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HYDROGEN RECOVERY SYSTEM DESIGN APPLICATION IN A PETROCHEMICAL REFINERY

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Abstract

Many processes in the refinery convert crude oil into high value-added products (gasoline, jet fuel, diesel, etc.) by consuming hydrogen and meet the hydrogen requirement from hydrogen producing processes or hydrogen purification units. In new trends, the need for hydrogen in the refinery industry is increasing, and so many studies on hydrogen networks are being made. In this study, hydrogen pinch analysis was performed between the hydrogen producing and consuming processes of the Tupras Izmir Refinery. Pinch analysis is an integration method that can be applied to the hydrogen network as it is applied for heat networks and allows to see the deficiencies and surpluses in the hydrogen network. The results obtained in this study show that the hydrogen supply meets the demand of hydrogen in the refinery and the hydrogen network is in equilibrium. If the hydrogen demand increases in the case of processing high sulfur crude oil, this excess hydrogen demand is provided from an off-gas source in the refinery. The economic analysis of PSA and membrane purification methods was carried out, and methods are compared.

Keywords: *Hydrogen pinch; Hydrogen recovery system; Hydrogen network.*

1. Introduction

Hydrogen production and consumption in oil refining industry is very crucial. The supply of hydrogen, which represents a cost to the refinery, must be maintained to avoid constraints on the refinery operations. If the demand for hydrogen exceeds the available supply, then the incremental demand must be met by debottlenecking the hydrogen distribution system, adding production capacity, or purchasing additional hydrogen from an external source. Besides producing hydrogen, also hydrogen management provides hydrogen supply to the system. When hydrogen management applies to any system, it is clearly seen that operating cost and hydrogen stock usage is reduced. Because of the much hydrogen consumption in refineries with respect to such industries, in this study refinery process have examined. Refinery process hydrogen network management is an integration process in which apply pinch analysis technology.

In this study, the graphical method of hydrogen pinch analysis is performed on the hydrogen network of the Tupras Izmir Refinery. Surplus and deficit amounts of hydrogen are examined between hydrogen sinks and sources. In this way, it has seen that sources meet the demand of hydrogen on hydrogen networks.

On the other hand, new specifications canalize refineries to low-sulfur fuels, increasing hydrogen demand over the years. Also, processing heavier crude oil causes higher hydrogen demand. In case of demand exceeds the current hydrogen availability, hydrogen recovery process is one of the appropriate options. For this reason, by using an existing refinery off-gas, which includes hydrogen, different hydrogen purifying methods are discussed. Economic analysis is performed with some assumptions, and two different purification methods are compared.

2. Refinery hydrogen management

A refinery consists of many processes that convert crude oils into valuable products such as gasoline, jet fuel, and diesel by consuming hydrogen. The required hydrogen in some processes can be supplied from other processes in the refinery, which are producers of hydrogen.

The new specification for low-sulfur fuels requires increased hydrogen consumption in hydrotreaters. At the same time, the limitations for aromatics content in gasoline and oxygenate requirements have led to reducing the hydrogen produced in catalytic reforming unit. The usage of heavier crude oils in the refinery causes increment of the hydrogen demand in hydrocracking and heavy oil hydrotreating units [1].

In hydrogen consumer processes, hydrogen is used as a reactant during the reaction. Some hydrogen consuming units are Hydrocracker (HYC), Naphtha hydro-treating (NHT), Isomerization (ISO), Hydrodesulphurization (HDS or DHP). The primary source of hydrogen within the refinery has been the catalytic naphtha reforming unit, which supplies the needs of hydrocracking and hydrotreating processes. Producer units produce hydrogen and energy during the chemical reaction, contrary to consumer unit. While hydrocarbons decomposed, hydrogen is produced [2]. Some producer units are Continuous Catalytic Reformer (CCR), Semi-Regen Reformer (SRR), Steam Methane Reformer (SMR).

2.1. Hydrogen pinch analysis

Linnhoff *et al.* [3] proposed the pinch technology for heat exchanger network synthesis. By plotting cold streams and hot streams data into a composite curve, the overall heat exchanger network's pinch point can be found, leading to a theoretically optimal solution.

Alves [4] utilized Linnhoff's work and extended the pinch technology into the hydrogen network field. Hydrogen sinks and sources are introduced similarly to the cold and hot streams in heat exchanger networks. By observing the balance between hydrogen sinks and sources, hydrogen pinch analysis gives a general overview of the hydrogen usage situation of a specific hydrogen network.

The first step in developing an analysis method for establishing the minimum flow rate of fresh hydrogen required by a hydrogen distribution system is to identify the sinks and sources of hydrogen in the system [5].

