each parameter a best case and a worst case is defined. Efficiency of storage is used together with the efficiency of discharging and DOD to calculate the installed capacity of the storage system (see Table 5). If there are hydrogen losses during storage or discharging process, the capacity of the storage system must be increased to guarantee the required hydrogen volume of the chemical processing plant (consumer). DOD indicates the usage rate of the storage; therefore, it is also an important factor for the calculation of the installed capacity of the storage. The efficiency of charging is not considered for the calculation of installed capacity of storage, because it only affects the amount of hydrogen

Table 2. Parameters for system analysis.

Parameter	Value
Density	0.0899 kg/nm^3
Lower heating value	33.33 kWh/kg
Density at 20 bars and 300 K	2 kg/m^3 [29]
Density at 45 bars and 300 K	3.6 kg/m^3 [29]
Density at 60 bars and 300 K	4 kg/m^3 [29]
Density at 180 bars and 300 K	13 kg/m^3 [29]
Density at 300 bars and 300 K	20.8 kg/m^3 [29]
Density at 2.5 bars and 20.4 K	64 kg/m^3 [2]

Table 3. Input data for all hydrogen storage systems.

Design data		Unit	Comment
Peak stream - charging	11,100	nm^3/h	1 t/h hydrogen input
Peak stream - discharging	11,100	nm^3/h	1 t/h hydrogen net output
Storage capacity requirement	133,500	nm^3	12 t hydrogen storage capacity
Number of cycles per day	1	#	Max. cycles number
Application lifetime	30	years	assumption
Interest rate for capital costs	8	%	assumption
Cost for hydrogen	45	€ct/nm^3	0.0899 kg/nm^3*33.33 kWh/kg*9 €ct/kWh_{th}/60%

Table 4. Input data for different hydrogen storage systems.

Specific data for storage system	**Best case**	**Worst case**	**Unit**
External energy demand for hydrogen treatment	–	–	%
Efficiency of charging	–	–	%
Efficiency of storage system	–	–	%
Efficiency of discharging	–	–	%
Maximum depth of discharge (DOD)	–	–	%
Costs for installed storage capacity	–	–	€/nm^3
Costs for peripherals of storage system	–	–	€/nm^3
Cycles of storage system at defined DOD	–	–	#
Maximum lifetime of storage system	–	–	years
Average maintenance and repair	–	–	% of invest/y

Table 5. Calculation results for hydrogen storage systems.

Calculated data for storage system	**Unit**
Installed capacity of storage system	nm^3
Total round trip efficiency	%
Total initial investment costs	€
Capital cost per nm^3 throughput	€ct/nm^3
Operational cost per nm^3 throughput	€ct/nm^3
Total cost per nm^3 throughput	€ct/nm^3

input into the storage. More input hydrogen is needed, if there are more hydrogen losses during charging process, which doesn't have any influence to the capacity of storage systems. Total round trip efficiency is calculated with external energy demand for hydrogen treatment, e.g. liquefaction or compression, efficiency of charging, storage system and discharging. Capital costs, like costs for tanks, salt cavity or pipeline, and costs for peripherals, like costs for purification plant, liquefier, compressor and buffer storage, are already introduced in the previous sections. Cycle life and lifetime of the storage system are also defined in case the application lifetime is longer than storage lifetime, if so, storage is required to be replaced. The last row in Table 4 calculates the costs for maintenance and repair. The analysis results of hydrogen system are shown in Table 5. Capital cost includes the costs for storage and the possible peripherals. Operational cost does not only include the energy requirement for hydrogen compression or liquefaction but also the hydrogen losses during charging, storage and discharging and the cost for system maintenance. What must be mentioned is that the flow rate of hydrogen is also inclusive in the cost calculation, since it affects the amount of hydrogen going through the storage system which also affects the operational expenditure of the systems.

B. Hydrogen system comparison

Comparison of all hydrogen storage systems is shown in Table 6. This cost estimation is based on the hydrogen profile in section 2. Besides the advantages and disadvantages of the systems, the capital expenditure and total cost per nm^3 are also determined by the mechanism introduced in the previous section.

Among all hydrogen storage systems, cryo tank system requires the highest capital investment because of the high cost of liquefier, and buffer field system needs the lowest capital investment (see Fig. 7). However, including the operational cost, buffer field is not the cheapest storage system any more, since in buffer field system hydrogen must be compressed before charging into tanks (see Fig. 9). Compression causes energy losses, which increases the operational

Table 6. Hydrogen storage system comparison.

Storage system	Advantages	Disadvantages	Capital expenditure [million euro]	Total cost [€ct/nm^3]
Cryo tank	Low cost and floor space for cryo tank	Limited input rate of tank; high additional costs and floor space for liquefier and buffer field; high energy requirement for liquefication; additional compressor needed	ca. 150	41
Buffer field	Flexible for rebuilding and repositioning	Additional costs and floor space for compressor and buffer field; additional energy requirement for compression	ca. 17	7
Salt cavity	Long life time; cheap if complete volume is used	Geology dependent; long construction period; low volume usage rate; high additional costs for cushion gas and pipeline; additional energy for compression	ca. 40	11
Pressure tank	No need for compressor; small floor space for vertical tanks; long cycle life	Large floor space for horizontal tanks	ca. 20	6
Pipe container	No need for compressor; underground installed and the above-ground is free for original agricultural use	High costs pipework and underground mining	ca. 23	7
Pipeline	Experience for natural gas pipeline available; to share existing pipeline systems possible	Intermediate compression stations needed for every 100 km pipeline	ca. 39	10

