Preliminary Performance Comparisons of Hydrogen Production by Auto-Thermal Reforming and Steam Methane Reforming of Natural Gas with Low CO_2 Emissions – Preliminary Estimates of Cost of H_2 from Auto-Thermal Reforming

Memorandum from Hensley Energy Consulting
to Clean Air Task Force

July, 2021

Introduction

At the request of CATF, Hensley reviewed selected published studies production of merchant hydrogen for use in industrial, power, transportation, and domestic markets. Throughout the industrialized world natural gas (NG) is used now to manufacture hydrogen primarily for use in the petroleum refining and petrochemical industry to produce transport fuels, ammonia, methanol, and other petrochemicals. These technologies can be easily adapted and applied to “fit for purpose” merchant hydrogen production.

Until recently, these NG based hydrogen plants reject the carbon contained in the NG to the atmosphere as carbon dioxide (CO_2) produced by burning process “tail gas” and additional NG. With growing demands to reduce global warming, there is significant new efforts by industry and government to produce hydrogen fuels without releasing CO_2 to the atmosphere. If such plants are to be constructed to support a new “hydrogen economy”, then the captured CO_2 must be sequestered or converted to beneficial uses that do not release CO_2 to the atmosphere. Geologic sequestration and beneficial use of CO_2 in enhanced oil recovery is being practiced today. Recycling of waste CO_2 to synfuels or chemicals is possible but not yet commercially practiced. This memo does not address the sequestration and beneficial uses of captured CO_2.

This memo focuses on NG based technologies that are demonstrated at commercial scale either as individual unit operations or fully integrated systems. Those technologies include non-catalytic partial oxidation (POX), catalytic steam methane reforming (SMR), and catalytic autothermal reforming (ATR). SMR is widely practiced in the refining industry worldwide and is most studied of the 3 options. SMR reacts methane and other light hydrocarbons with steam to produce carbon monoxide (CO) and hydrogen (H_2). The reaction is accelerated using solid catalyst. This process is “endothermic” and substantial heat is required to carry out the chemical transformation of methane (CH_4) to H_2. Hydrogen atoms in the water (as steam) used for reforming also provides a significant amount of the H_2 that is produced as product. Today’s reformers supply heat by combusting NG and unconverted “tail gas”. The steam required for reforming is supplied internally from waste heat recovery inside the reformer furnace. The reformer furnace is the primary source of CO_2 emissions.

SMR Process

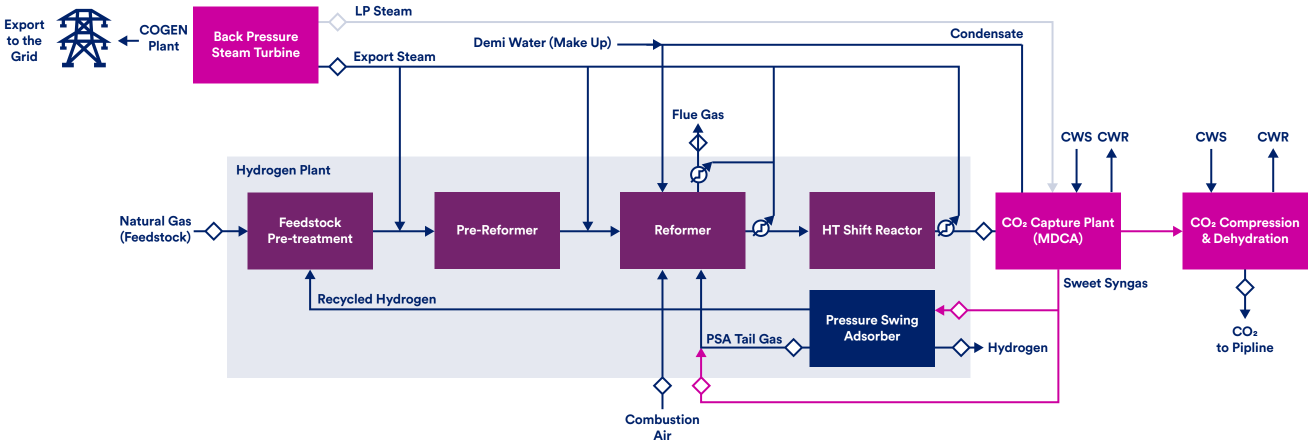
The SMR process uses a fixed bed catalytic reactor inside a "furnace" radiantly heated by burning NG and byproduct "tail gas". The catalyst forces the reaction to chemical equilibrium. High temperatures (800-900 deg C) favor conversion of methane to H_2. However, the temperatures are limited to avoid damaging the catalyst. At these conditions, methane is unavoidably left unreacted in a stream of hot "syngas" (CO and H_2). More steam is used to catalytically "shift" the CO and steam to CO_2 and additional H_2. This "water gas shift" reaction is exothermic and heat is removed by generating additional steam. This process is limited by chemical equilibrium and some CO is left in the "tail gas" with unconverted methane. The shifted syngas is separated into 99.9% pure H_2 using "pressure swing adsorption" (PSA) and the carbon gases are rejected as "tail gas". The rejected "tail gas" burned along with fresh NG to fire the reformer furnace. This is the primary source of CO_2 emissions in a SMR plant.