2.2. Hydrogen composite curve and surplus curve

The hydrogen composite curve is plotted by the hydrogen demand profile and hydrogen source profile, as Figure 1 shows. By plotting composite curve, demand and source streams are plotted from highest to lowest purities versus flow rates. While x-axis represents flowrate of hydrogen, y-axis represents hydrogen purity. A few regions have been created by these two curves indicating either hydrogen surplus or deficits in terms of "+" or "-" to indicate advice hydrogen resources in excess or shortage. The area of hydrogen surplus and deficit can be calculated and directly plotted into another diagram, a hydrogen surplus curve, which shows the current situation of hydrogen usage in a hydrogen network [4]. Figure 2 shows the hydrogen surplus curve which is generated using hydrogen surplus and deficit regions of Figure 1.

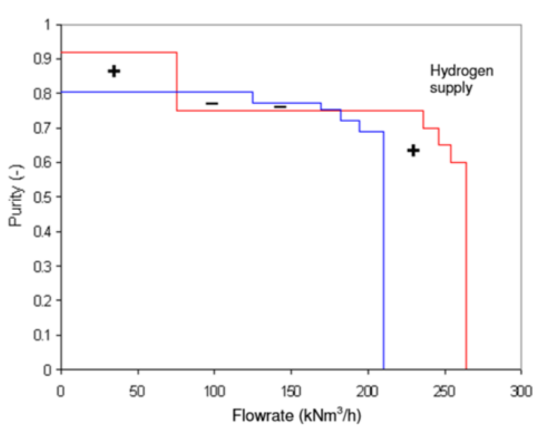

Figure 1. Hydrogen composite curve [4]

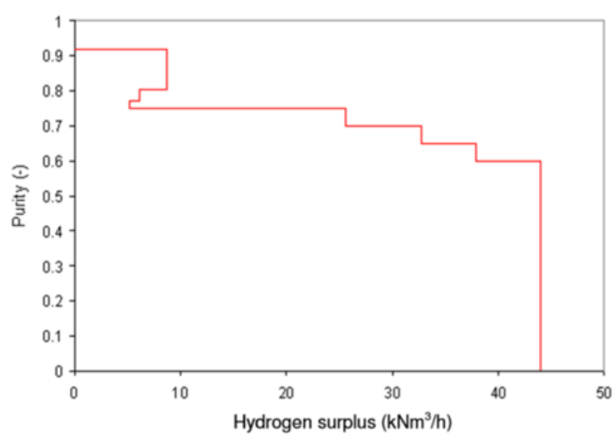

Figure 2. Hydrogen surplus curve [4]

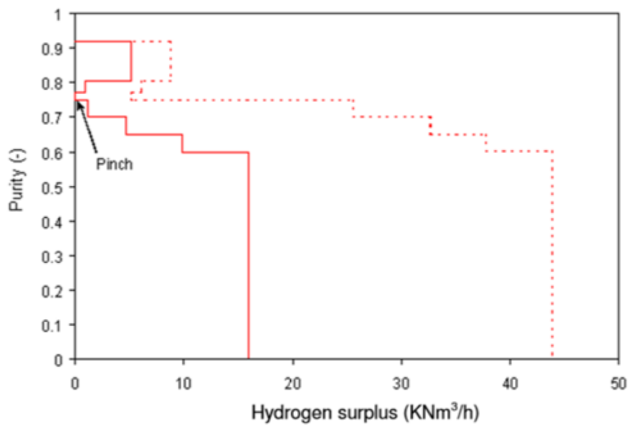

Figure 3. Hydrogen pinch point [4]

Hydrogen Surplus Curve provides gain clear view of potential hydrogen utility saving. The pinch point of the system can be found by moving the curve leftwards until vertical part touched the purity axis (Figure 3). This point shows a bottleneck between sinks and sources.

Hydrogen pinch analysis is a simple graphical method to analyze the hydrogen network quickly and clearly and enables to set target amount of utility hydrogen to be saved.

2.3. Hydrogen purifier processes

Basically, placing a hydrogen purifier somewhere in the hydrogen network leads to three possible situations with respect to hydrogen surplus, what goes above, across and below the pinch [4]. Certain savings of hydrogen would be achieved when a purifier is placed across the pinch, while no effect below the pinch and possible savings above the pinch.

The separation processes, namely pressure swing adsorption (PSA), polymeric membranes and cryogenic separation are based on different separation principles so that process characteristics differ significantly [6]. The purity and pressure of the hydrogen stream enable to consumers have significant effect on the design and operation of these units which is generally a hydro-processing unit. Each of purifier options is based on a different separation principle, and consequently, the characteristics of these processes differ significantly. The appropriate hydrogen purification technology selection depends not only on the economic but also, on flexibility and reliability.

