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# Hydrogen pinch analysis of a petroleum refinery as an energy management strategy

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**Abstract:** The glaring need for energy management in a petroleum refining industry is as a result of significant refinery energy costs, typically 40-50% of operating costs. Consequently, energy auditing is frequently carried out to identify energy management opportunities for higher profitability. Hydrogen management in a refining plant by means of the hydrogen pinch analysis approach aimed at identifying the optimum hydrogen network has been recognized as an effective way of optimizing the processes. The numerous benefits of hydrogen management include maximum processing revenue as a result of reduced hydrogen system operating costs and production benefits, minimum capital investment, reduced carbon dioxide emissions, and more importantly, up to 20% cost savings from energy efficiency improvements. Hydrogen pinch technology has been employed in this study to discover optimum hydrogen distribution systems which can be a potential energy management opportunity in a refining industry. The goal was to identify shortcomings in the hydrogen distribution of the system so as to improve the energy utilization of the plant. Analysis of the case study resulted in identification of optimum hydrogen target for the system. Achieving the target will reduce the power consumption of the catalytic reforming unit by 10.8% and also help to conserve hydrogen use by more than 20%. Implementation of suggestions for efficient utilization of energy made will increase the profit as well as the operating costs. However, there will be annual increase in marginal revenue as the profit is considerably greater than the operating costs. The payback period and return on investment (ROI) of these suggestions are less than 3yrs and 28% - 44% (depending on the option adopted) respectively. Another significant advantage of the project is that it will reduce the gas flaring and helps prepare the refinery for future environmental challenges.

**Keywords:** Petroleum Refinery, Energy Audit, Energy Management Opportunities, Hydrogen Pinch Analysis

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## 1. Introduction

The ever surging demand for energy in recent years has heightened the quest for successful, cost-effective investment into energy efficient technologies and practices which will meet the challenge of maintaining the output of high quality products with reduced production costs, and as a consequence greater profitability. This becomes an issue of pertinent importance in industrial processes with relatively high energy consumption such as the petroleum refining industry, and often led to additional benefits, such as increasing the productivity of the company further.

Energy consumption within the refining process is typically greater in units which have a large throughput, as opposed to units which is energy intensive per barrel processed [1-4]. The

major energy consuming processes are crude distillation, followed by the hydrotreater, reforming, and vacuum distillation [1]. Then comes a number of processes consuming somewhat similar amount of energy, i.e., thermal operations, catalytic cracking, hydrocracking, alkylate and isomer production as evident from Table 1. These values are representative of the average energy use at US refineries, and the top four highest energy consuming units (atmospheric and vacuum distillation, hydro treating and reforming) have been highlighted.

A large variety of opportunities exist within petroleum refineries to reduce energy consumption while maintaining or enhancing the productivity of the plant [1,5-6]. Studies by several companies in the petroleum refining and petrochemical industries have demonstrated the existence of a

substantial potential for energy efficiency improvement in almost all facilities. Competitive benchmarking data indicate that most petroleum refineries can economically improve energy efficiency by 10-20%. For example, a 2002 audit of energy use at the Equilon refinery (now Shell) at Martinez, California, found an overall efficiency improvement potential of 12% [1,6]. This potential for savings amounts to annual costs savings of millions to tens of millions of dollars for a refinery, depending on current efficiency and size.

**Table 1.** Energy usage by refinery process in US refineries [4]

Process	Specific Usage (MJ/bbl)	Average Usage (MJ/bbl)	Annual Energy Use, (%)
Atmospheric Distillation	87.196	120.1	25.79
Vacuum Distillation	54.119	96.5	9.6
Visbreaking - Coil	143	143.5	0.04
-Soaker	26-100	66.5	0.04
Delayed Coking	120-243	175.1	4.61
Fluid Coking	272	272.2	0.29
Flexi coking	176	176	0.27
Fluid Catalytic Cracking	53-172	105.5	7.66
Catalytic Hydrocracking	168-339	253.2	4.41
Catalytic Hydrotreating	64-173	126.6	18.83
Catalytic Reforming	225-361	299.6	15.13
Alkylation -Sulfuric acid	348-359	353.4	2.14
-Hydrofluoric acid	423	423	3.84
Ethers Production	311-595	425.2	1.34
Isomerization - Isobutane	379	379	0.52
-Isopentane/ Isohexane	108-249	184.6	1.09
Isobutylene	502	502	n/a
Lube Oil Manufacture	1589	1589	4.4