Existing SMR plants are optimized for economics, not carbon capture. High temperature shift is used to convert CO and steam to CO_2 and H_2. Only a partial shift is needed to produce high purity H_2 and CO is used for fuel gas. The emissions of CO_2 can be reduced by adding an "acid gas" recovery unit upstream of the PSA to remove "process" CO_2. Residual CH_4, CO_2, CO and H_2 not captured ends up in the tail gas as "combustion" CO_2 in the flue gas. There has been at least one existing SMR retrofitted to recover "process" CO_2 for sequestration. Typically, this amounts to 50-60% of the CO_2 that would otherwise end up in the reformer flue gas.

One of the more detailed studies of SMR carbon capture options is the IEA Technical Report 2017-02. The two highest carbon capture options are Case 1B and Case 3. Case 1B BFD I shown as Figure 1. It achieves about 66% capture of the carbon contained in the NG feed. This is achieved by removing the "process CO_2" down stream of the "shift unit" using widely proven amine absorption system. To further reduce CO_2 emissions shifted H_2 rich gas is burned in the reformer furnace to replace the NG fuel. Current reformer technology limits the amount of H_2 burned in the furnace.

Figure 1: SMR with Syngas CO_2 Capture

Source: IEAGHG Technical Report 2017-02 2/2017

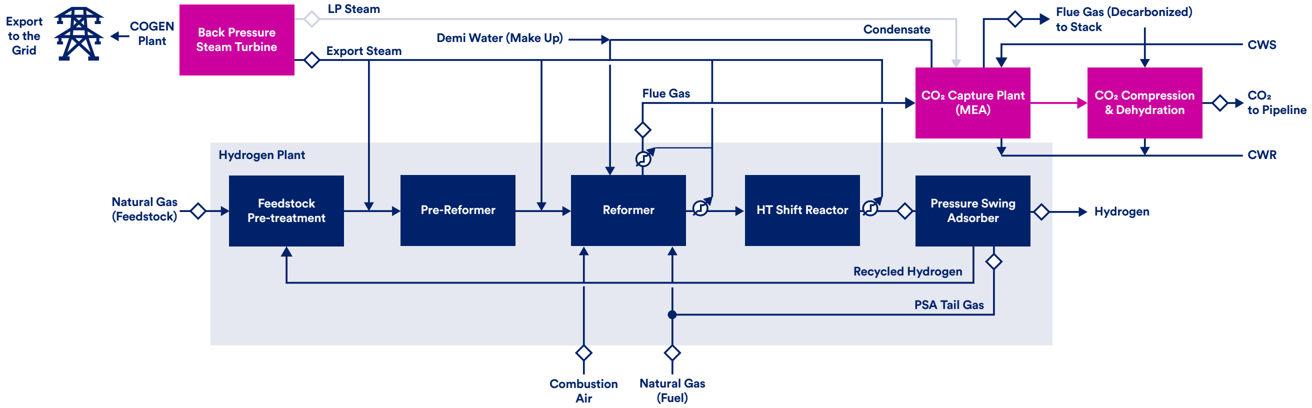


To achieve the highest carbon capture level (about 90%), the conventional SMR process remains and all the carbon leaving the system is in the reformer flue gas. A post combustion version of the amine system is used to remove the flue gas CO_2. The BFD for Case 3 is shown in Figure 2.

As concerns over global warming have grown, there have been many efforts to "redesign" the SMR process and optimize for minimum release of CO_2. Many private companies and government research labs are working on new technology to reduce the combustion of carbon in the system, including novel CO_2 separation technologies, membrane reformers, reformer furnaces designed for H_2 rich fuels, electrically heated reformers, and many other ideas. All of these require more laboratory and pilot plant testing before being applied on a commercial scale. In this memo, we are focused on proven technologies that could be applied today.

