REPRINT

Gas Turbine World

Steps to Achieving a Successful Global Decarbonization Strategy

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Steps to achieving a successful global decarbonization strategy

By Peter Baldwin, President, base-e

How does the world transition from producing over 60% of electricity by fossil fuel to less than 10% by 2040, just 20 years from now?

The current global trajectory of atmospheric CO_2 is set to breach 2900 gigatonnes by 2040, the internationally recognized "budget" for limiting atmospheric temperature rise to 2ºC.

Left unchecked, the energy-consumption growth scenario foretells a possibly disastrous rise of 4°-5ºC by 2100.

Virtually all agree that the best way forward must include CO_2-free electricity as a critical part of any global decarbonization strategy.

As reported last summer in the *2020 GTW Energy and Fuels Report*, for this to happen calls for immediate and urgent support:

☐ **Carbon capture.** Mandate that all fossil-fueled power plants, including natural gas-fired simple and combined cycle units, deploy 90% carbon capture and sequestration. CHP and district heating *"carve-outs"* cannot qualify for exemption.

☐ **Renewables.** Require wind turbines and solar include storage in their offerings to the grid, and remove any "first to dispatch" subsidies, embedded in the Renewable Portfolio Standards.

☐ **Nuclear.** Continue to utilize all existing nuclear power plants, support 15% power up-rates and system upgrades, and continue the development and deployment of advanced nuclear options.

☐ **Transmission.** Improve transmission capacity to get stranded renewables to market which will also spread the effects of intermittency over a wider area.

☐ **CO_2 disposal fee.** Put a value on CO_2 and use the proceeds to fund development of carbon capture and sequestration (CCS) technologies.

☐ **Hydrogen.** To be determined. Advocates gloss over costs to produce, transport and store hydrogen essential to its success.

Best way to proceed?

Carbon capture and sequestration (CCS) has long been considered an effective method to directly reduce CO_2 emissions from power generating units at scale. But to date that's been given more lip service than action.

Instead, industry and government agencies have fixated on hydrogen fuel as the most promising response to producing carbon-free electricity.

Near term the emphasis is on "blue" hydrogen produced from natural gas or methane (CH4) using a steam/methane reforming (SMR) process plus CCS – with the ultimate goal of advancing to 100% "green" hydrogen produced by electrolyzing demineralized water.

Besides its inherent benefit as a cleaner fuel than natural gas for power generation, hydrogen is also offered as an attractive energy storage medium for managing normal variations in wind and solar.

The question is what role hydrogen (and natural gas) can or should play in the global transition to 100% renewables future.

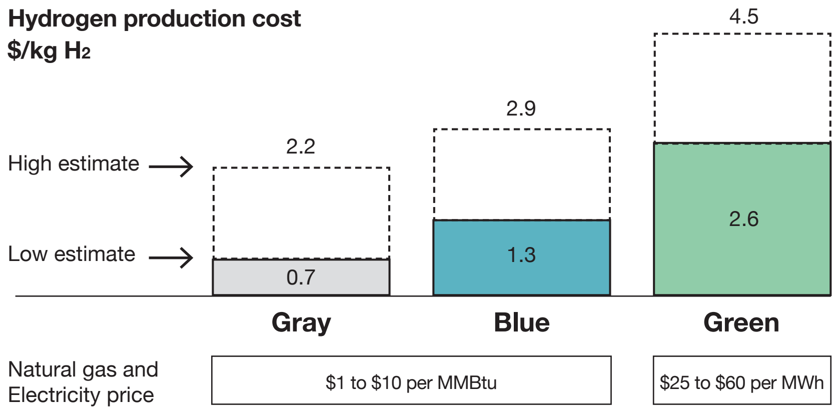
Expert opinions abound

The Energy Transitions Commission (ETC), a global coalition of leaders from across the energy landscape dedicated to achieving net-zero emissions by mid-century, has extensively reviewed these issues in their April 2021 report, ***"Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy"***.