Improved energy efficiency may result in co-benefits that far outweigh the energy cost savings, and may lead to an absolute reduction in emissions. Major areas for energy efficiency improvement are utilities (30%), fired heaters (20%), process optimization (15%), heat exchangers (15%), motor and motor applications (10%), and other areas (10%) [1]. Of these areas, optimization of utilities, heat exchangers, and fired heaters offer the most low investment opportunities, while other opportunities may require higher investments. Experiences of various oil companies have shown that most investments are relatively modest. However, all projects require operating costs as well as engineering resources to develop and implement the project [7]. Every refinery and plant will be different. The most favorable selection of energy efficiency opportunities should be made on a plant specific basis.

Table 2 summarizes the possible measures of improving on energy efficiency in various units, and provides access keys by process and utility system to the descriptions of the energy efficiency opportunities. For individual refineries, actual payback period and energy savings for the measures will vary, depending on plant configuration and size, plant location, and plant operating characteristics. Staff should be trained in both skills and the company's general approach to energy efficiency in their day-to-day practices. Personnel at all levels should be aware of energy use and objectives for energy efficiency improvement. Companies like the British Petroleum (BP) have successfully implemented aggressive greenhouse gas (GHG) emission reduction programs at all their facilities worldwide (including exploration and refining). BP has reduced its global GHG emissions to 10% below 1990 levels within 5 years of the inception of its program; years ahead of its goal, while decreasing operation costs [1].

**Table 2.** Matrix of Energy Efficiency Opportunities in Petroleum Refineries [1,6]

Process	Energy Management	Flare Gas Recovery	Power Recovery	Boilers	Steam Distribution	Heat Exchanger	Process Integration	Process Heaters	Distillation	H <sub>2</sub> Management	Motors	Pumps	Compressor Air	Fans	Lighting	Cogeneration	Power Generation	Other Opportunities
Desalting	x											x						
CDU	x	x			x	x	x	x	x		x	x		x				
VDU	x				x	x	x	x	x					x				
Hydrotreater	x				x	x	x	x	x	x				x				
Cat. Reformer	x	x			x	x	x	x	x	x				x				
FCC	x	x	x		x	x	x	x	x					x				
Hydrocracker	x	x	x		x	x	x	x	x	x				x				
Coker	x	x			x	x	x	x	x					x				
Visbreaker	x	x			x	x	x	x	x					x				
Alkylation	x				x	x	x	x	x					x				
Light End	x				x	x	x		x									
Aromatics	x				x	x	x	x	x									
Hydrogen	x				x	x	x	x		x								
Utilities	x	x	x	x	x	x	x			x			x		x	x	x	x

"x" denotes areas where opportunities can be implemented

These efforts demonstrate the potential success of a corporate strategy to reduce energy use and associated emissions. Yet, other companies used participation in voluntary programs to boost energy management programs. Petro-Canada participates in Canada's Climate Change Voluntary Challenge and Registry [8]. Petro-Canada has developed a corporate-wide emission reduction and energy efficiency program, and reports the results annually.

In Europe, various countries have voluntary agreements between industry sectors and governments to reduce energy or GHG emission intensity [1,9-13]. For example, all refineries in the Netherlands participated in the long-term agreements between 1989 and 2000. BP, ExxonMobil, Shell, and Texaco all operate refineries in the Netherlands. The refineries combined (processing about 61 million tons of crude annually) achieved a 17% improvement of energy efficiency. Today, the refineries participate in a new agreement in which the refineries will be among most energy efficient refineries worldwide by 2010, using the Solomon's index as a gauge.

Hydrogen is an important utility in the production of lighter and cleaner fuels to remove impurities and crack heavy components of crude oil [8,14-16]. This high demand and limit on the aromatics content of gasoline are some of the factors that make hydrogen production very expensive and energy intensive [16]. Therefore, hydrogen management is a critical issue in the refinery.

Hydrogen integration, as a tool for environmental and energy audit is an approach that identifies the optimum hydrogen network, improves process yield, reduces hydrogen system operating costs, minimizes capital investment and also reduces CO<sub>2</sub> emissions [8]. It is a form of process integration and a major technology development in hydrogen management within the refinery.

