IOP Conf. Series: Materials Science and Engineering **884** (2020) 012013 doi:10.1088/1757-899X/884/1/012013

Sustainable Supply of Hydrogen for Integrated Power Plant with Methanation via Pinch Analysis

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Abstract. The increment of greenhouse gaseous emission increases the needs to find the best solution to reduce emission of its gaseous. Carbon dioxide is the main contributor which comes mainly from energy sector. Capturing CO_2 from power plant does not fully solves the issue hence integrating power plant with methanation was proposed. In this paper, a pinch analysis technique is introduced to solve the challenge to implement the integrated power plant with methanation. The main drawback of the system is to deliver a sustainable and optimize capacity of hydrogen for methanation of carbon dioxide. Cascade pinch analysis is done which has been adopted from ESCA to calculate optimal hydrogen supply and hydrogen storage. From the analysis, after five iteration, the hydrogen supply capacity is obtained which is 281.38 Wh. The hydrogen storage capacity can also be determined which is 1352.52 Wh. Through the case study presented, it has proven that pinch analysis provides a simple methodology to solve the optimization issue of hydrogen supply and demand for integrated power plant with methanation system.

1. Introduction

Carbon dioxide has been widely known as the main contributor towards greenhouse gaseous emission (GHG) with a share of 60%. Renewable energy and carbon dioxide reduction, capture and storage are one of main strategies to reduce emission carbon dioxide[1]. However, the intermittency of the renewable energy and the limited underground storage capacity for the sequestration of carbon dioxide results in a lower preferability to implement the strategies to overcome the global climate change. Utilizing the carbon dioxide by transforming into another valuable products can be one of the promising solutions to solve the issues [2]. Hydrogenation of the captured carbon dioxide is by far the most attractive process where the product of the combination is methane. In comparison with hydrogen, methane is less harmful, easier to be transported and stored while also more feasible for industrial application [2]. The synthesized methane can be used directly into the gas distribution network with low limitation. Integrating power plant that release carbon dioxide with methanation process is the key driver to reduce the carbon dioxide emission. However, the drawbacks of the integration are also obvious. Investment on the methanation plant and hydrogen storage are the major issues [3]. In order to fully develop the integration, the supply of hydrogen for methanation needs further attention. The foreseeable opportunity is to optimize the supply of hydrogen for methanation by using pinch analysis technique.

Pinch analysis is used as a tool to determine the optimal performance of a process prior to the actual synthesis and design. It has evolved over the decades and used in many notable applications as tool for process integration and resource optimization[4]. [5] introduced pinch analysis for the first time and applied for heat integration. Pinch analysis was then been applied to other field such as water network, gas network and production planning. In 2011,[6] implemented PA for power system analysis which integrate design space for battery sizing. The storage technology was then been explored by [7] to determine the stored and outsourced electricity at each time period using a battery system. [4]proposed a numerical method analysis called Electric System Cascade Analysis (ESCA) to design a stand-alone DES and a storage system as an extension to the work done by [6]. In 2016, [4]applied the numerical approach for optimization of power to gas of hybrid power system using intermittent and renewable energy considering AC and DC demand. On the other hand, this work focuses on optimization of hydrogen supply and storage system for methanation of carbon dioxide captured from natural gas power plant.

2. Methodology and Case Study

This study aims to optimize the supply of hydrogen for methanation of captured CO2 and determine the optimal hydrogen storage capacity to minimize the cost of storage facilities. The system configuration consists of methanation process system, carbon dioxide capture system and electrolysis for production of hydrogen. The carbon dioxide is captured from power plant that generates electricity according to the demand of residential. Therefore, the increase of electricity demands will directly increase the demand of hydrogen supply. Following are the methodology for the cascade analysis as adopted from ESCA.