As discussed, there is universal agreement that "clean electrification" must be at the heart of any strategy to achieve a zero-carbon economy which also requires that clean electricity be applied over a far wider range of end applications:

- Thanks to both decreasing all-in generation cost and inherent efficiency gain associated with a switch to electricity, clean electrification can lower total energy system costs while also delivering major local environmental benefits.
- Direct electricity use could and should grow from today's 20% of total final energy demand to reach close to 70% by 2050, with electricity generation to support direct electrification growing from 27,000 TWh to around 90,000 TWh.

Hydrogen production cost. Spread between high and low cost estimates depends on site location and facilities. Cost of Blue hydrogen (SMR+CCS) assumes 90% capture; Green assumes 50% capacity factor and $850/kW for large scale electrolyzer facility plus 53 kWh/kg energy consumption.



Source: Energy Transition Commission report "*Accelerating Clean Hydrogen in an Electrified Economy*" April 2021.

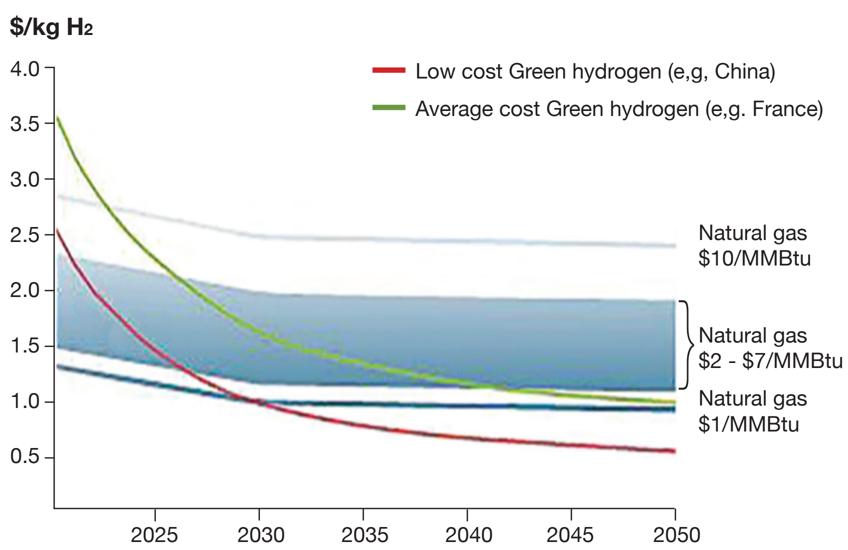
Hydrogen has major role

Hydrogen is expected to play a major role in decarbonization whether used directly as a fuel for electric power generation or in derived fuels such as ammonia and synthetic fuels (synfuels).

Hydrogen is also important as a potential energy storage medium, helping to balance supply and demand in future systems where electricity is supplied by variable renewable sources.

• Total global hydrogen use could grow 5-7 fold from today's 115 million tonnes per year to reach 500 to 800 Mt by midcentury, with hydrogen (and its derivatives) accounting for 15-20% of final energy demand, on top of the close to 70% provided by direct electricity.

Comparative Fuel Costs. Before the end of this decade, the cost of Green H2 via electrolysis (red line) could become competitive with the production cost of Blue hydrogen which depends highly on the local price of natural gas.



Source: Energy Transition Commission report *"Accelerating Clean Hydrogen in an Electrified Economy"* April, 2021)

• This hydrogen must be produced in a zero-carbon fashion via electrolysis using zero-carbon electricity (green hydrogen), or in a low-carbon fashion using natural gas reforming plus CCS (blue hydrogen) if deployed so it achieves near-total CO_2 capture and low methane leakage.

• Blue hydrogen will often be cost-effective during the transition, particularly via retrofit of existing gray hydrogen and, longer term, in locations with low natural gas prices.

• Green hydrogen will be lower cost in most locations over the long term, with dramatic production cost reductions to below $2/kg possible during the 2020s, and falls thereafter. (Editor's. Note: A $2/kg cost for hydrogen equals about $9/MMBtu.)

