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HP Special Report | Refining Developments

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Hydrogen perspectives for 21st century refineries

The growth market for transportation fuels is shifting from mature economies to developing and emerging nations, particularly in China and India. These developing regions, however, often suffer from limited domestic oil and gas availability, high energy costs, questionable power grid reliability, and potential water scarcity. Today, highly complex deep-conversion refineries face the challenging task of improving hydro-processing intensity and residue upgrading while processing increasingly lower-quality crudes under more stringent fuel specifications. Therefore, it is exceedingly important for 21st century refiners to manage hydrogen (H_2), power, water and carbon effectively and economically.

As refining market needs and trends continue to support increased demand for H_2, its availability and cost are increasingly critical for many refiners, creating a challenging environment for securing reliable, efficient and environmentally friendly H_2. Still, there are some proven solutions for reducing the net unit cost of (on-purpose) H_2, including advanced H_2 management, capacity revamps and over-the-fence H_2 supply, as well as some value-added options and case studies demonstrating ways to enhance refining economics.

CHANGING REFINERY LANDSCAPE

The unprecedented development of abundant unconventional gas reserves in the US and other regions of the world is expected to have a substantial impact on energy independence and security, as well as on the refining and petrochemical sector, at least in the US, in the coming decades. Projections of sustained low-priced natural gas (NG) and high-priced oil resulting in an "oil-gas price gap" support H_2 higher usage intensity via H_2 addition, rather than the carbon removal route.

Deeper hydroprocessing and bottom-of-the-barrel strategies are being implemented more extensively to increase the yield of premium clean-fuel slates via higher H_2 usage (scf/bbl). The economics of this approach are increasingly attractive when H_2 is generated from relatively cheaper feed gas and are further improved by applying various optimization options and smart concepts to lower the unit cost of H_2 (i.e., the combined capital, operating and maintenance cost for a unit of H_2, or UCH).

H_2 is, and will continue to be, an essential element for the refining industry, particularly in high-complexity deep-conversion refineries. H_2 constitutes a significant portion of refinery processing and operational costs, especially in high-growth economies. Consequently, there will continue to be strong incentives to lower the UCH while enhancing reliability to improve refinery profitability.

Despite its high operating and capital costs, H_2 is no longer just a critical utility for refinery operations; instead, it is gaining status as a valuable asset in the refining process.

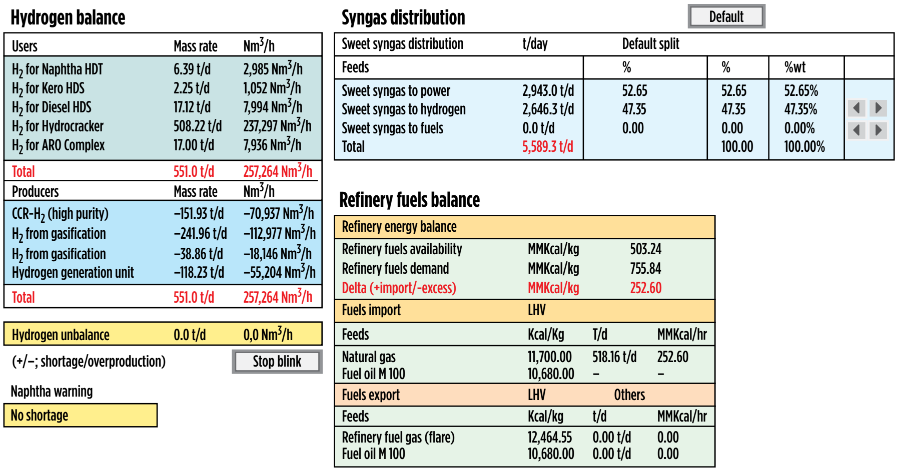
Several proven options can be used to reduce capital investment and to improve the thermal efficiency of both new and existing H_2 facilities. Such options include advanced H_2 management, along with the integrated utilization of refinery offgas (ROG), enhanced energy efficiency, increased economies of scale, augmentation of existing H_2 capacity, and strategic over-the-fence (third-party) H_2 supply. Furthermore, most of these options provide added benefits of improved availability and reduced environmental impact.

ADVANCED HYDROGEN MANAGEMENT

H_2 is typically supplied and balanced in a refinery through a network fed by H_2 recovered from offgas streams and mostly supplemented by on-purpose H_2 generation sources. Creative solutions are being developed to enhance refining profitability not only through optimized process integration, but also through advanced and smart H_2 management methodologies to optimize refinery H_2 networks. The traditional H_2 pinch analysis (HPA) technique is not sufficient to model the complexities and optimize a network design, especially in terms of realistic capital expenditure (CAPEX), operational and health, safety, and environment (HSE) constraints.