Table 1. The features of hydrogen recovery technologies [1]

Features	PSA	Membrane	Cryogenic
H_2 purity	99.99%+	90-98%	90-96%
H_2 recovery	50-92%	85-95%	90-99%
Feed pressure	10-45 kg/m^2-g	20-160 kg/m^2-g	>5-75 kg/m^2-g
Feed H_2 product	<40%	>25-50%	>10%
H_2 product pressure	Feed	<1/3 Feed Pres.	Feed/Low pres.
H_2 capacity	1.18×10^3 – 2.35×10^5 m^3/h	1.18×10^3 – 5.90×10^4 m^3/h	1.18×10^4 – 8.83×10^4 m^3/h
Pretreatment req.	None	Minimum	CO_2, H_2O remove
Multiple products	No	No	Liquid HCs
Power requirement	None/Fuel	H_2/Feed	None/H_2/Refrigeration
Capital cost	Medium	Low	Higher
Scale economic	Moderate	Modular	Valid

2.4. Cost analysis of hydrogen recovery in refineries

Towler *et al.* [7] developed the first systematic approach for hydrogen management. Economics analysis of hydrogen recovery against added values in the product by hydrogen is proposed as the main feature in this method.

2.4.1. Operating costs

Hydrogen is usually recovered from refinery off gasses using either membrane diffusion or pressure swing adsorption (PSA). The cost of recovered hydrogen, C_H, is given by [7];

$$C_H = C_F + C_W + C_R \qquad (1)$$

2.4.1.1. Fuel cost

The fuel value cost, C_F, is the cost of fuel lost by purification of hydrogen rather than combustion. In cost comparison study, C_F was taken as 0.431 $/kmol [1].

2.4.1.2. Compressor power cost

The compressor work, C_W, includes both feed and product compression and is given by;

$$C_W = \frac{c_p T_1}{\eta}\left[\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma} - 1\right] \qquad (2)$$

where, c_p : gas molar average heat capacity (J/mol K); T_1 : gas inlet temperature (K); P_1 : gas inlet pressure (N/m^2); P_2 : delivery pressure (N/m^2); γ : ratio of gas specific heats, and η : isentropic efficiency of compression, typically 0.85. For refinery gases, it is adequate to assume γ=1.4 [7].

2.4.1.3. Hydrogen recovery process control

a. Pressure Swing Adsorption Process (PSA)

For the PSA process, the cost of the purification can be estimated from equation (3) [7]:

$$C_R\left(\frac{\$_{1994}}{\text{kmol}}\right) = \frac{18.04}{Q} + \frac{0.2364}{Yz} \qquad (3)$$

where Y: recovery yield of hydrogen; z: feed gas hydrogen mole fraction and Q: production rate of purified hydrogen (kmol/h)

b. Membrane process

For Membrane Process, hydrogen recovery cost C_R is given by [7];

$$C_R\left(\frac{\$_{1994}}{\text{kmol}}\right) = 0.0391 + 0.0114\,\frac{AR_P P_L}{Q} \qquad (4)$$

$$\frac{AR_P P_L}{Q} = \frac{1}{\left[r\left(\frac{z - x_r}{\ln\left(\frac{z}{x_r}\right)}\right) - y\right]} \qquad (5)$$

$$x_r = \frac{y(1-Y)z}{(y - Yz)} \qquad (6)$$

where R_p : membrane permeability (kmol/N h); r : pressure ratio; y : hydrogen purity and x_r: hydrogen concentration in the residual gas.

2.4.2. Investment costs

The investment cost includes the costs of new compressors, purifiers, and piping.

2.4.2.1. Compressor cost

The capital cost of a compressor is the linear function of power consumption [8].

$$C_{comp}(\$) = a_{comp} + b_{comp}\ \text{x Power (kW)} \qquad (7)$$

For case study a_{comp} : 115000 , b_{comp}=1910 [1].

2.4.2.2. Purifier cost

a. Pressure Swing Adsorption (PSA)

The cost of a PSA unit is calculated as a linear function of the feed flow rate.

$$C_{PSA}(\$) = a_{PSA} + b_{PSA}\ \text{x}\ F_{in\,(PSA)} \qquad (8)$$

For case study a_{PSA}=503800, b_{PSA}=347400 [1].

b. Membrane Process

Cost of membrane unit calculated with equation (9) [7]:

$$C_{MEM}(\$) = C_R Q \qquad (9)$$

3. Application of hydrogen pinch

In this study, the hydrogen pinch analysis is to perform a mass balance on hydrogen sources and demands in the petrochemical refinery hydrogen network. In this way, surplus hydrogen amount of network is determined by using graphical method, minimum hydrogen demand for the refinery is identified, strategies are developed to achieve minimum demand, and yield is improved on key process units, capital cost reduces, and ongoing operating cost savings. Energy optimization is provided by hydrogen pinch approach.