Figure 2: SMR with Reformer Flue Gas Capture

Source: IEAGHG Technical Report 2017-02 2/2017



Existing SMR Plants Retrofitted with Carbon Capture

There are two notable projects that retrofitted refinery SMR plants for carbon capture. The Shell Canada "Quest" project and the Air Products SMR Retrofit project at Port Arthur, TX. Each of these projects have extensive reports available to the public.

The "Shell Quest" project in Canada was constructed to retrofit 3 existing SMR plants with carbon capture equipment. Funded by the Canadian and provincial governments, detailed data on the project has been made public. These retrofits were designed to produce CO_2 for geologic sequestration. The project has been operating successfully. The retrofits are designed to process NG and refinery byproduct H_2 mixed gas. The amine solvent system captures about 80-85% of the CO_2 in the shifted syngas. By burning some product H_2 in the furnace along with tail gas, overall capture rates as high as 60% have been demonstrated. The project demonstrates that retrofitting existing commercial scale SMRs is feasible and long-term operations are reliable.

The Air Products Port Arthur retrofit of an existing refinery SMR plant has also been successful. It focused on demonstrating the Vacuum Pressure Swing Absorption technology. This plant captures about 90% of the "process" CO_2 in the syngas stream but does not capture CO_2 in the reformer flue gas. The overall capture rate is estimated to be approximately 50%. The project also demonstrates sequestration of CO_2 in oil reservoirs where the CO_2 assists recovery of additional oil.

Based on commercially proven technology, our review of the literature and independent analysis indicates that new SMR based hydrogen plants can be designed today to capture up to about 50 to 60% of the carbon fed to the plant by treating the high-pressure syngas stream using proven amine scrubbing technology. If a H_2 rich syngas stream is used for part of reformer fuel, higher carbon capture rates may be possible with some modifications to the furnace design. 90% or more CO_2 can be captured if the reformer flue gas is treated with post combustion amine scrubbing technology. Independent analyses such as the IEA Study indicate that "post-combustion capture" pathway may be less economical overall.

Some of the published studies on this topic are listed in the reference list attached to this memo.

ATR Process

Autothermal Reforming (ATR) was developed by the industrial gas industry to improve on the performance and economics of SMR technology. The focus has been on larger scale reactors applied to the manufacture of ammonia and methanol. Large "mega" ammonia and methanol plants have been constructed outside the US where low-cost NG is available.

Instead of using an externally fired furnace, the ATR reactor generates heat internally by injecting air or oxygen into the reactor containing catalyst. For ammonia production, air is used to provide the required heat and nitrogen to synthesize ammonia. For methanol, pure oxygen from and air separation plant (ASU) is injected to the reformer reactor to produce syngas in the right mix to synthesize methanol. ATR also operates at higher temperatures. This drives the chemical equilibrium to higher CH_4 conversion, higher yields of product chemicals and reduces the residual CH_4 in the tail gas. This results in less carbon in the tail gas and less CO_2 emitted to the atmosphere.

Because of the high temperature operations, recovering heat is important to achieving high overall thermal efficiency and product yields. That high-level heat is recovered from the hot reformer syngas in the form of steam that is needed to drive the reforming reactions and feed the CO shifting reactions.

Traditional ATR plants have a "pre-reformer" which partially converts methane to syngas. The pre-reformer is typically a fired furnace to partially reform methane before feeding to the primary reformer. A fired pre-reformer generates flue gas and works against the goal of high carbon capture.

Most recently, some ATR licensors have developed an ATR process that uses the high temperature syngas product from the ATR reactor to "pre-reform" the feed stream without using a fired pre-reformer. This eliminates the need to burn carbon fuels in the reformer furnace. Johnson Matthey has been a leader in the concept of "heat exchange reforming". Other process developers have similar technology available for license. The unfired pre-reformer is referred to as a "reformer heat exchanger" or a "gas heat reactor". When modified for carbon capture, the capture of most of the high-pressure CO_2 is feasible using existing technology. This substantially increases the overall carbon capture rate and reduces the carbon in the tail gas. The concept has been commercially proven in one ammonia plant and one methanol plant. Two other ATR chemical plants are under development in the US but are not yet sanctioned for construction.