Hydrogen production will therefore be predominantly via a green route (circa 85%) and generate very large electricity demand, increasing the total required supply of zero-carbon electricity by 30,000 TWh or more on top of the 90,000 TWh potentially needed for direct electrification.

Strategies to achieve net-zero emissions by mid-century in both developed and developing countries must recognize the major role of green hydrogen, says the ETC report, and implications for adequate supply.

Although formidable, it is physically and financially doable, but timing is crucial.

The challenge is to ensure a sufficiently rapid take-off of hydrogen production and use during the 2020s to make it feasible to reach 2050 targets:

• Achieving this will require government policy support because using hydrogen in end applications often imposes a green premium (versus fossil fuel technologies) even when clean hydrogen production costs fall dramatically.

• Those policies must combine broad policy instruments such as carbon prices, with support focused on specific sector applications and on developing geographically-focused clusters of clean hydrogen production and use.

Net zero by 2050

The International Energy Agency (IEA) has articulated its views on clean energy in a May 2021 report, ***"Net Zero by 2050 – A Roadmap for the Global Energy Sector"*** which offers a "cost-effective and economically productive pathway, resulting in a clean, dynamic and resilient energy economy dominated by renewables like solar and wind instead of fossil fuels."

The report also examines key uncertainties such as the roles of bioenergy, carbon capture and behavioral changes in reaching net zero. *It suggests that success hinges on an unprecedented clean technology ramp-up to 2030.*

It states that the path to net-zero emissions is narrow and that staying on it requires immediate and massive 4x deployment of all available clean and efficient energy technologies, 18x increase in electric car sales, and 4% per annum decrease in energy intensity as a fraction of GDP (see chart).

These are huge leaps in clean energy innovation between now and 2030. Reaching net zero by 2050 will require further rapid deployment and widespread use of technologies not yet on the market.

Major innovation efforts must occur over this decade. Meanwhile, *most of the global reductions in CO_2 emissions through 2030 in our pathway come from technologies readily available today.*

In 2050, it is expected that almost half the reductions will come from technologies in the demonstration or prototype phase of development. In heavy industry and long-distance transport, the share of emissions reductions from technologies still under development today is even higher.

The biggest innovation opportunities concern advanced batteries, hydrogen electrolyzers, and direct air capture and storage, says IEA. "Together these

Hyping Green but Stuck on Blue

Europe's pending ESG-based "sustainable investment" regulation is expected to contain a "carve-out" for gas-fired CHP (aka cogeneration) projects. This would effectively enable permitting of unabated natural gas as a bridge fuel under a different label - "**Sustainable Transition Fuel**" - that will continue to grant natural gas a huge competitive emissions advantage.

The underlying principle behind this thinking is that natural gas need not do anything about mitigating its CO_2 emissions, while all other fossil-fueled power generation do. This privileged status for gas is driving carbon capture and nuclear out of the market – even some renewables.

Such special treatment is justified by claims that gas is "better than coal" or we "need to do coal first" advocating for its rapid deployment out through 2030. This is where the U.S. was with the New Source Performance Standards amendment in 2014, and exactly where we remain today!

The new U.S. administration is again taking aim at coal, while allowing gas to escape the spotlight. Permitting of unabated gas-fired power plants will continue as part of the "energy transition" as more uncompetitive coal plants and even some nuclear plants are retired.

Permitting natural gas fired power plants without carbon capture may be convenient, but would be a serious policy error for the long term.

Stuck… is where we are, and will be through the decade, and most likely beyond that, not making any real progress on absolute CO_2 reduction.

The result -- suppression of projects and technologies that could make a real difference, and simply changing the metric to "carbon intensity" in the name of progress doesn't help. Support is being diverted to blue sky ideas. Consider the mind-boggling emphasis and dependency that the International Energy Agency is placing on "*Direct Air Capture*". Really?.