Step 1:

The demand of hydrogen is calculated based on the data of carbon dioxide emitted from power plant. In order to calculate the amount of carbon dioxide emitted, the electricity demand trend is needed. Hence for this case study, the demand of electricity been adopted from [7]. Based on mass balance calculation done by previous paper [9], the data collected, and conversion is as shown in Table 1.
Carbon emission factor is used to calculate the emission of carbon dioxide per electricity generated. The amount of hydrogen required to be reacted with carbon dioxide is calculated by using mass balance data obtained from [9]. Electricity required to produce 1 kg of hydrogen is calculated by using energy density of hydrogen which is 120 MJ/kg which is about 33322.22 Wh/kg-H_2. Table 2 shows the data calculated for demand calculation using the conversion factors.

Table 1. Conversion Factors.

Demand				Efficiency	
Type	Factors	Unit	References	Type	Factors
Electricity to CO_2	0.000744	kg-CO_2/Wh	[8]	**Charging Hydrogen - storage**	0.900 % (estimated)
CO_2 to H_2	0.0459	kg-H_2/kg-CO_2	[8]	**Discharging Storage - Hydrogen**	0.900% (estimated)
H_2 to Electricity	33322.22	Wh/kg-H_2	Ludwig et. al. (1996)		

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Table 2. Calculated demand data.

Time	Electricity, E_d	CO_2generated, C_o	H_2 required, H_I	Electricityforhydrogen, E_h
Unit	Wh	kg	kg	Wh
1	150	0.1116	0.005	170.91
2	150	0.1116	0.005	170.91
3	150	0.1116	0.005	170.91
4	150	0.1116	0.005	170.91
5	150	0.1116	0.005	170.91
6	100	0.0744	0.003	113.94
7	100	0.0744	0.003	113.94
8	100	0.0744	0.003	113.94
9	100	0.0744	0.003	113.94
10	100	0.0744	0.003	113.94
11	450	0.3348	0.015	512.74
12	475	0.3534	0.016	541.23
13	225	0.1674	0.007	256.37
14	100	0.0744	0.003	113.94
15	100	0.0744	0.003	113.94
16	100	0.0744	0.003	113.94
17	175	0.1302	0.006	199.40
18	425	0.3162	0.014	484.26
19	425	0.3162	0.014	484.26
20	425	0.3162	0.014	484.26
21	425	0.3162	0.014	484.26
22	425	0.3162	0.014	484.26
23	425	0.3162	0.014	484.26
24	150	0.1116	0.005	170.91

Step 2:
Estimate the supply of hydrogen for the methanation of carbon dioxide. For this study, the first estimation of 1000Wh is made

Step 3:
Cascade analysis is conducted, and cascade table is constructed based on the estimated hydrogen supply where the total hydrogen needed to be reacted with carbon dioxide is arranged hourly.

(1) The first column is filled with the spread of 24-hour time period in ascending order with time interval of 1 hour.

(2) The hydrogen demand, Dt is then been arranged in column 2 .

(3) Followed by hydrogen supply, St that has been estimated in column 3.

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Calculate the net hydrogen using equation 1 and arrange the result accordingly in column 4.

$$N_t = S_t - D_t \tag{1}$$

(4) Calculate the hydrogen surplus and deficits by referring to the net hydrogen. If the net hydrogen demand is positive, this indicates that the hydrogen supply is in surplus mode and hence it needs to be stored. The storage of this surplus hydrogen will involve further processing and transportation and hence the amount of hydrogen stored will be subjected to the efficiency of the processing and transportation. This stored hydrogen,is calculated in the equation 2;

$$I_t = N_t f_x f_y \tag{2}$$

This stored hydrogen will be tabulated in column 5. However, if the value of net hydrogen is negative, this indicates that stored hydrogen from hydrogen storage need to be used. The usage of stored hydrogen, O_t is also subjected to processing and transportation efficiency and is calculated from equation 3 and tabulated in column 6.

$$O_t = \frac{N_t}{f_p f_q} \tag{3}$$

(5) Calculate the cumulative hydrogen demand and arrange the results accordingly in column 7. The cumulative hydrogen demand can be calculated using equation 4.