For effective hydrogen management, the hydrogen distribution system must be properly understood. A typical hydrogen system consists of three processes;

Producing processes- hydrogen sources in the system. For example, steam reforming unit and Catalytic Reforming Unit (CRU),

Consuming processes- hydrogen sinks in the system. Examples are Naphtha Hydrotreating Unit (NHU) and Kerosene Hydro treating unit (KHU),

Purifying unit- Examples are Pressure Swing Adsorption (PSA), Cryogenic Distillation and Membrane Separation.

Revamping and retrofitting existing hydrogen networks can increase hydrogen capacity between 3% and 30% [17]. The BP refinery at Carson (California), in a project with the California Energy Commission, has executed a hydrogen pinch analysis of the large refinery.

Total potential savings of \$4.5 million on operating costs were identified, but the refinery decided to realize a more cost effective package saving \$3.9 million per year. As part of the plant-wide assessment of the Equilon (Shell) refinery at Martinez, an analysis of the hydrogen network has been included [1]. This has resulted in the identification of large energy savings. Further development and application of the

analysis method at California refineries, especially as the need for hydrogen is increasing due to reduced future sulfur-content of diesel and other fuels, may result in reduced energy needs at all refineries with hydrogen needs [15]. One refinery identified savings of \$6 million/year in hydrogen savings without capital projects [5].

The development of process design methodologies for hydrogen management started in 1996 when a research consortium was established at the process integration department at University of Manchester Institute of Science and Technology (UMIST) [18]. Some companies came together having had the foresight to recognize that although hydrogen availability was not then a major issue, it would become so in future years. These companies funded the research, contributed engineering knowledge, case study data and industrial feedback for the research which was well documented in literature [16] and was also coded into a software package by UMIST for the use of the member companies.

Alves [18] utilized Linnhoff's work [19] 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 [18, 20]. With observation on the balance between hydrogen sinks and sources, hydrogen pinch analysis gives a general overview of the hydrogen usage situation of a specific hydrogen network.

For a wider applicable range of the hydrogen pinch analysis, Foo and Manan developed the theory of gas cascade analysis (GCA) [21]. Rather than considering only hydrogen, the GCA method can be used to work out the minimum flow rate target for various utility gas networks such as nitrogen or oxygen network integration [14]. Unfortunately, the technique has more than two limitations. First, the GCA technique does not allow the user to represent multiple source and demand streams having the same purity as separate streams with individual flow rates but lumps it together. This prevents the user from understanding the effects of changing the flow rate of an individual stream, making it difficult to do a sensitivity analysis [22]. Secondly, it is important to label each stream with a name, which the GCA technique does not do. Third, to identify the pinch, the GCA technique still requires an initial assumption of a fresh hydrogen flow rate and goes through two iterations [14-16, 22].

Hallale et al. [16] proposed three rules of thumb that should be avoided if possible;

- Flare hydrogen or use it as fuel if the concentration is higher than the pinch purity
- Produce hydrogen at concentration lower than the pinch purity
- Use streams with concentrations higher than the pinch purity to meet demands which requires a concentration lower than the pinch purity.

An un-pinched system always violates at least one of them.

Nigeria is a country blessed with sweet crude which is crude with low amount of impurities (sulfur) and consists of light hydrocarbons. It can be assumed that this type of crude needs

less hydro processing and therefore no need for hydrogen management. Research and development should be carried out because:

1. The refineries are old and have not been updated to compare with the level of current technological advancement.
2. Stricter measures to ensure cleaner fuel have been put in place, but this is yet to be implemented in the operations of the refineries in the country [23-27].

There is therefore the possibility of excess or shortage of hydrogen in the refineries. Each refinery has peculiar complexity and configuration. Port Harcourt Refining Company (PHRC) with a current combined installed capacity of 210,000 BPSD is chosen as case study for this study as it processes over 45% of the nation's crude oil at optimally production levels. Bearing in mind that CLEANER fuels regulations will become stricter as the world tends towards sustainability to address environmental issues. Proper research and development on energy utilization of the refineries in the country is required. This research is focused on identifying optimum hydrogen network, improving energy and environmental impacts and estimating cost benefits of suggested options.