The following steps are applied to achieve this strategy;

1. Identifying hydrogen sinks and sources, 2. Extracting the stream data for hydrogen sinks and sources, 3. Calculation of cumulative flow rates of hydrogen sinks and sources, 4. Construction of cascade analysis, 5. Plotting the hydrogen composite curve, and 6. Plotting the hydrogen surplus curve

The real and current data on the hydrogen network of Tüpraş İzmir Refinery were used. Hydrogen sinks and sources are defined, and stream data are obtained for each plant (Table 2 and Table 3). Hydrogen producer units of the refinery are Continuous Catalytic Reformer (CCR), Semi-Regen Reformer (SRR), Steam Methane Reformer (SMR). These units are the main hydrogen sources, and source data is defined using them.

Similarly, hydrogen consumer units of the refinery are hydrocracker (HYC), Naphtha hydrotreating (NHT), Isomerization (ISO), Hydrodesulphurization (HDS or DHP).

Table 2. Source data

Plant	Capacity (m^3/h)	H_2 production (Nm^3/m^3)	H_2 %vol
SRR	60	200	70
CCR	150	300	90
SMR	max 43 000 Nm^3/h		100

Table 3. Sink data

Plant	Capacity (m^3/h)	H_2 consumption (Nm^3 H_2/m^3)	H_2 %vol
NHT-1	60	10	min 70
NHT-2	150	10	min 70
NHT-3	100	10	min 70
NHT-4	60	35	min 70
ISO	100	45	min 90
HDS-1	50	50	min 70
HDS-2	50	50	min 70
HDS-3	400	100	min 85
HYC	120	310	100

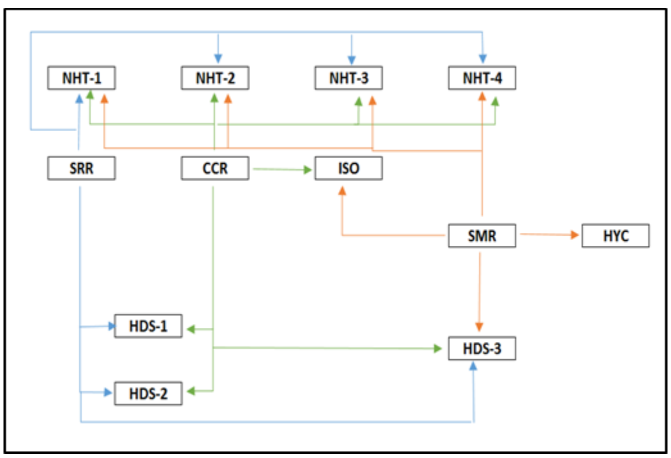

Figure 4. Schematic hydrogen network

Sink and source network is well-defined in Figure 4, which illustrates the schematic hydrogen network in the refinery.

In order to gain a clear view of hydrogen sink and source flows, hydrogen flow diagram is re-drawn as in Figure 5. The interactions among the hydrogen sink and hydrogen source determines the optimal design of the hydrogen network in a refinery, as well as the minimal demand for fresh hydrogen, and should be considered by integrating the hydrogen network.

In this system shown in Figure 5, there are 9 hydrogen consumer plants and 3 producer plants. Before applying cascade analysis, hydrogen flow rates of each plant and cumulative flow rates of sinks and sources are determined. For this purpose, source plants' hydrogen purities are ordered from highest to lowest. In case of purities are the same, order has completed from highest hydrogen flow rate to lowest. The same order procedure is applied for sink plants also.