If the gas turbine community would only rethink its continued support of unabated gas plants with an open mind it might realize that CCS on gas plants could better protect the industry's competitive position going forward and, in the long term, the environment.

Unfortunately, there appears to be a concerted bias toward short term coal-to-gas switching, with a lot of hype about the future of "green hydrogen", coupled with the fear that endorsing CCS would also enable coal with CCS to compete.

This strategy, regardless of how labelled, won't work any better in Europe than it has in the U.S. The sad reality is that the EIA's "*Annual Energy Outlook 2021"* projects that energy-related and total CO_2 emissions remain essentially flat through 2050.

All while the world wastes what little time is left!

three technology areas make vital contributions to the reductions in CO_2 emissions between 2030 and 2050 in our pathway."

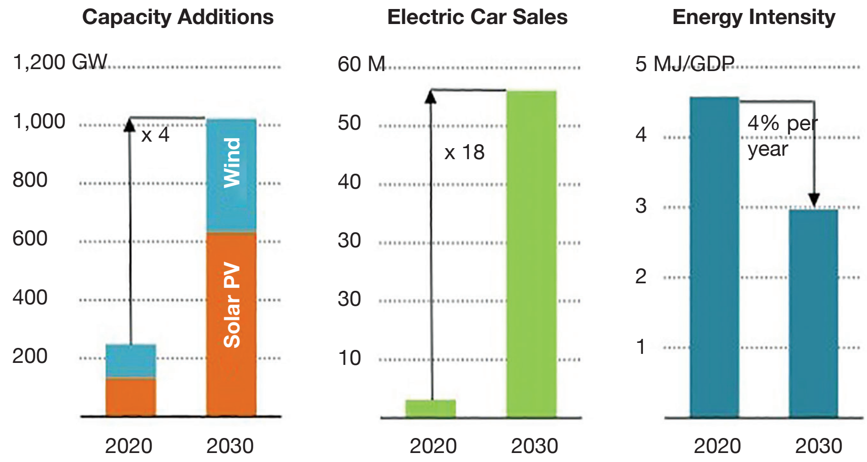
Innovation over the next ten years – not only through research and development (R&D) and demonstration but also through deployment – needs to come with the large-scale construction of the infrastructure the technologies will need:

- New pipelines to transport captured CO_2 emissions and systems to move hydrogen around and between ports and industrial zones.

- Rapid acceleration of clean energy innovation funded by government R&D, with project demonstration and deployment at the core of energy and climate policy.

- Increased government R&D in critical areas such as electrification, hydrogen, bioenergy and carbon capture, utilization and storage (CCUS).

On the path to Net Zero. Required ramping up of key clean technologies from 2020 to 2030 shows unprecedented technology push. Renewable capacity must grow fourfold and electric vehicle sales must grow 18 times today's level. Meanwhile "global energy intensity must fall by 4% per year via efficiency improvements and other measures; about 3 times the rate observed over past two decades.



Note: MJ = megajoules and GDP = gross domestic product in purchasing power parity

Source: International Energy Agency report "Net Zero by 2050 – *A Global Roadmap for the Energy Sector"* May 2021

Hydrogen Strategy Report

The U.S. Dept. of Energy published a ***Hydrogen Strategy Report in 2020*** that covers the full gamut of hydrodrogen production paths from both fossil and non-fossil sources.

Cost estimates referenced in the report (see chart) are quoted, in US dollars per kg of hydrogen (including the cost of carbon capture where applicable) where the cost of $1 per kg H2 equals about $8 per MMBtu.

Social and governance factors

A controversial European sustainability regulation published in June 2020, Environmental Governance and Social (EGS), has established a set of non-financial factors to evaluate companies and projects regarding sustainability risks and societal impacts.

The regulation defines sustainable economic activities as those substantially contributing to any of six environmental objectives: climate change mitigation, adaptation, protection of water, ecosystems, circular economy and tackling pollution.