## 2. Methodology

### 2.1. Hydrogen Sinks and Sources

Hydrogen sinks and sources were identified by studying the operation and flow diagram of the refinery.

Hydrogen sinks are units that consumes or whose inlet and recycle streams contains hydrogen. The outlet (purge) stream of sink units also has hydrogen. Hydrogen sources on the other hand have hydrogen in their inlet and recycle streams.

Streams with considerable fraction of hydrogen were considered for this research. The hydrogen distribution network is represented in Fig. 1.

### 2.2. Hydrogen Pinch Analysis

Extracted data were used in estimating sinks and sources streams to be considered for the hydrogen pinch analysis. The equations are as shown below

$$\text{Sink's flow rate} = F_{\text{MUG}} + F_{\text{RG}} \quad (1)$$

$$\begin{aligned} &\text{Sink's hydrogen purity} \\ &= [(V_{\text{MUG}}F_{\text{MUG}}) + (V_{\text{RG}}F_{\text{RG}})] / (F_{\text{MUG}} + F_{\text{RG}}) \quad (2) \end{aligned}$$

$$\text{Source's flow rate} = F_{\text{PG}} + F_{\text{RG}} \quad (3)$$

$$\begin{aligned} &\text{Source's hydrogen purity} \\ &= [(V_{\text{PG}}F_{\text{PG}}) + (V_{\text{RG}}F_{\text{RG}})] / (F_{\text{PG}} + F_{\text{RG}}) \quad (4) \end{aligned}$$

The estimated values from (1) to (4) served as input to Microsoft Excel spreadsheet program. The optimum hydrogen below and above the pinch was identified from the curve given by the spreadsheet. The data used on the spreadsheet can be found at the Appendix.

### 2.3. Options for Hydrogen Utilization

After identifying the minimum hydrogen target for the system, suggestions for efficient utilization of hydrogen were proposed. Analysis of these suggestions was done based on knowledge of the operation of the plant and putting into consideration the rules of thumb [16].

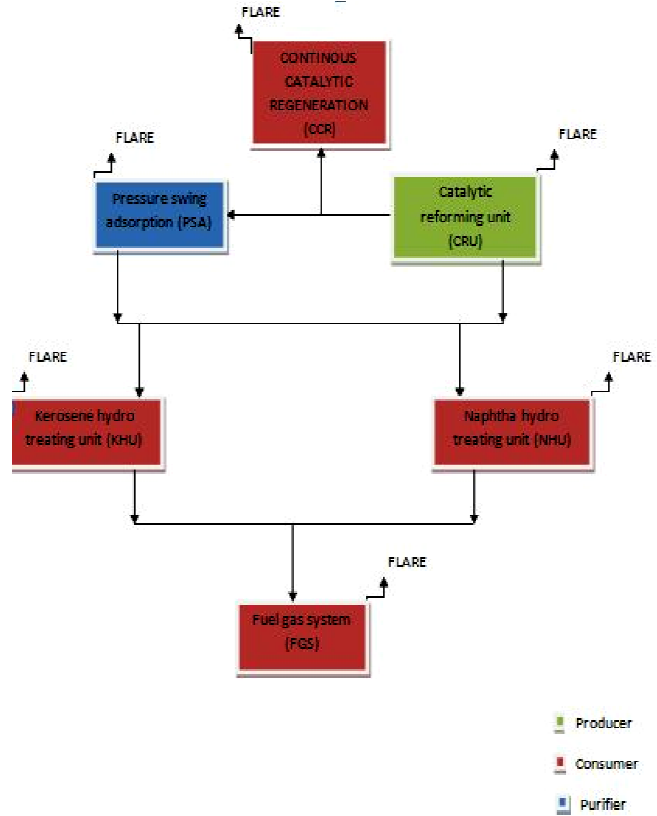


Figure 1. Hydrogen Distribution System

### 2.4. Cost Benefits Analysis

The investments proposed were evaluated in a payback period and return on investment perspectives. The considered expenses were investments and operating costs. The new unit introduced was estimated by using cost model of the system in literature (ballpark estimate) [28-33]. Equations and data used in computing costs are shown below

$$C_{\text{wk}} = \frac{c_p T_1}{\eta} \left[ \frac{P_2}{P_1} \left( \frac{\gamma-1}{\gamma} \right) - 1 \right] \quad (5)$$