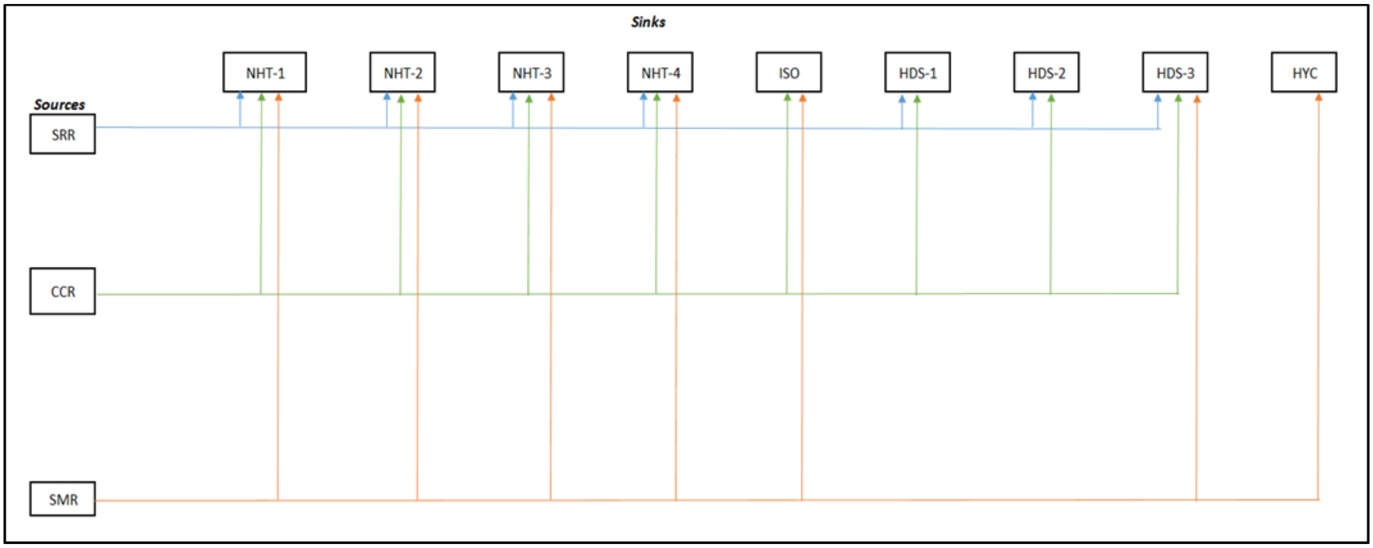

Figure 5. Hydrogen flow diagram

$$F_i = \text{Capacity } (m^3/h)_i \text{ x Hydrogen consumption}(nm^3 \text{hydrogen}/m^3)_i \quad (10)$$

$$F_j = \text{Capacity } (m^3/h)_j \text{ x}$$
$$\text{Hydrogen consumption}(nm^3\text{hydrogen}/m^3)_j \text{ x}$$
$$(\text{Hydrogen \%vol}/100)_j \quad (11)$$

Flow rates of each source plants are calculated using equation 10, but for sink plants calculated using equation 11. Because the production of hydrogen data is for pure hydrogen. Cumulative flow rates are calculated for each row by starting from up.

Table 4 and Table 5 represents the results of flowrates and cumulative flowrates. These data are the starting point of the cascade calculations.

Table 4. Flowrate for sources

Source	H_2 purity (%)	Flowrate (Nm^3/h)	Cumulative flow rate (Nm^3/h)
SMR	100	43 000	43 000
CCR	90	45 000	88 000
SRR	70	12 000	100 000

Table 5. Flowrate for sinks

Sinks	H_2 purity (%)	Flowrate (Nm^3/h)	Cumulative flow rate (Nm^3/h)
HYC	100	37200	37200
ISO	90	5000	42200
HDS-3	85	47059	89259
HDS-1	70	3571	92830
HDS-2	70	3571	96402
NHT-4	70	3000	99402
NHT-2	70	2143	101545
NHT-3	70	1429	102973
NHT-1	70	857	103830

Cascade analysis provides to determine the minimum hydrogen amount fed to the system.

Firstly, for the hydrogen demand (sink) purity column, all sink and sources are put in order from higher to lower by using equation 12.

$$0 < y^1 < y^2 < y^3 \ldots . . < y^{12} \quad (12)$$

For the flow interval column, likely purity column, all sinks, and sources' cumulative flow rates are ordered from lower to higher. Hydrogen source purity order is started from highest purity until second highest purity, and it is ended with "0" when the last source is written.

Maximum purity is calculated by taking the highest purity between demand and source purity in each row.

The hydrogen surplus column is calculated using equation 13 and applied for each row. Then cumulative hydrogen surplus is calculated from zero while adding hydrogen surplus in each row.

$$HS_n = \frac{FI_n - FI_{n-1}}{SP_n - DP_n} \quad (13)$$

where FI: flow interval; SP: source purity, DP: demand purity; and n: interval number in the cascade analysis table.

