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To: Connecticut Hydrogen Power Study Task Force – **Hydrogen Sourcing Subcommittee**
From: Jonathan Feinstein, ZoneFlow Reactor Technologies, LLC
Date: November 15, 2022
Re: Sourcing Hydrogen to Support Connecticut's Decarbonization Initiative

Summary

An analysis reported in April 2022 by the National Energy Technology Laboratories (NETL) of the DOE compares the costs and life cycle analysis (LCA) CO_{2e} emissions of the main processes currently used to make hydrogen, with and without carbon capture. In this memorandum, the NETL methods and the costs found in CT for industrial electricity and industrial natural gas and scope 2 emissions of electricity are used. The NETL assumption for scope 2 natural gas emissions (0.8% leakage, which is higher than assessed by the Environmental Defense Fund) is used. Options of electrolytic production of hydrogen from the CT grid electricity or hypothetically from dispatchable solar or wind electricity are also compared in emissions and costs.

Steam methane reforming with 99.5% carbon capture presents the lowest emissions and lowest cost opportunity for hydrogen production and the only route likely to be executed in a timeframe compatible with CT law for emission reduction. Importantly, this production route also requires the lowest capital expenditure and land use. It may require infrastructure not currently present in CT such as CO_2 pipelines to sequestration sites. Comments on infrastructure will be submitted separately.

Methodology

Below are summary numbers from LCA and techno-economic analysis (TEA) of various methods of producing high tonnage hydrogen based on the methods and assumptions found in the report, "Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies" by the NETL, April 2022,[1] with adaptations to CT prices and the carbon footprint of electricity in CT.

The table below itemizes the scope 1 and 2 CO_{2e} emissions per kg of hydrogen product. The first case, often referred to as grey hydrogen, is the process currently used to produce about 80% of the world's total production of hydrogen of 80 million (metric) tons per annum (MTPA). In this process, all carbon entering the steam methane reforming (SMR) unit is emitted as CO_2.

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[1] https://netl.doe.gov/projects/files/ComparisonofCommercialStateofArtFossilBasedHydrogenProductionTechnologies_041222.pdf

The next three columns are forms of what is often called blue hydrogen, in which some of the process and/or combustion carbon is captured and sequestered (CCS) as CO_2. ZH2 refers to a variant form of SMR+CCS developed by ZoneFlow Reactor Technologies, a Connecticut company. All forms of reforming can substitute renewable natural gas (RNG) for part or all their natural gas requirements. Such biogas is carbon neutral to the environment. When biogas is converted to RNG with CCS negative CO_{2e} emissions are created.

RNG carries credits called renewable identity numbers (RINs) that track physical molecules of pipeline quality natural gas with their zero-carbon footprint. The actual RNG and its associated RIN's can be sold together or separately on the open market. For example, it normally costs \$8-12/MMBTU (million BTU) to produce RNG which is sold for its heating value of about \$9/MMBTU in CT plus its RINs presently trading nationwide at about \$20/MMBTU. About 100 such projects are currently being executed in the US, limited only by the amount of targeted capital[2]. Production of hydrogen from methane can avail itself of RINs to create bona fide negative scope 1, 2, ands 3 CO_{2e} emissions for the production and consumption of energy.

EPA records indicate US landfills represent one opportunity for the effective conversion of landfill methane emissions to 3 MTPA of hydrogen[3] or 15 MTPA ammonia while converting 27 MTPA of CO2 emissions to 27 MTPA of direct air capture (DAC) of CO2, a net reduction of 54 MTPA CO_2.

ATR+CCS refers to the autothermal reforming process (ATR) with CCS. Whereas the SMR process uses natural gas both as a source of hydrogen and of heat, the ATR process reacts oxygen with natural gas to facilitate CCS at the expense of the additional carbon footprint of oxygen production. The CO_2 emissions of the electrolytic routes derive from production of the electricity they consume, with electricity from the CT grid, solar, and wind responsible for CO_2 emissions of 210, 46, and 21 g CO_2 /kWh, respectively.