$$\text{Payback period} = \frac{\text{capital investment}}{\text{profit or costs saved}} \quad (6)$$

$$\text{Return on Investment} = \frac{\text{net annual profit}}{\text{total investment}} * 100\% \quad (7)$$

$$C_w = A_{\text{comp}} + (B_{\text{comp}} * \text{Power}) \quad (8)$$

$$C_R = \frac{18.04}{Q} + \frac{0.2364}{Y * Z} \quad (9)$$

$$C_{\text{PSA}} = A_{\text{PSA}} + (B_{\text{PSA}} * F_{\text{PSA}}) \quad (10)$$

$$C_{\text{sf}} = [(F_{\text{FGS1}} * V_{\text{H2}} * H_{\text{H2}} * C_{\text{H2}}) - (F_{\text{LPG}} * H_{\text{LPG}} * C_{\text{LPG}})] \quad (11)$$

Annual operating hours = 8200 hrs

Hydrogen cost,  $C_{H_2} = \$850/\text{Nm}^3$

LPG cost,  $C_{LPG} = \$162/\text{Nm}^3$

Lower heating value of  $H_2$ ,  $H_{H_2} = 10.6 \text{ MJ}/\text{Nm}^3$

Lower heating value of LPG,  $H_{LPG} = 112.6 \text{ MJ}/\text{Nm}^3$

Electricity cost =  $\$0.08/\text{kWh}$

Nelson Farrar's Refinery Index  $N_2$ , 2012 = 2465.2

Nelson Farrar's Refinery Index  $N_1$ , 2006 = 1961.6

When hydrogen is made available for reuse in the process instead of being sent to the fuel gas network, this hydrogen must be replaced with another fuel in order to produce heat. For this work, we proposed the use of LPG (75% butane and 25% propane) to be used as replacement. The amount of fuel needed is calculated through heating values of the streams being redirected from the fuel gas.

### 3. Results and Discussion

Fig. 2 represents the hydrogen demand- source (composite) curve. It is clearly evident that the difference between sources and sinks is about  $46000 \text{ Nm}^3/\text{hr}$  in the system. This is properly shown on the surplus curve (Fig. 3) below.

These figures reveal that the system is not pinched (the closest vertical line is not touching the y-axis) and therefore there is room for improvement in the hydrogen management of the system.

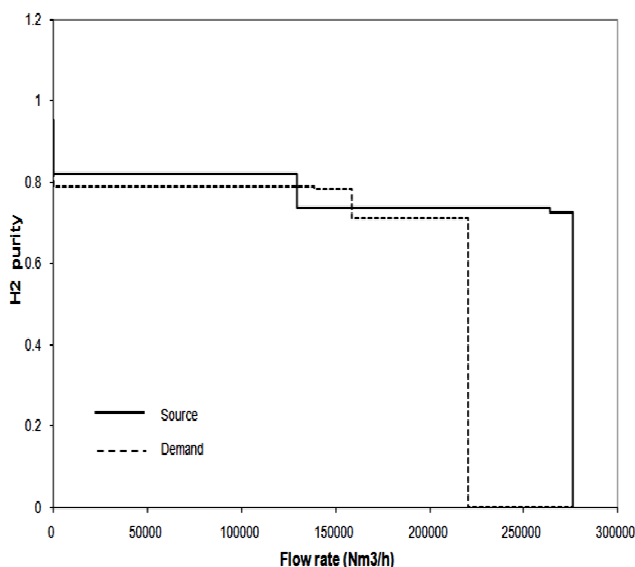


Figure 2. Hydrogen Composite Curve (before pinch analysis)

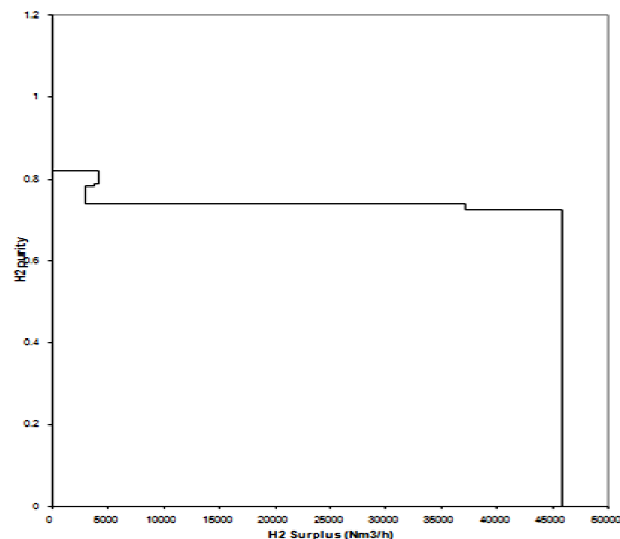


Figure 3. Hydrogen Surplus Curve (before pinch analysis)