Table 6. Flowrate for sinks

H_2 demand purity(%)	H_2 demand purity (vol fraction)	Flow interval (Nm^3/h)	H_2 Source purity (vol fraction)	Maximum purity (vol fraction)	H_2 surplus (Nm^3/h)	Cumulative H_2 Surplus (Nm^3/h)
	1	0	1			
100	1	37 200	1	1	0	0
	0.9	37 200	1	1		0
100	0.9	42 200	1	1	500	500
	0.85	42 200	1	1		500
90	0.85	43 000	1	1	120	620
	0.85	43 000	0.9	0.9		620
90	0.85	88 000	0.9	0.9	2250	2 870
	0.85	88 000	0.7	0.85		2 870
85	0.85	89 259	0.7	0.85	-189	2 681
	0.7	89 259	0.7	0.7		2 681
70	0.7	92 830	0.7	0.7	0	2 681
	0.7	92 830	0.7	0.7		2 681
70	0.7	96 402	0.7	0.7	0	2 681
	0.7	96 402	0.7	0.7		2 681
70	0.7	99 402	0.7	0.7	0	2 681
	0.7	99 402	0.7	0.7		2 681
70	0.7	100 000	0.7	0.7	0	2 681
	0.7	100 000	0	0.7		2 681
70	0.7	101 545	0	0.7	-1081	1 600
	0.7	101 545	0	0.7		1 600
70	0.7	102 973	0	0.7	-1000	600
	0.7	102 973	0	0.7		600
70	0.7	103 830	0	0.7	-600	0
0	0	103 830	0	0		0

Hydrogen demand purity versus flow interval is plotted with hydrogen source purity versus flow interval in same graph which is hydrogen composite curve. Regions between demand and source curves are called hydrogen deficit or surplus. In case of source curve is the up part, this region is called surplus, "+", and if demand is up, region is called as deficit, "-".

Cumulative hydrogen surplus is plotted with maximum purity, which is hydrogen surplus curve. When pinch point is on y-axis, also shows that network is balanced. It can be clearly seen that no fresh hydrogen source needed, so hydrogen sources cover the hydrogen demand of the network.

Sulfur contamination in fuel causes large scale air pollution. Therefore, new specifications for low-sulfur fuels, require increase hydrogen consumption in hydrotreaters. In case of refining high sulfur content crude oil or aiming produce low sulfur content fuels with new trends, need of hydrogen will be increased. If the demand for hydrogen exceeds the availability supply, then the incremental demand must be met by increasing hydrogen plant production (turning up productions or revamping existing equipment), build a new hydrogen plant, purchasing hydrogen from outside suppliers, or recovery of hydrogen that was going to fuel by installing a hydrogen purification unit [1]. Additionally, costs of purification methods are compared.

In this part of the study, increased hydrogen requirement is supplied with an off-gas in the refinery. For this purpose, 50 vol% hydrogen content off-gas is selected to send purification process. As mentioned in literature survey, there are 3 purification processes; PSA, membrane and cryogenic process. Since there are disadvantages of cryogenic process in refineries, which are mentioned before, cryogenic process is not considered in cost comparison.

Flow rate, pressure, temperature, and composition data of refinery off-gas is given below in Table 7. Since the pressure and compositions of the given off-gas are suitable for PSA and membrane processes, an economic comparison for these two methods has been made.

Table 7. New hydrogen source data

Flow rate (Nm^3/h)	10000
Pressure ($kg/cm^2.g$)	22
Temperature (°C)	20
Composition (vol%)	
Hydrogen (H_2)	50
Methane (CH_4)	20
Ethane (C_2H_6)	15
Propane (C_3H_8)	10
Butane (C_4H_{10})	5

The following assumption is considered for the comparison of the costs of the new purified systems:

– Pressure loss for PSA is neglected.
– Pressure loss for the membrane is taken as 12 kg/cm^2g.
– Compressor work is calculated due to hydrogen is needed with 65 kg/cm^2 pressure.
– The piping cost in the case study is taken as 20% of purifier cost. Because the detailed information about the piping length between refinery process units was not available.
– Service life both for PSA and membrane assumed as 20 years.
– Taxes for both processes are considered as 30% of gross earning, and interest has taken account as 12.5% in 20 years.
– Depreciation is calculated for both processes with the straight-line method for 20 years.
– Hydrogen production cost has taken as 2 $/kmol
- Chemical Engineering Plant Cost Index (CEPCI) for 1994 has taken as 368.1 and for 2019 as 619.2.

4. Results and Discussion

The graphical analyzing method of hydrogen surplus is proposed for establishing the minimum flow rate of fresh hydrogen required by a hydrogen distribution system. The analysis method is useful to achieve minimum demand and operating cost savings. In addition, refinery can also save hydrogen utility by applying hydrogen pinch approach and mass integration.

In this study, the graphical method of pinch analysis over hydrogen network of Tüpraş İzmir refinery is performed. The hydrogen composite curve (Figure 6) and the hydrogen surplus curve (Figure 7) are plotted. It has seen that pinch point is at 70 % hydrogen purity where curve firstly touches the y-axis.