One such advanced refinery H_2 management methodology, which is based on linear programming (LP) using platform independent models (PIMs) . Such software carries various process and utility models for rigorous simulation and reconciliation to identify an optimized overall H_2 balance and its network. It uses a real-life cost database, scaling indices and various objective functions for economic analysis and case assessment for grassroots refineries as well as upgrading or expansion of existing refineries (**FIG. 1**). It conducts sensitivity analysis for optimizing the level of H_2 recovery from ROG and, additionally, can recommend the appropriate steam-power system along with the overall CO_2 footprint based on a refinery-wide energy philosophy without compromising on safety, reliability and operational flexibility.

Case study. Advanced refinery H_2 management methodology was applied to identify an optimized master plan for a large grassroots deep-conversion refinery processing high-sulfur crude. It was also applied to establish an optimum level of H_2 recovery based on the trade-off between the investment in the



Hydrogen balance

Users	Mass rate	Nm^3/h
H_2 for Naphtha HDT	6.39 t/d	2,985 Nm^3/h
H_2 for Kero HDS	2.25 t/d	1,052 Nm^3/h
H_2 for Diesel HDS	17.12 t/d	7,994 Nm^3/h
H_2 for Hydrocracker	508.22 t/d	237,297 Nm^3/h
H_2 for ARO Complex	17.00 t/d	7,936 Nm^3/h
Total	551.0 t/d	257,264 Nm^3/h
Producers	**Mass rate**	**Nm^3/h**
CCR-H_2 (high purity)	–151.93 t/d	–70,937 Nm^3/h
H_2 from gasification	–241.96 t/d	–112,977 Nm^3/h
H_2 from gasification	–38.86 t/d	–18,146 Nm^3/h
Hydrogen generation unit	–118.23 t/d	–55,204 Nm^3/h
Total	551.0 t/d	257,264 Nm^3/h

Hydrogen unbalance	0.0 t/d	0,0 Nm^3/h

(+/–; shortage/overproduction)

Naphtha warning

No shortage

Syngas distribution

Sweet syngas distribution	t/day	Default split			
Feeds		%	%	%wt	
Sweet syngas to power	2,943.0 t/d	52.65	52.65	52.65%	
Sweet syngas to hydrogen	2,646.3 t/d	47.35	47.35	47.35%	◀ ▶
Sweet syngas to fuels	0.0 t/d	0.00	0.00	0.00%	◀ ▶
Total	5,589.3 t/d		100.00	100.00%	

Refinery fuels balance

Refinery energy balance			
Refinery fuels availability	MMKcal/kg	503.24	
Refinery fuels demand	MMKcal/kg	755.84	
Delta (+import/-excess)	MMKcal/kg	252.60	
Fuels import	**LHV**		
Feeds	Kcal/Kg	T/d	MMKcal/hr
Natural gas	11,700.00	518.16 t/d	252.60
Fuel oil M 100	10,680.00	–	–
Fuels export	**LHV**	**Others**	
Feeds	Kcal/kg	t/d	MMKcal/hr
Refinery fuel gas (flare)	12,464.55	0.00 t/d	0.00
Fuel oil M 100	10,680.00	0.00 t/d	0.00

FIG. 1. Select optimized H_2 network case output display.

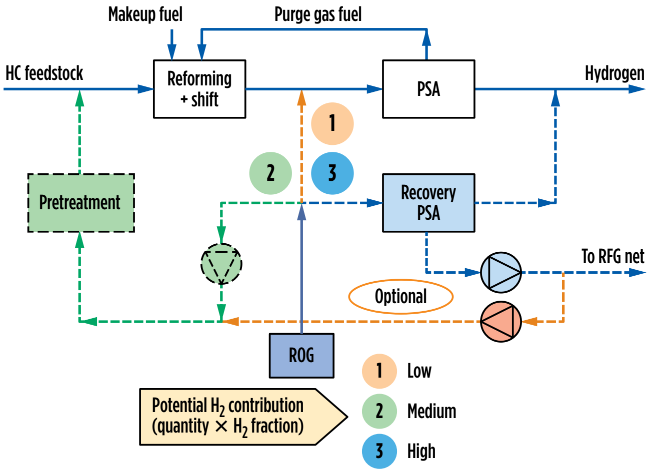


FIG. 2. Routes for ROG integration with H_2 plant.