Any ***substantial activity*** to achieving one objective must go with not harming the other objectives. This EU regulation will be an essential reference in several forthcoming sustainable finance regulations in Europe such as those addressing disclosures for the EU green bond standard.

We have seen ESG ratings appear as part of European discussions on financing unabated natural gas fired power plants, coupled to "sustainability".

The discussion is ongoing and centers on whether CHP and/or district heating schemes qualify as "sustainable" to receive some exemption and therefore, able to qualify for project financing, without CCS.

Hurdles adopting hydrogen

One of the major environmental issues for gas turbine engineers and operators is to limit NOx emissions produced by the combustion of hydrogen.

The gas turbine community is well-versed in hydrogen combustion technology and stands ready, willing and able to resolve all the issues within the gas turbine itself.

Given the substantial differences in physical and chemical properties of hydrogen vs. natural gas, the main challenge is with adapting today's modern, dry low NOx (DLN) combustors.

While waiting for the design modification and development of DLN combustors able to burn 100% H2, the industry is gradually improving its ability to grow from 20-30 % vol. hydrogen to 100% over the next few years.

Formidable issues are also related to hydrogen production, storage and transportation to point of use at required pressure, and integration into the natural gas distribution system for widespread use as a natural gas replacement.

In Europe, enthusiasts are promoting and pilot testing hydrogen fuel for industrial power and heating, and domestic home use. To succeed, they face serious challenges in demonstrating safety, cost effectiveness and reliability of such a distribution system.

High bar for electrolyzers

The economics of a green hydrogen fuel supply from electrolyzer point-of-production to point-of-use are not well defined. It can be done, but compressing the hydrogen involves capital and operating cost penalties not detailed.

As for electrolyzer technology, overall unit capacity is limited, and their 65% efficiency barrier poses a serious system parasitic loss. It also will be difficult to blend the hydrogen output into the natural gas distribution system.

There are just too many end-use variations and with limited understanding and agreement on where and how to create an equivalent fuel-supply network. Successful deployment will require a dedicated H2 supply.

Hydrogen storage is a way to manage some of these challenges and, importantly, to pick off additional value in support of large-scale deployment.

As energy storage has become an essential component to integrate renewables into the grid, hydrogen storage seems to have become an essential part of the hydrogen discussion.

However, its extremely low round-trip efficiency of 25-45% compared to ~90% for batteries may limit hydrogen storage to only a long-term storage option.

Green vs Blue: Follow the CO_2

Green hydrogen produced in electrolyzers powered by renewable energy to provide CO_2-free electricity is a major theme in European planning, and elsewhere, and is the subject of several planned demonstration projects.