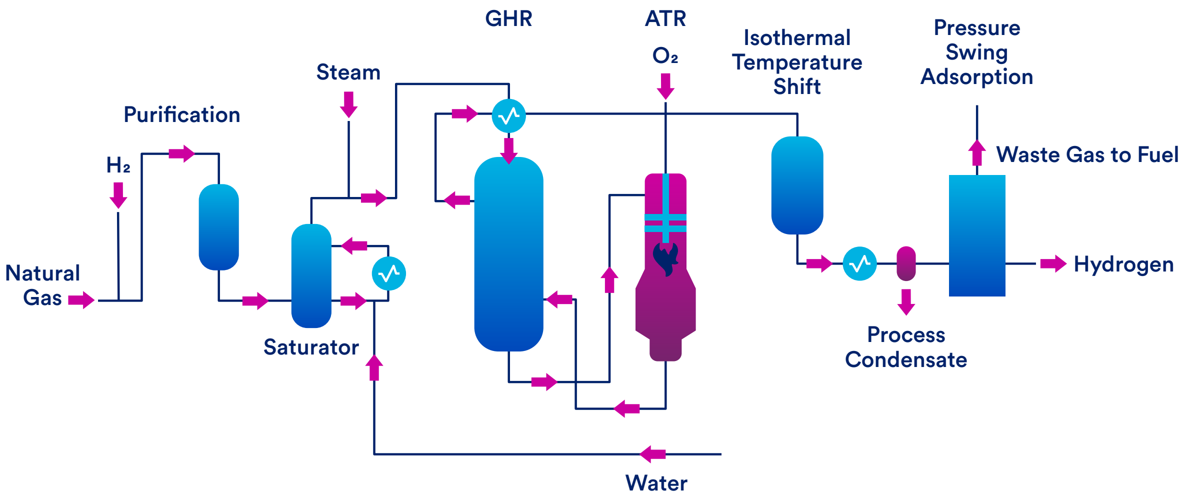
A disadvantage of ATR is the higher power requirements to produce oxygen in an air separation plant (ASU). If this power comes from a carbon intensive source, then the higher carbon capture rate of an ATR H_2 plant is partially offset by the CO_2 associated with the higher power requirement. If that power is from a low-carbon power source then this is not an issue.

At this time, a high carbon capture ATR merchant hydrogen plant has not been constructed. The most advanced ATR CCS merchant H_2 plant under development appears to be the "HyNet" project in the UK. Figure 3 is a conceptual process flow diagram for the proposed HyNet Project. Note that the only source of CO_2 emissions is the tail gas which is used to generate steam for internal use.

Progressive Energy is developing this project and a UK government funded "pre-FEED" feasibility study has been completed. Progressive Energy has received funding for the detailed FEED which is underway. Some details of the pre-FEED study have been published. The reference list to this memo lists the HyNet project and many other published studies on ATR and comparative studies to SMR.

Figure 3: ATR GHR CCS Hydrogen Plant Flow Diagram

Source: Phase 1 Report for BEIS Progressive Energy Ltd



Preliminary Performance Estimates for ATR CCS Merchant Hydrogen Production

Currently, the HyNet project appears to be the best example of a high carbon capture merchant hydrogen plant using proven commercial technology. The detailed process stream data has not been published. The published reports provide sufficient information to construct overall performance data.

Table 1 (on page 7) summarizes the performance of the first phase HyNet "LCH" plant using the ATR technology with Reformer Heat Exchanger, based on published data and our analysis. The overall CO_2 capture rate for the HyNet project is 97%. The CO_2 is compressed to dense phase pressure for pipeline transport to sequestration.

Excluding purchased power, the plant converts NG to high purity hydrogen at 84.7% thermal efficiency.

At 89.3 MMSCFD H_2 (100 KnM3/Hr), this plant is about half the size of the largest single train conventional SMR plant without carbon capture. A single train ATR H_2 much larger than the HyNet first of a kind plant could be designed in the future. ATR plants typically are most economic at scales larger than the largest single train SMR H_2 plants. The HyNet report states that this is their long-term goal.

The steam and power balances were estimated using data from HyNet reports. It is not clear if the steam from the tail gas steam generator is used for power generation or process use. However, the net imported power matches the reported data.