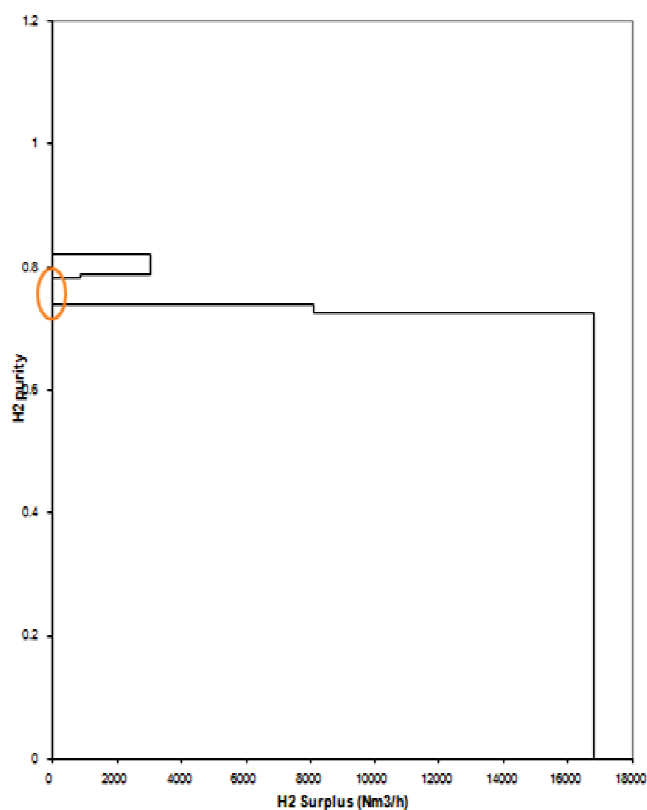
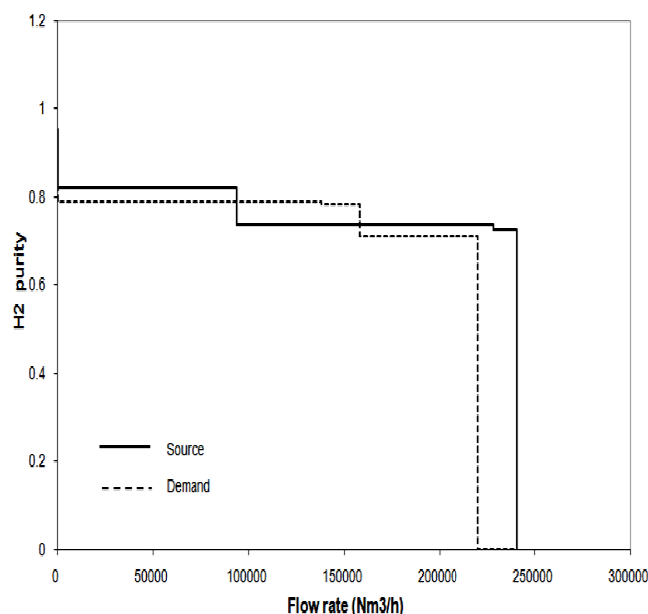


Figure 4. Hydrogen Composite Curve (after pinch analysis)

The hydrogen composite curve of the optimized system (pinched) is shown in Fig. 4. The curve shows that the hydrogen margin between source and sink units has drastically reduced to about  $17 \text{ kNm}^3/\text{hr}$  (about 63% reductions).

Fig 3 reveals the hydrogen pinch of the system. The hydrogen pinch of the system (enclosed within the orange circle) is between  $0.7825 - 0.74$ . The sink hydrogen pinch is  $0.74$  and that of source is  $0.7825$ . This implies that hydrogen purity in the outlet of source stream must not be lesser than  $0.7825$  (pinch above system) while stream with hydrogen purity greater than  $0.74$  must not be used to meet the need of

hydrogen sink units. Also, hydrogen with concentration greater than the pinch of the system must not be flared or used as fuel as this will violate the pinch system.