expenditure in buffer field system (see Fig. 8). On the contrary, systems without compressor, pressure tank, pipe container and pipeline, have lower operational expenditure. Because of the high maintenance cost, the operational cost of pipeline system is much higher than pressure tank system and pipe container system (see Fig. 8). In salt cavity system, since the pressure difference between input hydrogen 50 bars and hydrogen storage 180 bars is less than the difference in buffer field system (between 50 bars and 300 bars), the operation cost of salt cavity is lower than buffer field. Cryo tank system has the highest operational cost because of the highest energy losses in liquefaction process. Fig. 9 shows the total cost of all hydrogen storage systems for 30 years operation. Considering the total cost, pressure tank system is the cheapest system. All the cost analysis results have intervals that is caused by the best and worst case setup for “specific data for storage system” as shown in Table 4. But because of the small difference in best and worst case setup (assumptions are made for some unavailable parameters) and high cost of cryo tank system, the intervals are not shown clearly in Fig. 7, Fig. 8 and Fig. 9.

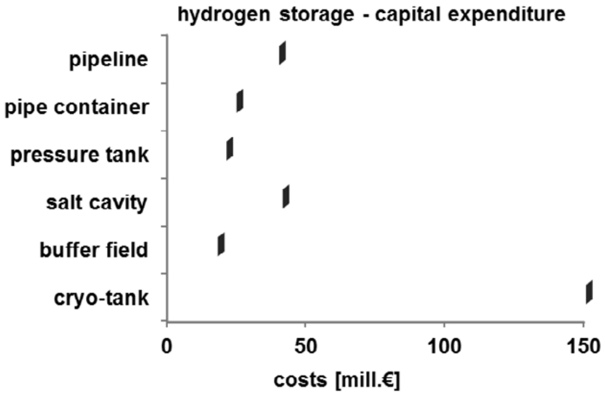

Fig. 7. Comparison of capital expenditure of hydrogen storage systems.

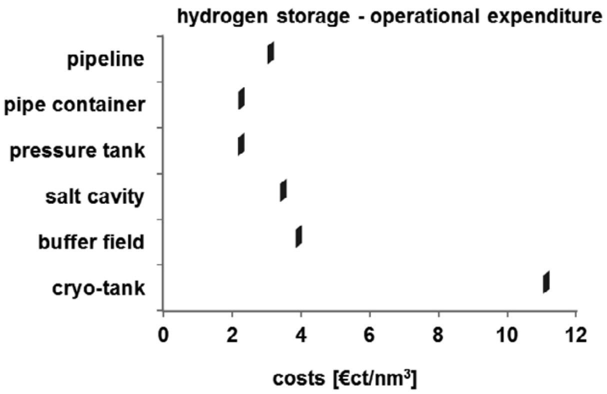

Fig. 8. Comparison of operational expenditure of hydrogen storage systems.

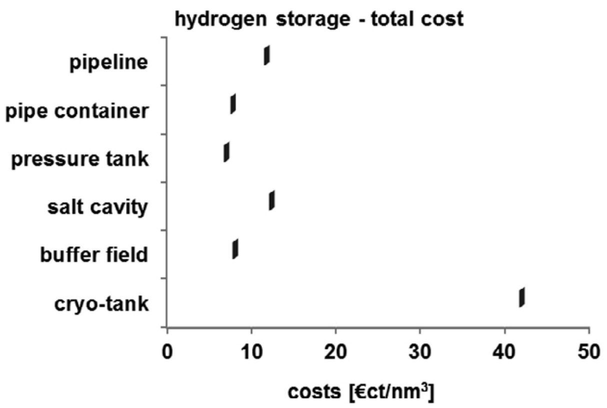

Fig. 9. Comparison of total cost of hydrogen storage systems.

CONCLUSIONS

In this work, many hydrogen storage methods and systems have been investigated for the application of large scale hydrogen storage in the range of tons. The physical hydrogen storage is more suitable than other technologies for this kind of applications. Cryo tank, buffer field, salt cavity, pressure tank, pipe container and pipeline and their systems have been studied in detail with reference to system efficiency, system capital expenditure and operational expenditure. To analyze capital and operational expenditure of the hydrogen storage systems, a calculation mechanism is developed in this work. Because of the high investment for liquefier and the low efficiency of liquefaction process, cryo tank hydrogen storage system is out of consideration. Buffer field system is also unacceptable because of the inefficiency of compression. Pressure tank system and pipe container system are relatively cheaper and can be considered for the application. But if the system fluctuation must be taken into account, like electrolyser disruption or consumption black out, the storage system capacity must be increased, and then the investment increases accordingly. On the contrary, salt cavity has a large storage volume and hence it has a high potential for system fluctuation. The possibility of sharing the existent salt cavity highlights its advantages. Similar to this, sharing the existent pipeline system can help to decrease the cost of pipeline storage system. As long as the locations of hydrogen producer and hydrogen consumer are determined, the conditions of existent salt cavity or pipeline nearby can be investigated. Considering all the factors optimal hydrogen storage can be determined based on its cost estimation.

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