						Electrolysis		
kg CO_{2e}/kg H2	**SMR**	**SMR + CCS**	**Z Fossil**	**Z Bio**	**ATR + CCS**	**Grid**	**Solar alone**	**Wind alone**
Contained in scope 1 natural gas consumed	9.72	10.33	10.07	10.07	9.71	0.00	0.00	0.00
Scope 1 CO_2 Capture	0.0%	96.2%	99.5%	99.5%	94.5%	0.0%	0.0%	0.0%
Sequestered	0.00	9.94	10.02	10.02	9.18	0.00	0.00	0.00
Scope 1 emissions	9.72	0.39	0.05	0.05	0.53	0.00	0.00	0.00
Scope 2 Natural gas	2.8	3.0	2.9	-10.02	2.8	0.0	0.0	0.0
Scope 2 Electricity CO_2	0.13	0.42	0.37	0.75	0.84	9.99	2.19	1.00
CO_2 scrubbers		0.15	0.14	0.14	0.14	0	0	0
Displacement by steam export	-2.2							
NET scope 1 + scope 2 emissions	**10.4**	**3.9**	**3.5**	**-9.1**	**4.3**	**10.0**	**2.2**	**1.0**

The "Z Fossil" and Z Bio" columns assume the use of NG and RNG, respectively, as feedstocks.

Note, the columns for solar and wind-based electrolysis are idealized. Because those are non-dispatchable sources of energy, they could only be the sole sources of electricity if enough

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[2] It should be noted Black Rock Capital invested \$200MM a few months ago in Vanguard Energy of Massachusetts, which converts manure and industrial food waste to RNG,

[3] Compared to present US production of 10 MTPA and world production of 80 MTPA hydrogen

overcapacity by a factor of 4 or so were available to the system and surplus energy were stored (at some additional cost) to levelize the electricity supply. Battery storage of electricity is only economical for round trips of up to 2-4 hours or it becomes too capital intensive. Energy storage in the form of hydrogen could be an option except it requires geology not available in New England. Electrolysis units become expensive from low utilization and degrade in performance if operated intermittently. The solar and wind columns are included as “what ifs” for comparison to solutions presently available.

The main assumptions used in calculating emissions and costs are shown in the following table.

Key economic assumptions		Source
3	Years of construction	DOE, 4/2022
25	years or operation	DOE, 4/2022
5.95%	Nominal Weighted Ave Cost of Capital	DOE, 4/2022
3.88%	Real WACC	DOE, 4/2022
$7.64	Industrial NG in CT, $/MMBTU[5]	IEA, last 60 months
$157.70	Industrial electricity in CT, $/MWh[6]	IEA, 8/2022
$20	Premium cost of RINs, $/MMBTU	
$840	Cost of electrolyzer, $/kw[4]	Footnote 4
Key environmental assumptions		**Source**
0.8%	Scope 1 NG leakage	DOE, 4/2022
36	kg CO_{2e} per kg CH_4	DOE, 4/2022
210	Scope 1 CT grid electricity, g CO_2/kwh	
46	Scope 1 solar electricity, g CO_2/kwh	
21	Scope 1 wind electricity, g CO_2/kwh	
95%	Precombustion CO_2 removal	DOE, 4/2022
90%	Post combustion CO_2 removal	DOE, 4/2022
70%	Electrolysis energy efficiency	Wikipedia

The alternative costs of hydrogen production in CT are listed in the table below using the methods of the NETL report.

Levelized costs of hydrogen (LCOH)	SMR	SMR + CCS	ZH2	ATR + CCS	Electrolysis
MMSCFD hydrogen	200	200	200	280	
metric tpy hydrogen	176,000	176,000	176,000	241,000	
Capital	$0.1318	$0.334	$0.247	$0.264	$0.384
Natural gas	$1.335	$1.420	$1.402	$1.335	$0.000
Electricity	$0.099	$0.319	$0.275	$0.632	$7.502
Other variable Costs	$0.042	$0.097	$0.082	$0.071	?
Fixed Costs	$0.067	$0.147	$0.114	$0.114	?
CO2 transport & Sequestration	$0.000	$0.099	$0.100	$0.092	$0.000
LCOH ($/kg H2)	**$1.68**	**$2.42**	**$2.22**	**$2.51**	**$7.89**
LCOH at of ATR+CCS at 200 MMSCFD with 0.7 scaling factor				**$2.62**	

The “ZH2” column assumes the use of natural gas as a feedstock. 45V tax credits are earned, as shown below, if credits from production of renewable natural gas are obtained, the credits stemming either from local production of RNG from CT landfills or the purchase of such credits from more distant producers.