**Figure 5.** Hydrogen Surplus Curve (after pinch analysis)

In order to implement the identified opportunities in the system, the refinery has to be retrofitted to accommodate hydrogen recovered. It was suggested that the purifying unit (PSA) of the refinery should be expanded. This will give more room for surplus hydrogen initially wasted in the system to be purified and put to better use. Considering the economics of this expansion, two options can be adopted;

- Expansion of PSA to 18kNm<sup>3</sup>/hr. This expansion requires recovering all hydrogen in the system including those used in fuel gas system (FGS). Recovering hydrogen in the FGS requires replacing it with another source of fuel. In this case, LPG was chosen.
- Expansion of PSA to 12kNm<sup>3</sup>/hr. This option considers recovering all hydrogen but those used in the FGS.

The recycling rate of hydrogen has to be reduced in the catalytic reforming unit (CRU). It was therefore suggested that the compressor in the CRU driven by turbine should be replaced with an electric motor with adjustable speed drive (ASD) to regulate the speed. This will further reduce the energy expended in the plant.

Table 3 presents the summary of the cost analysis of suggested options. The operating cost of option (i) is greater than that of “(ii)” because of the cost LPG used to replace hydrogen. All purge gases are re-routed to meet at a header before being channeled into the PSA for recovery. Profits from the options were evaluated with the assumption that the hydrogen from the optimized system will be a product from the refinery.

As shown in Table 3, the payback period for “(i)” is almost 3 years while that “(ii)” is less than 2½ years. However, there is a significant difference between their return on investment (ROI); 28.2% for “(i)” and 43.1% for “(ii)”.

**Table 3.** Summary of Cost Analysis

Options	(i)	(ii)
Operating Cost (₦/million-yr)	951.5678	11.0234
Cost of Investment (₦/million)	4241.73695	2530.446
Total cost(₦/million)	5193.30475	2541.4694
Profits (₦/million-yr)	1461.9282	1096.44615
Payback Period (yr)	2.901467	2.30786163
Return on Investment (%)	28.150249	43.142213

## 4. Conclusion

Hydrogen pinch violations do exist at Port Harcourt Refinery Company (PHRC) as revealed from the analysis done in this work. Therefore, there is a possibility for improvement and that the hydrogen pinch of the system exists between 0.74 for sink units and 0.7825 for source units. Reduction in the energy expended in the refinery is an indication that hydrogen pinch technology is an excellent tool for energy audit.

There will be an annual increase in the profit as well as the operating costs. However, there will be increase in marginal revenue as the profit is considerably greater than the operating costs.

The choice of option to be implemented is dependent on the factors beyond the scope of this research. It is however recommended that the infrastructure of option (i) should be put in place but option (ii) should be practiced. This will make operation of the unit to be flexible. Processing and management of hydrogen will then depend on cost and demand for energy at that period, all which is needed, is to reset the operating conditions appropriately. Implementation of the proposed options will reduce gas flaring which is the order of the day in the refinery. This implies that hydrogen management is also an environmental audit tool.

Although the adoption of these suggestions will increase the revenue of the refinery, the best advantage is that it will prepare the refinery for future challenge. As it was discussed earlier, it had been forecast that sulfur content will increase, and so this work will accommodate the envisaged future problem and help promote sustainability.

## Acknowledgements

We are indeed grateful to many people inside and outside the refining industry for their contributions and helpful ideas toward the success of this work. We express thanks to the Management of the Port Harcourt Refinery Company for the permission granted to collect the data from the appropriate process plants and also especially to Mr. Joshua, Mr. Pagbara, Mr Ibiam, Mrs. Onitsha and other members of staff of the Company. We would also like to thank the Director, Centre for Gas, Refining and Petrochemicals, University of Port Harcourt, Prof. Godwin Igwe for providing valuable ideas toward the realization of this project.