Table 1: Analysis of Merchant Hydrogen ATR CCS Plant Performance Data

Description	Units, Features	Reported or Calculated Data
Location		Gulf Coast USA
Reformer Fuel		None ATR with PreReformer HX
Basis: UK Hynet Project	Feed/Fuel	Natural Gas (Typical USA)
	Steam Generator Fuel	Tail Gas Only
	Process Configuration	Johnson Mattey ATR/RHX
	Reformer Oxygen	O_2 from ASU
	Scale	One Train – Hynet UK
NG Feed	Mmbtu, hhv / hr	1,429.8
NG Heating Value	Btu HHV/scf	1,013.7
NG Feed	MMSCFD	33.8
NG Fuel to Reformer burners	Mmbtu, hhv / hr	none
Total NG feed + fuel:	Mmbtu, hhv / hr	1,429.8
H_2 Product stream:	MMSCFD	89.63
H_2 prod stream Total HHV	MMBTU/hr	1,211.4
H_2 Product mass rate	lbs/hr	19,680.9
H_2 Product mass rate	kg/hr	8,929.6
H_2 Product Volume rate	KnM3/hr	100.0
Thermal Efficiency	H_2/NG HHV	84.7%
Thermal Efficiency	H_2/NG+Power	80.3%
Hydrogen Composition	mol% H_2	99.999%
Pressure (w/o compress.)	psig	676
Temperature	deg. F	59
H_2 product Heating Value	BTU/SCF HHV	323.8
CO_2 Product Stream	sT/hr	82.97
	vol % CO_2	99.7%
Pressure	psig	dense phase
Temperature	deg. F	32-67
Utilities		
Raw Water, gpm (BFW/CT)	gpm	416
Power:		
Air Separation Unit	KW	5,500
H_2 Plant	KW	6,500
Offsites, BOP	KW	4,900
CO_2 compressor	KW	6,000
Total kW (net purchased)	KW	22,900

Preliminary Carbon Balances for ATR CCS Merchant Hydrogen Production

Table 2 summarized key carbon balance data for the ATR H_2 CCS plant described in Table 1. As reported, the overall carbon capture ratio is 97%. This is substantially higher than the 55-67% capture rate for SMR plants with capture only of the “process CO_2”. (See EIA Foster Wheeler Study reference). If the reformer furnace flue gas is treated using amine solvent technology designed for oxidizing conditions, 90% capture can be achieved in a traditional SMR H_2 plant.

Table 2: Analysis of Merchant Hydrogen ATR CCS Plant Carbon Balance Data

Carbon Metric	Units	Amount
Carbon Balance		
Carbon in Feed (CO_2 basis)	sT/hr	85.56
Carbon in tailgas to steam gen	sT/hr	2.59
CO_2 captured	sT/hr	82.97
% CO_2 captured	%	97.0%
Carbon Intensity		
CO_2 equiv NG/Btu NG Feed	lb/mmbtu hhv NG	114.98
CO_2 emissions/Btu H_2 product	lb/mmbtu hhv H_2	4.27
CO_2 adjusted for Power Req'ts		
Grid Power Carbon, lbs/mwhr		
1000 (Texas Grid 2019)	lb/mmbtu hhv H_2	23.17
	lb CO_2/ lb H_2 product	1.43
446 (CA Grid 2019)	lb/mmbtu hhv H_2	12.70
H_2 prod stream Total HHV	lb CO_2/ lb H_2 product	0.78
Zero Emitting Power	lb/mmbtu hhv H_2	4.27
	lb CO_2/ lb H_2 product	0.26

Preliminary Comparison of Carbon Intensities for ATR CCS SMR Merchant Hydrogen Plants

ATR has a disadvantage of higher power requirements due to the ASU load. For this reason, carbon intensities should be adjusted to include the CO_2 emissions from the purchased power. Table 2 above uses two metrics: lbs of CO_2 emitted per MMBtu of H_2 fuel product and lbs of CO_2 emitted per lb of H_2 product. If the plant is powered by 100% carbon free energy, the carbon intensity is low at 4.27 lb/mmbtu of H_2 product. If the grid carbon intensity is high at 1000 lb CO_2/mwhr (the 2019 average in Texas), the effective carbon intensity including the power grid emissions, is 22.17 lb CO_2/mmbtu. Methane combustion generates about 115 lb CO_2/mmbtu. The typical NG used in this plant design contains about 2-3% higher hydrocarbon gases, so the actual CO_2 emissions would be slightly higher. In 2019, the California grid had fallen to 446 lb CO_2/mwhr. At this rate, the effective carbon intensity of the ATR CCS plant would be 12.7 lb CO_2/mmbtu or about 90% lower than the CO_2 emissions from burning NG. Table 2 also shows the same information using the lb CO_2/lb H_2 metric. To achieve 90% CC, an SMR plant would need to use post combustion carbon capture. The IEA Foster

Wheeler study (see references) of the same size SMR plant with CCS, shows that the plant is approximately balanced in power requirements due to surplus steam used to generate on-site power. Thus, SMR CCS plant CO_2 emissions are not sensitive to grid carbon intensity.