Since the area under the region below pinch point is "0" on the hydrogen surplus curve (Figure 7), no needed reduction in utility because hydrogen network is balanced with respect to hydrogen sources and demands. It means that hydrogen sources cover hydrogen demand of the network.

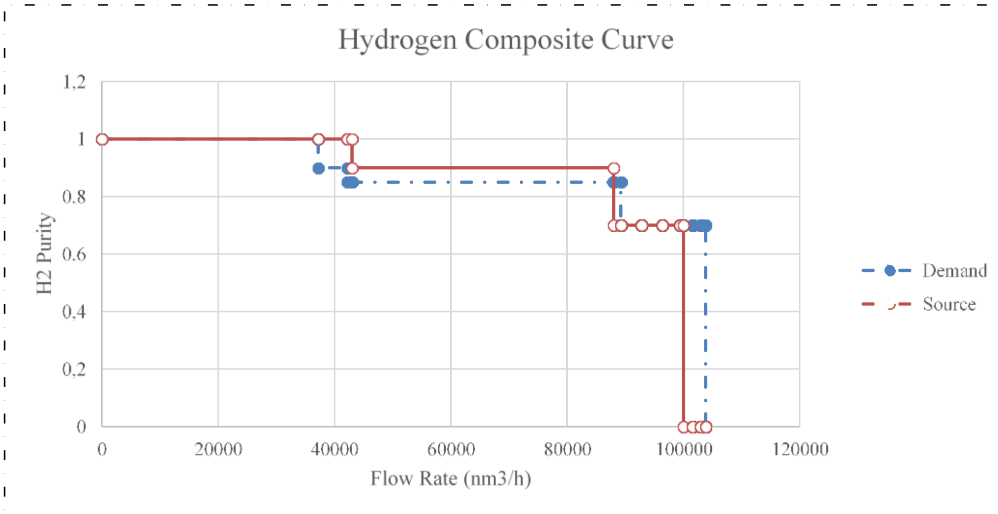

Figure 6. Hydrogen composite curve

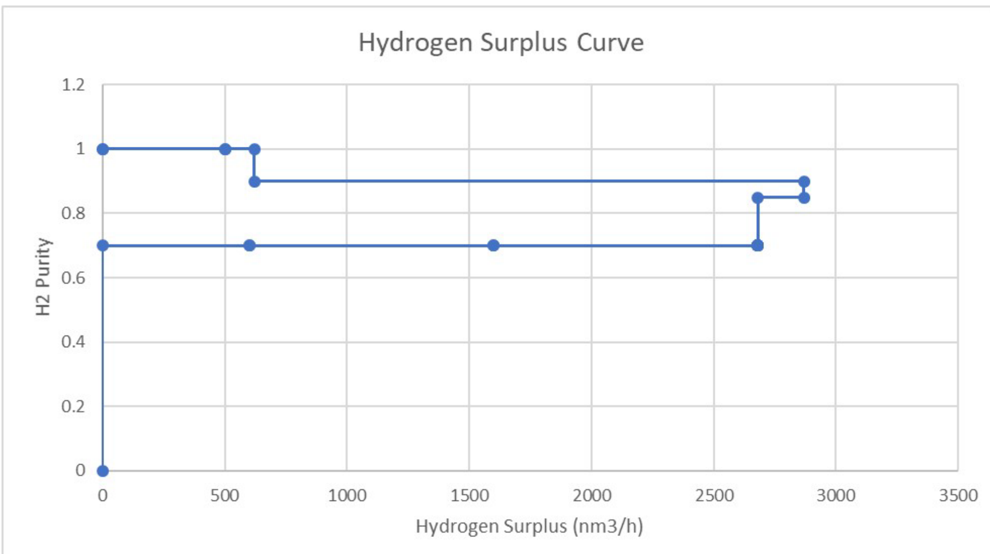

Figure 7. Hydrogen surplus curve

Secondly, in the part of the economic analysis of two hydrogen purifiers, equations in the part of literature survey are used. Operating and investment costs for both PSA and membrane processes are calculated and tabulated in Table 8. For comparison, yearly income, gross earning, yearly taxes, cash flow, net profit, and some parameters (net present value, rate of return on investment, payback period) are also calculated and tabulated in Table 9.

While recovery and purity of hydrogen for PSA are 90% and 99%, for membrane process 85% and 94%, respectively. Also, the compressor cost of membrane is approximately double of PSA because of pressure drop in membrane, but comparing the recovery of both processes, fuel cost for PSA is higher likely recovery cost. To sum, annual total operating cost of PSA is approximately two times of membrane process in contrary to total investment cost.