$$C_{t+1} = C_t + I_{t+1} + O_{t+1} \tag{4}$$

From the cumulative hydrogen in column 7, negative numbers show that hydrogen is used up more than it is stored, representing the infeasibility of the system. Therefore, a new cumulative number then needs to be recalculated using equation 5 and arranged in column 8. Absolute value of smallest negative number (the largest magnitude of negative value) is used as the new cumulative number for the first hour of the calculation, C0. However, if there is no negative number, zero is stated at the first hour of the cumulative hydrogen calculation.

$$Cnew{,}0 = |min(Ct) \tag{5}$$

Thus for the stated iteration, the size of the hydrogen storage can be described as the largest capacity of hydrogen stored, or the maximum value of C_{new},t in the iteration. To determine the optimum value of hydrogen storage, the optimum value hydrogen supply is calculated. This is due to the fact that storage of hydrogen can be reduced by reducing the supply of hydrogen that created net positive hydrogen supply in the first place. The difference between the starting of hydrogen in the storage tank at the start of time, Co and the remaining hydrogen in storage at the end of the time, C_{final} is essentially excess hydrogen and can be reduced to reduce the size of storage. This excess storage can be reduced by reducing the supply of hydrogen that accumulated to the excess storage. Thus, to calculate the new hydrogen supply capacity, equation 6 is used.

$$S_{new} = S - \frac{(C_{final} - C_{h\ initial})}{T} \tag{6}$$

Where S is the previous estimated capacity of hydrogen supply and T is total time duration (for this case study, 24 h).

The value of S_{new} is fed into the next iteration as the hydrogen supply while the value of hydrogen supply from new and previous iteration is compared by comparing the percentage change in the value using equation 7.

$$P=\frac{|S_{(new)}-S|}{S}\times 100 \tag{7}$$

The iteration needs to be repeated if the percentage change is larger than 0.05% in order to control the accuracy of the results.

3. Results and Discussion

For this case study, the percentage change for the first iteration is 66.18%, followed by 16.31 % for the second iteration. Since the percentage change is still high, as mentioned by[4], the analysis need to be repeated. Five iteration is needed to achieve the percentage change lower than 0.05%. The result for the iteration is as shown in Table 3. Figure 1 illustrated the trend of the percentage change with respect to the iteration number. Table 4 shows the final iteration. From the final iteration, the size of the final hydrogen supply is calculated which is 281.38 Wh. Figure 2 shows the composite curve for the final iteration.

As the cascade analysis is done, the optimal size of hydrogen storage capacity can also be determined. The final iteration results in Table 4 is used by referring to the largest positive number in column 8 which is 1352.52 Wh. The storage capacity calculated value represents a feasible value which is around five times the calculated hydrogen supply. Hence, through the case study presented it is proven that this method can be used to determine the optimal storage capacity and optimal hydrogen supply. This method provides simplest methodology for optimization to overcome the challenge of implementing integrated power plant with methanation with a goal to reduce emission of carbon dioxide.

Table 3. Iteration Results.

Iteration Number	Hydrogen Supply capacity, Wh	Percentage Change, %
1	1000	-
2	338.1	66.18
3	283.06	16.31
4	281.43	0.58
5	281.38	0.01

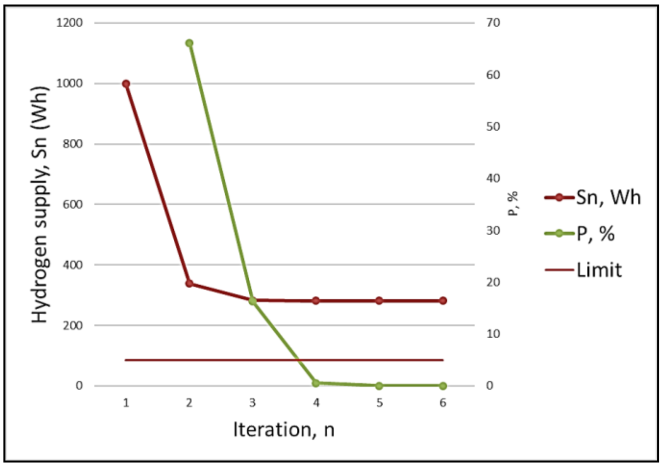

Figure 1. Iteration results.