TABLE 1. ROG integration as SMR feed (45 MMscfd H_2)

	Case 1 ROG as partial feed	Case 2 NG feed only
Operating cost savings[1], US\$/hr	188	Base
Additional investment[2], MM, \$	4.1	Base
Payout, years	2.5	Base

[1] Pricing data: ROG: 260 \$/t (avg. 40 vol% H_2); natural gas: 180 \$/t; steam: 8 \$/t; and power: 60 \$/MW

[2] For compression and pretreatment

pressure swing adsorption (PSA) recovery system and the potential savings from recovered H_2.

Based on the optimized H_2 network configuration and the objective function, the program identified the most cost-effective H_2 recovery level of about 68%, beyond which it was not economical in terms of incremental capital payoff against extra H_2 recovery credit. The integrated H_2 network, with dual purity headers and minimized losses, resulted in lowering the on-purpose H_2 generation capacity by 30% compared to the base case without the advanced refinery H_2 management methodology. The program also conducted the overall fuel-steam-power balance together with CO_2 loads and related C-efficiency while satisfying captive power needs and minimized unit cost of H_2.

REFINERY OFFGAS INTEGRATION

To capture their full potential, there has been an increasing trend to use ROG for on-purpose H_2 generation. The underlying driver is that H_2 burned as fuel is a loss of its "asset" value above its heating value. Accordingly, by integrating ROG in a H_2 generation plant, not only does most of its H_2 content get recovered, but the price attached to the ROG is often lower than that of hydrocarbon feedstocks for H_2 production.

There are enough financial incentives to identify potential ROG streams in the refinery that can be integrated cost-effectively with the H_2 plant to enhance its economics. Utilization of ROG through integration with the H_2 plant can be mostly accomplished by three routes (**FIG. 2**):

- **Low contribution**—H_2 recovery by mixing with the process gas upstream of the H_2 generation PSA
- **Medium contribution**—Direct use as (part) feedstock for H_2 generation
- **High contribution**—Dedicated recovery PSA with optional extended integration of its purge gas as (part) feed for H_2 generation.

The typical reduction in net H_2 costs can be between 2% and 10% depending upon the relative pricing of ROG vs. the base feed, available quantity of ROG stream(s), H_2 (or hydrocarbon) fraction, available pressure and level of impurities.

To illustrate this concept, a case study was undertaken using ROG (with 40 vol% H_2) as the primary feed for H_2 generation based on medium level contribution. Comparative economics are presented in **TABLE 1.** Though ROG pricing was similar to NG in terms of its heating value basis, the operating cost benefit from the potential H_2 contribution was substantial (approximately 7%). The payout of the additional investment was less than three years, without downsizing the reformer and downstream section, which were still sized for NG feed as the controlling design case.

If NG compression was required, the payout for ROG integration would have been even shorter. Other inherent benefits of operating with a ROG feed mix included relaxation on recycle H_2, easier startup and longer reformer tube life. Various ROG integration schemes have been implemented and proven, ultimately providing better refinery margins.

ENHANCED ENERGY EFFICIENCY AND DESIGN OPTIMIZATION

On-purpose H_2 generation plants are capital intensive due to high-temperature catalytic processing and necessary gas-phase purification. The total investment can vary considerably depending upon site-specific factors such as location, feedstock, export steam conditions, degree of utility integration and reliability needs.

TABLE 2. H_2 flowsheet initial optimization guidelines based on relative price ratios

	Higher reformer outlet temperature, > 1,600° F	Lower steam/carbon ratio, < 2.8	Level of CO conversion, > high temperature shift	Enhanced PSA H_2 recovery, > 86%–89%
OPEX				
Feed/fuel price	> 1.1	<= 1.0	> 1.2*	> 1.1
Steam/fuel price	> 1.0	> 0.9	> 1.2	N/A
Steam/feed price	N/A	>1.2	N/A	N/A
CAPEX	>>	<	> Medium temperature shift >> Low temperature shift	>

* Relevant for steam/carbon ratios > 2.7

The energy-related costs become more important for optimizing larger H_2 plant designs and for lowering the hydrogen unit cost (UCH). Accordingly, it allows higher incremental capital investment payoffs for applying enhanced and advanced heat recovery below the heat pinch by extending the so-called "cold composite," as shown in **FIG. 3.**

A typical H_2 plant energy balance is illustrated in **FIG. 4.** The main thrust for improving the thermal efficiency lies in reducing eventual heat loss through the flue gas to stack and through process cooling to cold utility (air or cooling water).

Energy efficiency optimization based on operating expenses (OPEX)/CAPEX evaluations depends upon the H_2 generation unit (HGU) capacity and related steam reformer (SMR) size. It is further sensitive to whether application of pre-reforming is required (for feed flexibility) or is optional.