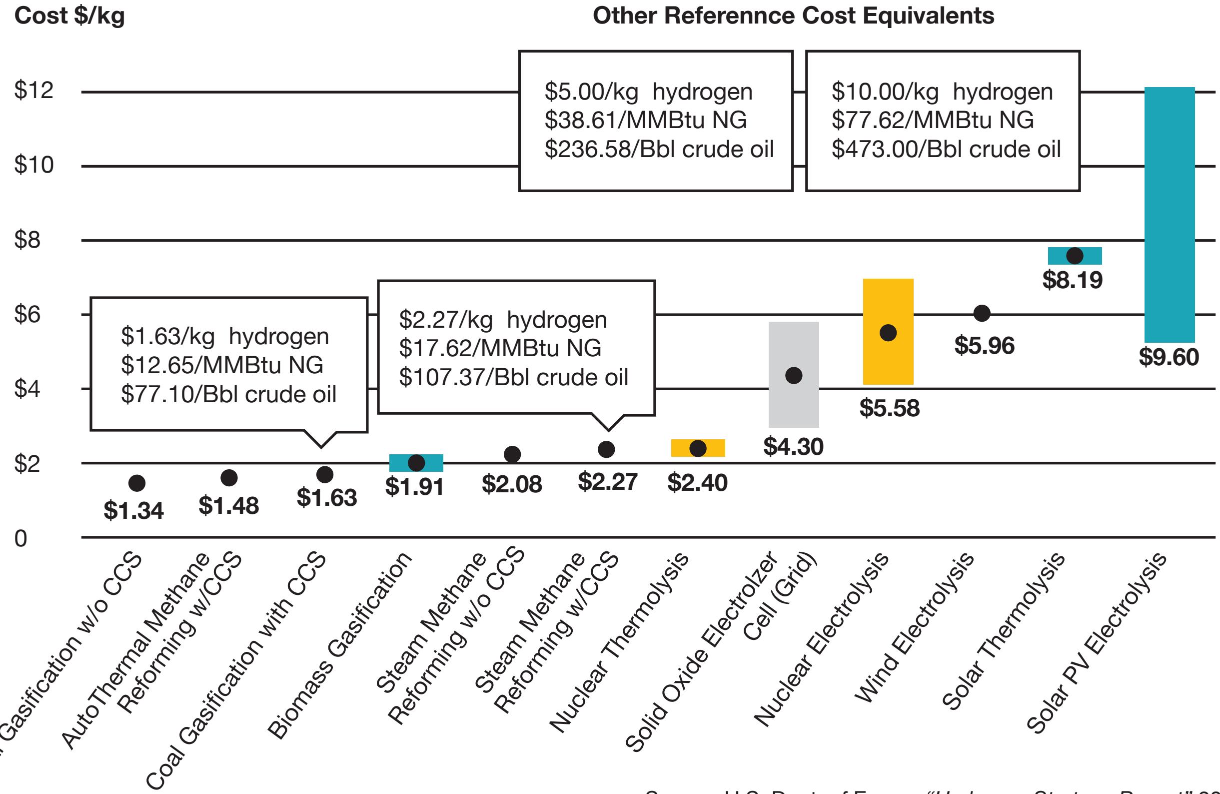
Although gas turbines can be modified to use 100% hydrogen the quantities required within the limited time available, and the cost of green hydrogen, will most likely force the long-term use of blue H2 made from natural gas requiring use of CCS to achieve the goal of carbon-free electricity.

A simple calculation shows it takes almost ***4 kwh electrolyzer input energy*** to produce enough hydrogen to produce ***1 kwh of output gas turbine energy*** (or 1.5 kwh of output combined cycle energy). This is based on a typical electrolyzer power requirement of approximately 52 kwh per kg hydrogen produced, and a gas turbine efficiency of 40% (or combined cycle efficiency of 60%).

John Gulen, ASME Fellow and frequent GTW guest author, has provided data (see table) to help evaluate the impact of using various natural gas/hydrogen mixes for power generation in a 460MW combined cycle power plant.

The data includes amount of CO_2 produced both by the gas turbine burning the blended mixtures and by steam methane reforming (SMR) used to produce the blue hydrogen.

Hydrogen production paths. Comparative costs of hydrogen show ranges and averages, by process technology and energy source, with and without carbon capture and sequestration (CCS) as applicable. Linear relationship of cost equivalency data indicates that $2/kg hydrogen production cost is roughly equivalent to $16/MM Btu.



Source: U.S. Dept. of Energy *"Hydrogen Strategy Report"* 2020

Gas turbine fired with hydrogen/natural gas blends. Data for nominal 460MW combined cycle plant show CO_2 emissions both in plant exhaust and that from production of hydrogen fuel using steam methane reforming (SMR) process. In case of 100% hydrogen, exhaust emissions reflect CO_2 in ambient air.