Today, there is growing interest in producing "zero carbon" hydrogen by splitting water in an electrolysis cell. This process is proven on a small scale and several projects have been announced that would demonstrate electrolysis H_2 on a larger scale. At low temperatures, thermodynamic laws limit the thermal efficiency of electrolytic cells to about 66% where the feed is electricity. This compares to about 74 to 80% for SMR CCS or 80-85% for ATR CCS where the feed is lower cost NG.

Figures 4 and 5, illustrate the relative carbon intensity of ATR, SMR and electrolytic production of H_2.

These Figures illustrate the dramatic differences in carbon intensity of H_2 product from these 3 alternative sources depending on the energy source used to produce H_2. If the electrolysis plant is located where abundant zero carbon power is available (wind, solar, hydropower, nuclear), then the H_2 product is essentially carbon free. However, if the grid power feeding the electrolysis cells is over about 20 to 30 lb CO_2/Mwhr, then ATR will have a lower carbon footprint. If the grid power carbon intensity is at the recent California level or higher, electrolysis generates 10 times or more CO_2 emissions than ATR. Since SMR CCS plants are in power balance, the carbon intensity is not significantly affected by the power grid carbon intensity. Note that SMR CCS with 66% carbon capture is always higher than ATR CCS with 97% capture. However, if 90% CC SMR flue gas capture is used, then ATR produces less carbon intensity if grid intensity is below 600 lb CO_2/Mwhr (lb/lb) or 200 lb CO_2/Mwhr (lb/mmbtu). If the goal is to reduce US power grid carbon intensity, then ATR CCS will have a growing environmental advantage over these other alternatives.

Figure 4: Carbon Emissions – Electrolysis vs ATR CCS vs SMR CCS Carbon Intensity per Lb H_2

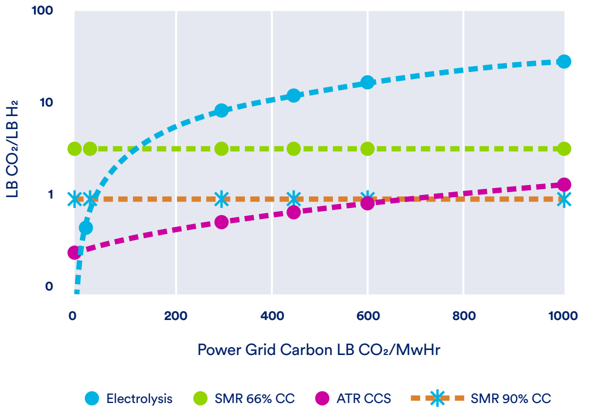
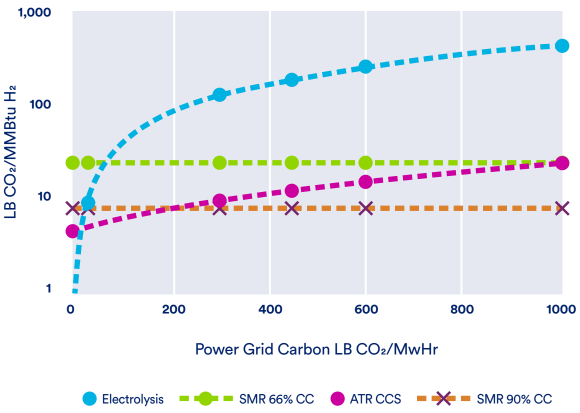


Figure 5: Carbon Emissions – Electrolysis vs ATR CCS vs SMR CCS Carbon Intensity per MMBtu H_2



Preliminary Economics for ATR CCS Merchant Hydrogen Production

Although the goal is to produce H_2 with the smallest possible carbon intensity, each alternative must also compete on economic grounds. This report does not include an economic comparison of the alternatives. However, a preliminary economic analysis of an ATR CCS H_2 plant located on the US Gulf Coast has been developed.

For this study, we used HyNet reports on capital costs as these were prepared by reputable engineering and construction companies. The HyNet design is based on specific site near an existing refinery in the UK. The breakdown includes a large component labeled “air and gas systems”. Based on the plant utility data, it appears that the ASU is included in this line item. We converted the capex estimate to US dollars using the current exchange rate. No effort was made to convert the estimate to a US Gulf Coast site. In general, construction in the Gulf Coast would be expected to cost less than in the UK. However, we have not made that adjustment. We added to the reported capex (assumed to be total installed costs) additional soft costs for owner’s expenses and a contingency of 10%.

