There is a growing focus in the refining industry on hydrogen capacity. Hydrogen is generally required for sulfur removal and quality improvement of hydrocarbon products. As sulfur restrictions on gasoline and diesel become increasingly stringent, the refining demand for hydrogen continues to grow.

By evaluating the hydrogen utilisation in their facilities, refiners are realising that they need additional hydrogen supply. There are a number of options available to address this need. Refiners may be able to meet the increased demand by improving the operations of their existing hydrogen plants. They may choose to separate hydrogen from waste or offgas streams or even purchase hydrogen from third parties. As an alternative, after careful technical and economic evaluation, they may conclude that the most cost effective solution over the longer term is to build a new hydrogen plant.

In recent years, substantial advancements in hydrogen plant technology have significantly improved overall life cycle costs. Based on experience with hydrogen plant benchmarking, it has become clear that the optimum economic solution in some cases may be to replace an existing hydrogen plant with a new modern hydrogen plant.

**Hydrogen plant technology**

Old style

Many refiners are still operating hydrogen plants that were designed and built 20 or more years ago. These older plants...
There are a number of options available to refiners to meet the increase in hydrogen demand. Before proceeding, refiners should conduct a comprehensive technical and economic evaluation of their existing operations and evaluate the benefits of the options available to them. The option that provides the optimum economic and operational benefits will be different for each situation and will depend on such things as the existing steam balance, the cost and availability of utilities, plot limitations, and the condition of existing hydrogen plants.

The first option for refiners who are operating old style hydrogen plants is to consider ways to increase the capacity of these plants. Following an evaluation of the condition and efficiency of the existing plant, they may be able to effectively increase the capacity by either operating with tighter control or selectively upgrading portions of the old plant.

In many refineries, hydrogen is treated as a utility. There may not be much of a focus on the details of the actual production and the plants are sometimes operated ‘loose.’ In this case, simple operational changes could significantly increase production and efficiency. Refiners could also debottleneck an existing hydrogen plant by revamping or upgrading portions of it. Debottlenecking options can also have a positive efficiency impact. Some of these potential upgrades may include:

- Replacing reformer tubes with upgraded metallurgy and thinner walls will allow for more throughput and a higher heat flux, which would increase capacity.
- Adding a pre-reformer unloads the primary reformer so capacity can be increased.
- Adding a secondary reformer increases methane conversion, which increases capacity.
- Adding combustion air preheat lowers the fuel requirement and potentially unloads the waste heat recovery unit and fluegas fan, resulting in a capacity increase.
- Upgrading the CO₂ removal unit can minimise hydrogen loss in the methanator, resulting in a potential capacity increase.
- Adding a PSA unit decreases hydrogen production, but would typically produce more cost effective and higher purity hydrogen.

A second option is to separate hydrogen from a waste stream or an offgas stream that is currently being sent to fuel. This typically requires adding separation equipment and possibly some compression. In addition, separating hydrogen out of the fuel system will usually result in additional makeup fuel. This could change the heating value of the refinery fuel system and possibly have an impact on other fuel burning equipment. A third option is to buy hydrogen from a third party. Various industrial gas suppliers are willing to sell hydrogen to refiners either by pipeline or, depending on location, by a stand-alone plant. This option requires a minimal capital investment by the refiner but the delivered hydrogen is generally more expensive per unit than if self produced.

The last option is to build a new hydrogen plant. Building a modern hydrogen plant is typically the most capital intensive of the options available. However, the capital investment could pay off if there is a significant gain in efficiency. Below the typical overall production cost of hydrogen between a modern and an old style hydrogen plant is analysed and compared.

Overall hydrogen production cost
The most significant economic factor in evaluating options to increase hydrogen capacity is the overall cost of producing hydrogen. The overall production cost can be estimated over the life of the hydrogen plant by using the different cost parameters of constructing, operating, and maintaining the hydrogen plant. This overall production cost reflects a complete picture of the hydrogen plant economics over the life of the plant.

The efficiency of producing hydrogen and byproducts is
very important in minimising the production cost of hydrogen. Utility costs are the major operating cost in hydrogen production. Utilities typically include usage of feed, fuel, boiler feed water, power, cooling water, and generation of export steam (steam is typically a by product of the hydrogen production process). Of these, feed and fuel make up the largest portion of the utility costs. In addition, the credit for export steam can have a significant impact on utility costs, especially when refinery utility costs are favourable for steam production. The remainder of the utilities combined generally makes up less than 10% of the total operating cost.