Based on case-specific data, a sensitivity analysis was conducted for key variables such as feed/fuel price ratio and fuel/steam price ratio to optimize OPEX against incremental CAPEX investment while keeping overall economics within the given evaluation criteria. The results, presented in **TABLE 2,** can be summarized as follows:

1. When feed is more expensive than fuel, which is often the case with liquid feeds, it calls for higher feed conversion and H_2 yields by increasing SMR outlet temperature and/or increasing the steam/carbon (S/C) ratio, extended shift conversion level and higher PSA recovery in order to lower the OPEX. For CAPEX, however, it increases appreciably when raising the SMR outlet temperature beyond a certain level (chosen as 1,600°F for the study). It may be more economic if steam credit is high relative to fuel value in view of reduced radiant efficiency.
2. When feed and fuel are similarly priced, increasing reforming severity in terms of lower S/C ratios and higher SMR outlet temperatures can improve OPEX, but CAPEX must be carefully considered. To lower S/C ratios below 2.7, a medium temperature (MT) shift is necessary, since HT shift is restricted due to concerns of over-reduction. CAPEX can be slightly reduced with lower S/C ratios based on reduced heat recovery load downstream of the reformer. Having higher credit for export steam further supports lowering of S/C ratios.
3. Additional CAPEX is necessary to increase PSA recovery beyond 86%–89%, and therefore should be evaluated on a case-to-case basis: The economics get favorable when feed is more expensive than fuel.

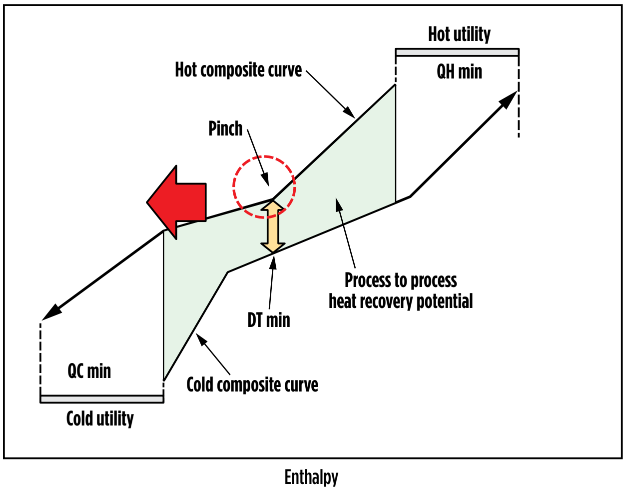


FIG. 3. Enhanced heat recovery below pinch.

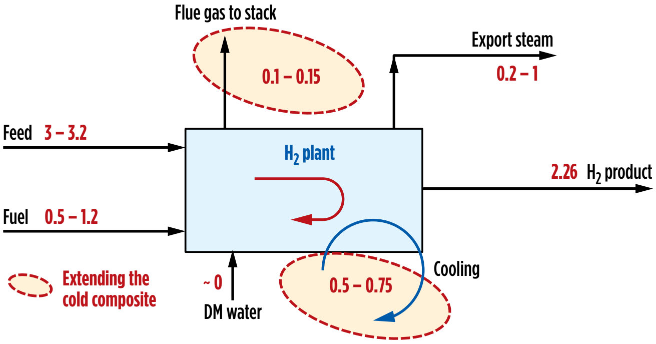


FIG. 4. Energy balance of a H_2 plant, where 1 Gcal/kNm^3 = 104.31 Btu/scf.

HIGHER ECONOMIES OF SCALE

For larger H_2 plants, variable costs linked to specific energy consumption costs tend to govern the unit cost of H_2. **TABLE 3** provides an overview of the sensitivity of variable and fixed costs to plant capacity. The unit cost of H_2 (UCH) is the sum of variable and fixed costs.

A 1% reduction in energy costs in a 100-MMscfd H_2 plant can result in approximately $750,000 savings per year based on $5/MMBtu natural gas. For larger H_2 plants, the focus is more on efficiency optimization and there is a bigger incentive for incremental investment in terms of extended heat recovery and flowsheet optimization based on a typical payback period of two to four years.

While CAPEX is relatively less critical for larger plants, its reduction becomes vital for lowering the UCH. The UCH produced by a single-train large-capacity H_2 plant can be appreciably lowered by economies of scale. **FIG. 5** illustrates the UCH reduction from a 50 MMscfd to a 200 MMscfd H_2 plant based on US Gulf Coast economics with $5/MMBtu NG price. For higher energy pricing, as observed in Europe and Asia, the benefits of economy of scale continue to hold true.