In order to compare these two purifiers, cost comparison criteria for both purifiers are calculated and tabulated. Since the recovery percentage of PSA unit is higher that membrane unit, it is expected to see higher income for PSA. Because exceed amount of recovered hydrogen by using PSA unit may be supplied for producing the high-added product in the refinery so that cost return may be higher.

Table 8. Operating and investment costs comparison

	PSA	Membrane
Operating cost		
Fuel cost ($/y)	7.48 $\times 10^5$	6.70 $\times 10^5$
Compressor work cost ($/y)	4.62 $\times 10^5$	8.96 $\times 10^5$
Recovery cost ($/y)	2.40 $\times 10^6$	2.81 $\times 10^5$
Total operating cost ($/y)	3.61 $\times 10^6$	1.85 $\times 10^6$
Investment cost		
Compressor cost ($)	1.89 $\times 10^6$	3.48 $\times 10^6$
Purifier cost ($)	1.37 $\times 10^6$	3.53 $\times 10^6$
Piping ($)	2.75 $\times 10^6$	7.06 $\times 10^5$
Total investment cost ($)	3.54 $\times 10^6$	7.71 $\times 10^6$

The net present value for 20 years with a 12.5% interest rate is approximately $ 16 million for membrane and $14 million for PSA. Other comparison criterions are rate of return of investment and pay-back period. Rom Table9, it is seen that PSA has higher rate of return and less payback period; therefore, it makes PSA good purifier option.

Table 9. Cost comparison criteria

	PSA	Membrane
Income ($/y)	6,927,751.37	6,270,966.27
Gross earning ($/y)	3,252,218.0	4,247,377.58
Tax ($/y)	975,665.40	1,274,213.27
Net profit ($)	2,276,552.60	2,973,164.31
Cash flow ($)	2,345,223.07	3,149,555.31
Net present value ($)	13,982,237.06	15,811,861.07
Rate return on investment (ROROI)	0.66	0.41
Pay back period	1.51 years	2.45 years

5. Conclusion

In this study, the hydrogen network of Tüpraş İzmir Refinery has examined to develop hydrogen interaction by applying graphical pinch method. This method is for estimating the minimum fresh hydrogen supply to the hydrogen distribution system. For this aim, hydrogen surplus and composite curves have been plotted. Potential hydrogen utility saving on network can be determined on surplus curve; therefore, pinch point is found at 70 % hydrogen purity. Since the area below the pinch point is zero and pinch point is at y-axis, hydrogen demand is met by sources. This means that hydrogen producing processes are enough to meet the requirement of hydrogen, so hydrogen distribution is in equilibrium.

Additionally, cost analysis for off-gas purifiers has been applied in the case of sources were not sufficient to meet the demand of hydrogen. An off-gas that contents 50% of hydrogen is purified by applying two different purification methods, PSA and membrane processes. Cost analysis calculations carried out for each unit by making some assumptions like assuming service life of both processes as 20 years. As a result of calculations, PSA has 90% recovery with 99% hydrogen purity, while membrane has 85% recovery with 94% hydrogen purity. After economical calculations, total operating cost of PSA and membrane are 3,606,862.90 $/y and 1,847,197.68 $/y and total investment costs for PSA and membrane are $ 3,535,172.15 and $ 7,713,427.34, respectively. In addition, comparison criteria have calculated and seen that PSA has higher rate of return and it pays back in less period time. Based on these assumptions, PSA can be better option than membrane for refinery hydrogen network.

Appendix

$$F(\frac{kmol}{h}) = \sum_{i=1}^{5} \frac{Q(\frac{m^3}{h})_i \, x \, \rho_i \, (\frac{kg}{m^3})}{MW(\frac{kg}{kmol})_i}$$

$$Income = \; F_{H_2} x \; (purity) \; x \; (Recovery) \; x \; MW_{H_2} x \; 2 \; \$/kmol$$

$$Gross \; Earning = Income - Total \; operating \; Cost - Depreciation$$

$$Net \; Profit = Gross \; Earnign - Tax$$

$$Cash \; Flow = Net \; Profit + Depreciation$$

$$Net \; Present \; Value = \; -(Total \; Investment \; Cost) + \sum_{i=1}^{20} \frac{CF_i}{(1+k)^i}$$

$$\sum_{i=1}^{20} \frac{1}{(1+k)^i} = 7.4694$$

$$Rate \; Return \; of \; Investent = \frac{Cash \; Flow}{Total \; Investment \; Cost}$$

$$Pay \; Back \; Period = \frac{Total \; Investment \; Cost}{Cash \; Flow}$$

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