These utility costs, together with other economic parameters applicable to the plant being evaluated, can be incorporated into a cash flow model, and the overall production costs of hydrogen can then be evaluated. The other economic parameters include such things as capital cost, startup cost, other operating costs (including catalyst replacement and tube replacement), and maintenance costs. From this model, the internal rate of return (IRR), net present value at various rates of return (NPV), net cash flow, and a generated income statement can also be developed.

**Overall production costs comparisons**

Building a new hydrogen plant is typically not the most appealing alternative to refiners. A new hydrogen plant requires a significant capital investment, and although hydrogen is required to support many of the refinery unit operations, it is generally not viewed as a direct ‘money maker.’ However, once all factors are taken into account and a total production cost of hydrogen over the life of the plant is determined, the best economic solution may be replacing an old style hydrogen plant with a new modern hydrogen plant. The following evaluation illustrates this potential.

**Evaluation basis**

To demonstrate the economics of building a modern hydrogen plant versus continuing to operate an old style plant, two representative plants, each producing 90 MMSCFD of contained hydrogen from a natural gas feed, will be compared, ‘standard’ refers to conditions of 60 °F and 14.7 psig. Natural gas will also be used for fuel, and both plants will export 600 psig superheated steam. The old style plant will consist of the major processing units described above and will produce hydrogen with a purity of 95%. Other parameters for the old style plant will be based on typical observed values. The modern plant will consist of the major processing units described above and will produce hydrogen with a purity of 99.99%. The modern plant design will be based on producing maximum export steam.

This evaluation could be done based on a variety of other plant configurations, but for demonstration purposes, this evaluation is limited to the plant types described. For comparison purposes, the cost of utilities will be based on the following:
- Natural gas: US$ 4 per million Btu LHV.
- HP steam: US$ 5 per 1000 lbs.
- Boiler feedwater: US$ 0.5 per 1000 lbs.
- Power: US$ 0.05 per kWh.
- Cooling water: US$ 0.1 per 1000 gal.

**Utilities**

As previously discussed, the utility costs of a hydrogen plant are among the most important economic factors in determining the overall production cost of hydrogen. Simulation models are used for both the old style and modern plants to calculate utility costs. The old style plant utilities are based on a simulation model built to reflect typical plant performance. The modern plant utilities are based on a simulation model for the
design of a typical new plant. Table 1 shows the utilities and utility cost of hydrogen for each plant.

Table 1. Total utility cost of hydrogen

<table>
<thead>
<tr>
<th>Utilities per 1000 ft³ of contained hydrogen</th>
<th>Old style</th>
<th>Modern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas feed, million Btu LHV</td>
<td>0.275</td>
<td>0.317</td>
</tr>
<tr>
<td>Natural gas feed, million Btu LHV</td>
<td>0.2</td>
<td>0.196</td>
</tr>
<tr>
<td>Total feed + fuel, million Btu LHV</td>
<td>0.475</td>
<td>0.443</td>
</tr>
<tr>
<td>HP export steam, lbs</td>
<td>20</td>
<td>90</td>
</tr>
<tr>
<td>Boiler feedwater, lbs</td>
<td>45</td>
<td>120</td>
</tr>
<tr>
<td>Power, kWh</td>
<td>0.66</td>
<td>0.52</td>
</tr>
<tr>
<td>Cooling water, gal.</td>
<td>0.530</td>
<td>8</td>
</tr>
</tbody>
</table>

**Utility costs**

- Natural gas feed @ US$ 4/million Btu LHV 1.1
- Natural gas fuel @ US$ 4/million Btu LHV 0.8
- Total feed + fuel @ US$ 4/million Btu LHV 1.9
- HP export steam @ US$ 5/1000 lbs -0.1
- Boiler feedwater @ US$ 0.5/1000 lbs 0.023
- Power @ US$ 0.05/kWh 0.033
- Cooling water @ US$ 0.1/1000 gal. 0.053
- Total utility cost, US$ 1.908