Though economies of scale favor larger plants, there is a capacity limit above which a single train plant starts becoming cumbersome and requires detailed evaluation to establish the breakpoint for two or more trains. Physical size, weight and transportable limits on the equipment, valves and piping, and construction facilities must be considered. Such limits have progressively increased from 100 MMscfd up to a recent project size of 220 MMscfd H_2 based upon compacting equipment, advanced equipment design, piping modeling and modular construction concepts.

CAPACITY REVAMP OF EXISTING H_2 PLANTS

Refiners are often faced with a H_2 shortfall when addressing changes in crude mix against the market-based clean fuels product slate. Such variations can be large enough to impact overall operation, H_2 balance, and refinery profitability, but may not be large enough to justify a new dedicated H_2 plant.

Achieving additional H_2 by revamping existing plants can be an attractive alternative with lower UCH through cost-effective retrofitting. Actual economics will depend upon the degree of uprate, available design margins, the condition of existing equipment and the level of modifications required. Normally, a capacity revamp not only provides additional H_2 at lower cost, but also offers the benefits of shorter time schedules because of already existing interfacing-facilities/offsites, and can also provide feedstock change or flexibility, improved efficiency and environmental performance.

TABLE 3. H_2 generation cost split

Capacity MMscfd	Small < 15	Medium 15-60	Large > 60
% Variable costs	40–60	50–70	60–80
% Fixed costs	40–60	30–50	20–40

TABLE 4. H_2 plant capacity revamp

Option	Typical incremental H_2, %[1]	Level of investment[2]
Reformer upgrade	5–15	Medium
Regenerative reformer integration	15–30	Medium–High

[1] Typical additional H_2 between 2 MMscfd and 25 MMscfd

[2] Based on the typical range of $0.5–$2 MM per MMscfd H_2 depending upon % increase and design-specific factors

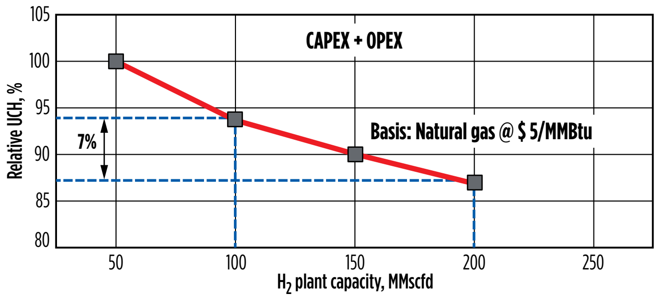


FIG. 5. Economy of scale for H_2 generation plant.

There are various proven options to cost-effectively augment H_2 capacity up to 30%; in each case, however, bottlenecks must be identified and a proper assessment conducted to select the most appropriate option.

If the target capacity increase is substantial (> 15%) with major limitations on the reforming section, an effective solution without overloading the reformer is regenerative reforming. The underlying concept is to use the reformed gas' high-level heat to reform additional feed through convective heat exchange, also known as post-reforming. This option also provides a 10%–15% reduction in CO_2, NO_x and SO_x emission levels per unit of H_2.

With additional H_2 capacity range between 2 MMscfd and 25 MMscfd, a regenerative reforming retrofit investment largely depends upon the percent increase in H_2 capacity, design conditions, available design margins and the level of modifications required in the existing plant. Generally, when compared with a new H_2 plant for the same additional capacity, together with the necessary offsite/utilities and auxiliaries, such investments can be economically attractive, as shown in **TABLE 4.**

RELIABLE H_2 OUTSOURCING

H_2 is the lifeblood of modern refineries and is essential to the production of cleaner-burning transportation fuels. When refiners need H_2, they typically have two choices: buy a H_2 plant design license; pay other parties to build the plant; and then own, operate, and maintain the plant themselves (known as the make case) or purchase the H_2 requirements from a third party (known as the buy case, sale of gas model or over-the-fence supply).

In the buy case, an industrial gas company designs and builds the H_2 plant with its capital and supplies H_2 directly to the customer over the course of a long-term contract. The buy case has advantages that the refiner can benefit from: the gas company uses its H_2 experience for the refiner, enabling the refiner to focus on its core refining business; assumes responsibility for operational and maintenance activities; and can provide guaranteed on-stream reliability, availability, and efficiency levels.

Another way to secure high reliability of H_2 supply is to obtain H_2 from a H_2 pipeline. Pipeline supply can provide high reliability and, often, the lowest UCH due to economies of scale.

The various solutions described previously are all able to satisfy the focal objective of lowering the net UCH. These options enhance reliability and HSE compliance while providing refiners with improved economics and margins. It is imperative to the success of 21st century refiners that they manage hydrogen efficiently and diligently. **HP**

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