We developed a simple “overnight” cost of producing H_2 using the performance data from Table 1 (on page 7). This estimate is intended to be illustrative only. The current FEED study will produce more accurate costs for construction in the UK. Local site conditions could substantially change the cost estimates. The HyNet report projects a plant operating factor of about 95%. For our estimate, we assume a more conservative 90% annual operating factor. Fixed and variable O&M costs were estimated using typical process industry factors. Detailed operating costs are not available. A “levelized” weighted average cost of capital of 8% was assumed. This rate is reasonable considering the very low long-term cost of debt in today’s credit markets.

Table 3 (on page 11) summarizes our findings. Assuming US Gulf Coast location, the DOE EIA reports that the industrial rate for purchased power may be about $50/Mwhr and cost of natural gas at the Henry Hub is about $3/MMBTU. The cost to sequester CO_2 in that region will vary significantly based on proximity to geologic reserves. A DOE 2017 study estimated the cost to transport and sequester at around $10/ton. Recent reports from Shell on the Quest project in Canada reported long term costs at about $25/ton. For this study we have used the higher cost of $25/ton. With those assumptions we estimated today’s “overnight cost” of H_2 from ATR technology would be about $10.18/MMBTU (HHV) or $1.38/kg. This cost is substantial lower than most published cost estimates of hydrogen from electrolysis plants. However, those costs are forecasted to drop if large scale markets develop.

These economics for ATR CCS will vary with cost of power, natural gas, CO_2 sequestration costs and changes in capital costs and capital market conditions. The technology is available today for large scale applications. This study is not intended to favor one technology over another. However, it illustrates that current NG reforming technologies may be commercialized to produce merchant H_2 with low carbon emissions at an attractive price that appears to be substantially lower than those published for electrolysis renewable power resources. Given the uncertainty of future technology performance and costs, the promise of future technology improvements, and significant locational differences, we expect all these technologies will continue to attract capital for large scale demonstrations.

Table 3: Analysis of Merchant Hydrogen ATR CCS Plant Estimated Required H_2 Selling Price (at Plant Gate)

Overnight $2020	UK location US$	$1.23 per UK pound
Capex, $MM 2018-20 (TIC)	$MM US	$312.30
Owner's cost	$MM US	$17.70
Contingency, 10%	$MM US	$33.00
Capex, with Owner's Cost	$MM US	$363.00
Capex per unit H_2 capacity	$MM/MMSCFD	$4.05
	$/N3/hr	$3,630
Capacity Factor	planned/forced	90.0%
Commodity Pricing	indicative pricing	
Natural Gas	$/MMBtu HHV	$3.00
Power	$/kwhr	$0.05
CO_2 Transport, Sequestr.	$/Ston	$25.00
Annualized Rates		
Natural Gas	MMBtu	11,259,310
Hydrogen	MMBtu	9,539,511
Hydrogen	kg	70,401,286
CO_2 captured	short tons	653,390
Purchased Power	kwhr	180,543,600
	% Capex	**$MM/yr**
Capital Charge	8.00%	$29.04
Fixed O&M, Labor, Materials	1.50%	$5.44
Prop Taxes, Insurance, G A	1.50%	$5.44
Variable Maint, Chems, Cat	0.70%	$2.29
Purchased Natural Gas		$30.40
Purchased Power		$8.12
CO_2 Transport and Storage		$16.33
Total Revenue Requirements		$97.08
Required H_2 Price	$/MMBtu	$10.18
	$/MSCF	$3.30
	$/lb	$0.63
	$/kg	$1.38