## Nomenclature

$F_i$	flow rate of component 'i' (Nm <sup>3</sup> /hr)
$V_i$	volume fraction of component 'i'
$C_{WK}$	Capital cost of compressor (\$)
$C_{SF}$	cost of surplus fuel (\$/Nm <sup>3</sup> /hr)
$C_{PSA}$	capital cost for PSA unit (\$)
$C_R$	cost of the recovery process (\$/kmol)
$C_W$	cost of compressor work per unit hydrogen recovered (\$/kmol)
$c_p$	gas average heat capacity (J/mol/K)
$P_1$	compressor inlet pressure
$P_2$	compressor outlet pressure
$T_1$	compressor gas inlet temperature (K)
$Q$	flow rate of hydrogen (kmol/hr)
$Y$	recovery yield of hydrogen
$z$	feed mole fraction of hydrogen
$\gamma$	ratio of gas specific heats

Data before pinch analysis

Flow Interval (Nm <sup>3</sup> /hr)	Source Purity (%vol.)	Demand Purity (%vol.)	Diff. in Purity (%vol.)	H <sub>2</sub> Surplus (Nm <sup>3</sup> /hr)	Cumm. H <sub>2</sub> Surplus	Max. Purity (%vol.)
0	0.955	0.872	0.083	0	0	0.955
95	0.955	0.872	0.083	7.885	7.885	0.955
95	0.8212	0.872	-0.0508	0	7.885	0.872
142	0.8212	0.872	-0.0508	-2.3876	5.4974	0.872
142	0.8212	0.7889	0.0323	0	5.4974	0.8212
129095	0.8212	0.7889	0.0323	4165.182	4170.679	0.8212
129095	0.74	0.7889	-0.0489	0	4170.679	0.7889
138142	0.74	0.7889	-0.0489	-442.398	3728.281	0.7889
138142	0.74	0.7825	-0.0425	0	3728.281	0.7825
158142	0.74	0.7825	-0.0425	-850	2878.281	0.7825
158142	0.74	0.71	0.03	0	2878.281	0.74
220262	0.74	0.71	0.03	1863.6	4741.881	0.74
220262	0.74	0	0.74	0	4741.881	0.74
264095	0.74	0	0.74	32436.42	37178.3	0.74
264095	0.7259	0	0.7259	0	37178.3	0.7259
276095	0.7259	0	0.7259	8710.8	45889.1	0.7259
276095	0	0	0	0	45889.1	0

Data after pinch analysis

Flow Interval (Nm <sup>3</sup> /hr)	Source Purity (%vol.)	Demand Purity (%vol.)	Diff. in Purity (%vol.)	H <sub>2</sub> Surplus (Nm <sup>3</sup> /hr)	Cumm. H <sub>2</sub> Surplus	Max. Purity (%vol.)
0	0.955	0.872	0.083	0	0	0.955
95	0.955	0.872	0.083	7.885	7.885	0.955
95	0.8212	0.872	-0.0508	0	7.885	0.872
142	0.8212	0.872	-0.0508	-2.3876	5.4974	0.872
142	0.8212	0.7889	0.0323	0	5.4974	0.8212
93648.19	0.8212	0.7889	0.0323	3020.25	3025.747	0.8212
93648.19	0.74	0.7889	-0.0489	0	3025.747	0.7889
138142	0.74	0.7889	-0.0489	-2175.75	850	0.7889
138142	0.74	0.7825	-0.0425	0	850	0.7825
158142	0.74	0.7825	-0.0425	-850	2.8E-05	0.7825
158142	0.74	0.71	0.03	0	2.8E-05	0.74
220262	0.74	0.71	0.03	1863.6	1863.6	0.74
220262	0.74	0	0.74	0	1863.6	0.74
228648.2	0.74	0	0.74	6205.788	8069.388	0.74
228648.2	0.7259	0	0.7259	0	8069.388	0.7259
240648.2	0.7259	0	0.7259	8710.8	16780.19	0.7259
240648.2	0	0	0	0	16780.19	0

$\eta$  isentropic efficiency of compressor

## Abbreviation

PHRC	Port Harcourt Refining Company
CRU	Catalytic Reforming Unit
KHU	Kerosene Hydrotreating Unit
NHU	Naphtha Hydrotreating Unit
CCR	Continuous Catalytic Regeneration
PSA	Pressure Swing Adsorption
FGS	Fuel Gas System
MUG	makeup gas
RG	recycle gas
PG	purge gas
Nm <sup>3</sup> /hr	m <sup>3</sup> /hr at 288.6K

## Appendix



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