**Overall production cost of hydrogen**

Table 2. Overall production cost of hydrogen

<table>
<thead>
<tr>
<th>Plant capacity, MMSCFD (contained)</th>
<th>Old style</th>
<th>Modern</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Capital cost, million US$</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average Hz production cost, US$ per 1000 standard ft³</th>
<th>Old style</th>
<th>Modern</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.996</td>
<td>1.605</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Average Hz production cost, US$ million per year</th>
<th>Old style</th>
<th>Modern</th>
</tr>
</thead>
<tbody>
<tr>
<td>65.6</td>
<td>52.6</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Average annual production cost savings, US$ million</th>
<th>Old style</th>
<th>Modern</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>12.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Calculation of the ‘life of the plant’ economics

A cash flow economic model can be generated using the utility costs developed for each plant, the capital cost required for the modern plant, as well as a number of other economic factors. These other economic factors, along with their associated values, are listed below:
- New plant construction length: two years.
- Escalation rate 1.5% for all feed, product and utilities.
- Labour: two operators per shift.
- Overhead: 50% of labour.
- Maintenance: 2% of plant cost per year.
- Miscellaneous: 1% of plant cost per year.
- Catalyst costs accrued in year of change out.
- Reformer tube replacement: every 10 years.
- Onstream time: 98.5%.
- Working capital: 45 days.

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The cost of feed and fuel is typically the largest component of the overall production cost of hydrogen. Feed and fuel usually account for more than 80% of the total before the steam credit is taken. The overall operating cost changes significantly as the natural gas price varies. Figure 4 shows the effect of varying the natural gas price. For this evaluation, the export steam credit to natural gas price ratio was held constant.

As the price of natural gas increases, the modern plant becomes more favourable. This is due to the overall feed and fuel efficiency advantage of the modern plant. For example, if the natural gas price were changed from US$ 4 to US$ 8 per million Btu (double the base case credit), the overall production cost would increase by US$ 1.326 per 1000 standard ft³ of hydrogen for the modern plant and US$ 1.804 for the old style plant. The higher natural gas price would increase the average annual savings for the modern plant from US$ 12.9 million to US$ 28.6 million.

Export steam credit
The export steam credit also has a significant effect on the overall production cost. The value a refinery places on steam depends on utility factors and the existing steam balance in the refinery. For example, during the winter, steam tracing is generally used more heavily and the value of steam could be higher than average. Conversely, in the summer, when less steam tracing may be utilised, steam may have a lower than average value. Modern hydrogen plants typically export much more steam due to the fact that they are more efficient and do not have a CO₂ removal regeneration requirement. Figure 5 shows the effect of varying the export steam credit.

As the export steam credit increases, the economics for the modern plant become more favourable. For example, if the export steam credit were changed from US$ 5 to US$ 10 per 1000 lbs (double the base case credit), the overall production cost would drop by US$ 0.45 per 1000 ft³ of hydrogen for the modern plant and US$ 0.1 for the old style plant. The higher steam credit would increase the average annual savings for the modern plant from US$ 12.9 million to US$ 24.4 million. For this evaluation, the price of natural gas stays the same.

Conclusion
Refiners have a number of different options to consider in addressing the demand for additional hydrogen. With the cost of utilities and particularly natural gas on the rise, overall plant efficiency has become a key factor in defining the economics of what option to pursue. A comprehensive technical and economic evaluation of existing operations is required to determine the optimum solution for each specific application.

The optimum solution for each refinery will be different and will depend on such things as the refinery steam balance, the cost and availability of utilities, plot limitations, and the condition of any existing hydrogen plants. Today’s modern hydrogen plants take advantage of numerous technological improvements and offer a much lower overall life cycle cost. Once technical and economic evaluations are done, it should not be a surprise to anyone that the most economically attractive and feasible approach may be to build a new hydrogen plant.

Sensitivity to economic variables
Economic parameters for each refinery are different. The major parameters that can significantly alter these results are the efficiency of the existing plant, the feed and fuel price, and the export steam credit. The efficiency of the existing plant can span a wide range and should be assessed for each plant independently. For the remaining evaluations, the old style and modern plant utilities will be held constant. The overall production cost of hydrogen will be analysed as a function of the other two major factors, feed and fuel price and export steam credit.

Feed and fuel price
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