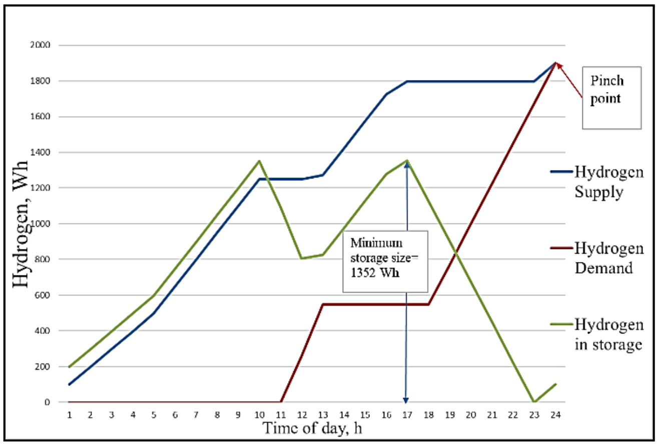

Figure 2. Composite curve of final iteration.

Table 4. Final Iteration.

Time, t	Hydrogen demand, D_t	Hydrogen supply, S_t	Net hydrogen demand N_t	Charging, I_t	Discharging, O_t	Cumulative hydrogen, C_t	New Cumulative hydrogen, $C_{new,\,t}$
h	Wh	Wh	Wh	Wh	Wh	Wh	Wh
0						0.00	99.38
1	170.91	281.38	110.47	99.42	0.00	99.42	198.80
2	170.91	281.38	110.47	99.42	0.00	198.84	298.22
3	170.91	281.38	110.47	99.42	0.00	298.26	397.64
4	170.91	281.38	110.47	99.42	0.00	397.68	497.06
5	170.91	281.38	110.47	99.42	0.00	497.09	596.48
6	113.94	281.38	167.44	150.69	0.00	647.79	747.17
7	113.94	281.38	167.44	150.69	0.00	798.48	897.86
8	113.94	281.38	167.44	150.69	0.00	949.17	1048.56
9	113.94	281.38	167.44	150.69	0.00	1099.87	1199.25
10	113.94	281.38	167.44	150.69	0.00	1250.56	1349.94
11	512.74	281.38	-231.36	0.00	-257.07	993.49	1092.87
12	541.23	281.38	-259.85	0.00	-288.72	704.77	804.15
13	256.37	281.38	25.01	22.51	0.00	727.27	826.66
14	113.94	281.38	167.44	150.69	0.00	877.97	977.35
15	113.94	281.38	167.44	150.69	0.00	1028.66	1128.05
16	113.94	281.38	167.44	150.69	0.00	1179.35	1278.74
17	199.40	281.38	81.98	73.78	0.00	1253.14	1352.52
18	484.26	281.38	-202.88	0.00	-225.42	1027.72	1127.10
19	484.26	281.38	-202.88	0.00	-225.42	802.30	901.68
20	484.26	281.38	-202.88	0.00	-225.42	576.88	676.26
21	484.26	281.38	-202.88	0.00	-225.42	351.46	450.84
22	484.26	281.38	-202.88	0.00	-225.42	126.04	225.42
23	484.26	281.38	-202.88	0.00	-225.42	-99.38	0.00
24	170.91	281.38	110.47	99.42	0.00	0.03	99.42

4. Conclusion

ESCA was adopted to determine the optimal capacity of hydrogen storage and optimal hydrogen supply for methanation of carbon dioxide. From the analysis, this work has managed to show the applicability of ESCA for the system. With the simple pinch analysis method, the issue involved to implement integrated power plant with methanation is possible to cater the needs to reduce the emission of carbon dioxide.

Acknowledgements

The authors gratefully acknowledge the research grant supported by UniversitiTeknologi Malaysia (UTM) with vote number Q.J130000.2446.04G33 and also dedicated to UTM ZAMALAH scholarship from UTM for the first author.

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