Key Findings

- Large scale merchant hydrogen plants can be constructed today using proven commercial technology based on natural gas reforming and gas purification technology.
- Merchant H_2 plants designed for minimum carbon intensity can be built today. SMR technology can achieve carbon emission reductions of 50 to 65% or 90% with post-combustion carbon reduction. ATR CCS technology can achieve 96-98% reduction in carbon emissions.
- ATR CCS H_2 plants have the disadvantage that oxygen is needed to achieve low carbon intensity goals. Additional power is needed to produce the oxygen. If this power comes from a power grid that has substantial renewable energy content, then ATR appears to retain is lower carbon intensity lead over SMR.
- When compared to water electrolysis technology, the ATR CCS technology has much lower carbon intensity unless the power supplied to the electrolysis cells has very low carbon intensity. If such grid power is available, then the same low carbon intensity power can benefit the ATR CCS option.
- Current research and development is underway for both ATR and SMR and associated gas purification technologies can be expected to further reduce the carbon intensity of NG to H_2 processes.
- Electrolysis technology is under development and expected to lead to lower capital costs. Lowering the power requirements may be possible but there are thermodynamic limitations set by the energy required to break the water chemical bonds.
- ATR single train plants can be constructed at 2 to 3 times the capacity of the HyNet project. Thus, economies of scale, design optimization, technology improvements are expected to bring down the cost of very low carbon hydrogen.
- The NG reforming and gas purification industry is highly competitive worldwide and actively competing to bring merchant hydrogen production into widespread use today. Some of the technology suppliers include Linde, Air Products, Air Liquide (Lurgi), Haldor Topsoe, Johnson Matthey, Thyssen Krupp Uhde, UOP, Axens, Fluor, KBR, Foster Wheeler, Wood Group, and many more.
- Similarly, numerous types of electrolysis cell technology are available, and there appears to be growing competition to serve this market.
- Markets for H_2 fuels, grid power carbon intensity, NG prices, construction costs, cost of capital, government incentives, and local conditions will all impact the selection of merchant H_2 technology.

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This work was prepared by Hensley Energy Consulting at the request of CATF. For more information please contact **Mike Fowler** at mfowler@catf.us

References

A. Project Specific Reports

1. Air Products Port Arthur Retrofit Carbon Capture Project IEAGHG report 2018
   http://documents.ieaghg.org/index.php/s/4hyafrmhu2bobOs/download
2. BOC HPU CCS STUDY REPORT
   28603-8111-RP-001
   Foster Wheeler Energy Limited (FWEL) to Stockton Borough Council on behalf of Tees Valley Unlimited (TVU), solely to assist TVU in its study into the potential application of CCS in Teesside UK, Nov. 2014
3. Department for Business, Energy & Industrial Strategy
   BEIS Hydrogen Supply Programme
   HyNet Low Carbon Hydrogen Plant
   Phase 1 Report for BEIS
   Progressive Energy Ltd
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4. SHELL CANADA LIMITED
   Quest Carbon Capture and Storage Project
   2018 ANNUAL STATUS REPORT
   Prepared By: Shell Canada Limited
   Calgary, Alberta
   March 31, 2019
5. IEAGHG Technical Report 2017-02 February 2017
   Techno – Economic Evaluation of SMR Based Standalone (Merchant)
   Hydrogen Plant with CCS (detailed process data)

B. Articles on Comparisons of Technologies for Hydrogen Production

1. Air Liquide – Technology status of hydrogen production from fossil fuels w/CCS
   Chatou France • November 6th, 2019
   Fabrice Del Corso • R&D
2. Overview: Hydrogen Production Today and Tomorrow
   Mary-Rose de Valladares Paul Lucchese
   Workshop on Hydrogen Production with CCS
   EDF Chatou Campus
   6 November 2019
3. STATUS OF HYDROGEN PRODUCTION WITH CO_2 CAPTURE-INCLUDING PERSPECTIVES ON EMISSIONS AND SCALE
   Sigmund Ø. Størset, SINTEF
   Research Manager, Leader of SINTEF Coorporate Hydrogen Initiative
   CSLF Workshop, Chatou Nov. 6 2019
4. Saltend
   The first step to a Zero Carbon Humber
   Equinor, 2020
   www.zerocarbonhumber.co.uk
5. MITiLAB Presentation on SMR vs Electrolytic H_2
6. Hydrogen Production from Natural Gas with Very Low CO_2 Intensity
   HYPER Closing Seminar 2019-12-10, Julian Straus, Vidar Skjervold, Rahul SINTEF
   Anantharaman, David Berstad
7. “Hydrogen production from natural gas and biomethane with carbon capture and storage – A techno-environmental analysis”
   Sustainable Energy and Fuels, Issue 6, 2020 (compares SMR and ATR in various configurations)
   https://pubs.rsc.org/en/content/articlelanding/2020/SE/D0SE00222D#!divAbstract

C. Articles on Cost of CO_2 Transport and Sequestration

1. Cost and Performance Baseline for Fossil Energy Plants Volume 1b: Bituminous Coal (IGCC) to Electricity Revision 2b – Year Dollar Update
   July 31, 2015 DOE/NETL-2015/1727