Plant Parameters		Gas	Mixed Fuel Cases						H2
Natural Gas Fuel	% (v)	**100%**	85	70	50	30	20	10	0
Hydrogen Fuel	% (v)	0	15	30	50	70	80	90	**100%**
Molecular Weight	lb/lb-mol	17.6	15.2	12.9	9.8	6.7	5.1	3.6	2
GT Fuel Flow	lb/sec	34.1	33.0	31.7	29.2	25.5	22.7	18.8	13.2
Hydrogen Flow	lb/sec	0	0.65	1.5	3.0	5.4	7.1	9.5	13.2
LHV Fuel Input	MMBtu/h	2,533	2,528	2,522	2,511	2,495	2,484	2,468	2,444
GT Power Output	MW	312.4	312.4	312.4	312.4	312.4	312.4	312.4	312.4
GT Efficiency	%	42.1	42.2	42.3	42.4	42.7	42.9	43.2	43.6
GT Exhaust Flow	lb/sec	1,359	1,358	1,357	1,354	1,351	1,348	1,344	1,338
GT Exhaust Temp	°F	1,156	1,154	1,150	1,144	1,134	1,127	1,118	1,104
STG Power Output	MW	155.2	155.2	154.2	152.5	149.8	147.9	145.2	141.4
CC Net Plant Output	MW	453.0	460.1	459.1	457.4	454.8	452.9	450.3	446.5
CC Net Efficiency	%	61.1	62.1	62.1	62.1	62.2	62.2	62.3	62.3
CC Net Heat Rate	Btu/kWh	5581	5493	5493	5491	5487	5485	5480	5473
GTCC CO_2	lb/hr (1000)	332.2	315.8	294.9	256.1	196.2	152.4	91.8	2.2
	lb/MWh	**733.3**	686.5	642.3	559.9	431.5	336.5	203.9	4.9
SMR Process CO_2	lb/hr (1000)	0	23.5	53.2	107.3	189.7	249.4	329.1	434.2
	lb/MWh	0	51.1	115.9	234.5	417.1	550.8	730.9	972.4
GTCC + SMR CO_2	lb/hr (1000)	332.2	339.3	348.1	363.4	385.9	401.8	420.9	436.4
	lb/MWh	**733.3**	737.7	758.2	794.4	848.7	887.2	934.8	**977.3**

1. Gas turbine output is held constant at 312.4 MW.
2. Increase in gas turbine efficiency (and reduced GT exhaust temperature) with increasing H2 reflects change in turbine inlet conditions due to fixed GT power setting and higher volumetric flow with increasing hydrogen content.
3. Accompanying improvement in CC efficiency is muted by drop in STG output due to reduced gas turbine exhaust energy (lower GT exhaust flowe and temperature).

Source: John Gulen, private correspondence, May 2021

About the Author

Peter Baldwin has been involved for over 50 years in the engineering and global marketing aspects of the gas turbine and compressor industries.

His independent Boston-based consulting company, ***base-e***, is focused on existing and new product positioning and commercialization strategies for distributed energy technologies, gas turbines, and air & gas compression interests.

Before this, Pete was President of ***Ramgen Power Systems***, a developer of advanced shock compression technology for utility scale CCS systems. During his 10-year tenure at Ramgen he was the principal point of contact for all equipment selection, technical and commercial issues,

The company was acquired by Dresser-Rand in 2015 and since acquired by Siemens. Before Ramgen, Pete worked for 33 years at ***Ingersoll-Rand*** where he was V-P Sales & Service for the Air Compressor Group and, later, president of ***NREC*** which developed and marketed Ingersoll's microturbine-based product line.

As shown in the table, the SMR process to support 100% hydrogen firing produces 977 lb-CO_2/MWh – which is 33% more than an unabated natural gas combined cycle at 733 lb-CO_2/MWh.

In all cases, the combined CO_2 (gas turbine exhaust plus SMR) will be more than that using 100% natural gas. If these cases require 90% carbon capture, the cost of added CCS capacity required to use Hydrogen must be considered.

This comparison assumes a combined cycle plant operating at efficiencies of better than 60%.

With 100% hydrogen, the gas turbine fuel flow is 13.2 lb/sec and the plant CO_2 emissions are nil. But the SMR process produces the equivalent of 977 lb-CO_2/MWh.

If, instead of a 60+% efficient combined cycle plant, simple cycle units at about 40% efficiency are used with 100% blue hydrogen fuel, the SMR-produced CO_2 emissions entering the CCS system is close to 1400 lb-CO_2/MWh and approaching the levels associated with those of a "dirty coal" plant.

The bottom line

Clearly, a conventional natural gas fired combined cycle plant equipped with CCS is far easier to implement, produces better outcomes, and can be applied to much of the existing fleet.

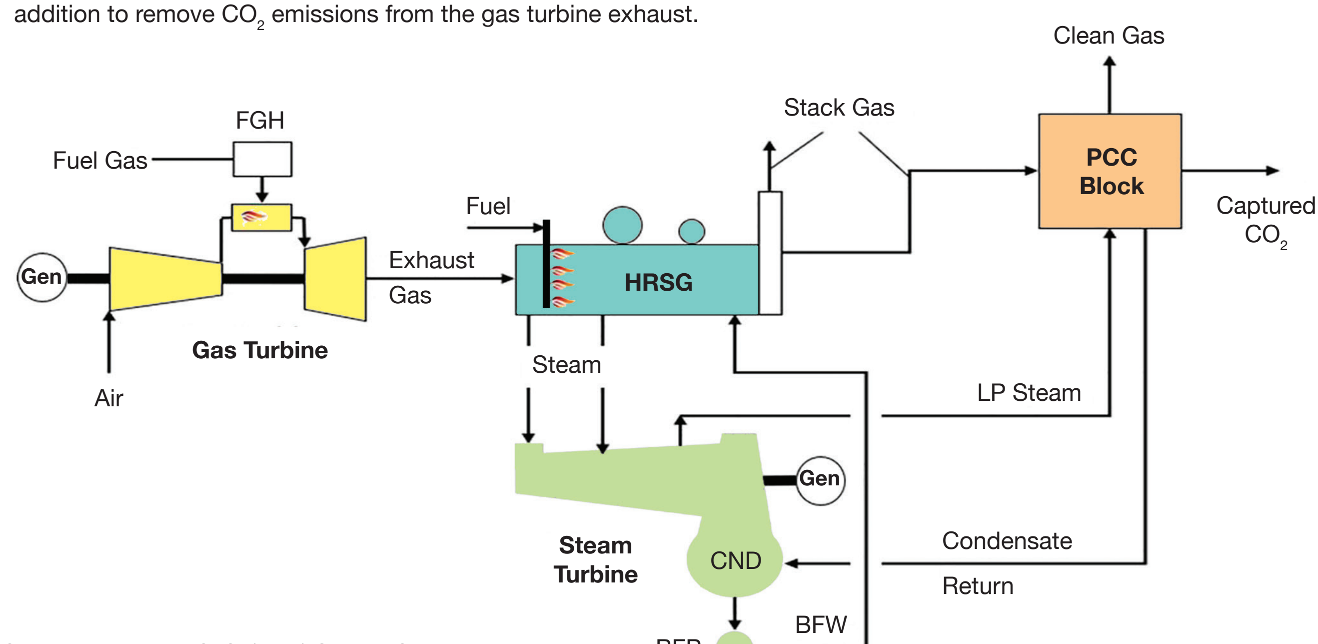
It can be done quickly with known technology and should not create the potential for stranded assets which can add 90% capture technology.

A blue H2 approach with an attached SMR process unit, followed by adding a CCS system or requirement to use the CO_2 as a feedstock elsewhere, becomes too complex.

As we know from experience, e.g., with several integrated gasification combined cycle plants, some otherwise good ideas just don't survive their own complexity.

Although we all sell the benefits of green H2, it seems more than likely we will get "stuck" and learn to live with blue hydrogen. ■

Combined cycle plant with CCS. Schematic of gas turbine combined cycle plant with post combustion capture (PCC) addition to remove CO_2 emissions from the gas turbine exhaust.



Compliments of Dr. S. C. (John) Gulen, ASME Fellow