The above costs would be reduced by the tax credits of the Inflation Reduction Act of 2022 (IRA), either taking advantage of the 45Q credits or the 45V credits, but not both (as stipulated in the Act). The 45V credits could be attractive if the rules (TBD) permit the purchase of carbon credits in the form of Renewable Identification Numbers (RINs), as in other commercial uses of RINs.

In the depiction of 45V tax credit possibilities in the following tables, both SMR+CCS and ZH2 are compared with minimal purchase of RIN's and minimal tax credits and with maximum RINs and credits. Note, the costs after taxes in the last table only consume enough RINs to satisfy the emission level of 0.45 kg CO_{2e}/kg H_2 to qualify for the highest 45V tax credit. Although the creation of negative emissions is feasible, there is no commercial incentive for those lower emissions.

	SMR	SMR + CCS	ZH2	ATR + CCS	Grid	Solar alone	Wind alone
LCOH (\$/kg H_2) before tax credits	**\$1.68**	**\$2.42**	**\$2.22**	**\$2.62**	**\$7.89**	**\$7.89**	**\$7.89**

45Q tax credit: \$85/ton CO_2 sequestered

	SMR	SMR + CCS	ZH2	ATR + CCS	Grid	Solar	Wind
45Q tax credit, \$/kg H_2	\$0.00	(\$0.85)	(\$0.85)	(\$0.78)	\$0.00	\$0.00	\$0.00
LCOH (\$/kg H_2) after 45Q credits	**\$1.68**	**\$1.57**	**\$1.37**	**\$1.84**	**\$7.89**	**\$7.89**	**\$7.89**

45V tax credit

Process	**SMR+CCS**		**ZH2**		**ATR + CCS**		**Grid**	**Solar**	**Wind**
45V emission target, kg CO_{2e}/kg H_2	**4.00**	**0.45**	**4.00**	**0.45**	**4.00**	**0.45**	**0.45**	**0.45**	**0.45**
NET emissions, kg CO_2/kg H_2	3.9	3.9	3.5	3.5	4.3	4.3	10.0	2.2	1.0
Required reduction via credits, kg CO_2/kg H_2	0.00	3.49	0.00	3.01	0.31	3.86	9.54	1.74	0.55
RINs needed, MMBTU/kg H2	0.00	0.05	0.00	0.05	0.005	0.06	0.14	0.03	0.01
Cost before RINs and tax, \$/kg H2	\$2.42	\$2.42	\$2.22	\$2.22	\$2.62	\$2.62	\$7.89	\$7.89	\$7.89
Cost of RINs, \$/kg H2	\$0.00	\$1.06	\$0.00	\$0.91	\$0.09	\$1.17	\$2.89	\$0.53	\$0.17
45V credit, \$/kg H2	(\$0.60)	(\$3.00)	(\$0.60)	(\$3.00)	(\$0.60)	(\$3.00)	(\$3.00)	(\$3.00)	(\$3.00)
LCOH (\$/kg H2) after 45V credits	**\$1.82**	**\$0.47**	**\$1.62**	**\$0.13**	**\$2.12**	**\$0.79**	**\$7.77**	**\$5.41**	**\$5.05**

In summary and for discussion, it appears that the ZH2-Biotechnology with CCS would have the lowest emissions and costs for hydrogen production in CT.

Steam reforming with CCS requires disposal of CO_2, either to industrial use of the gas or through CO_2 pipelines to sites for CO_2 sequestration. Regarding the latter, of the \$0.75/kg incremental CO2 avoidance only \$0.10/kg is attributable to CO_2 transportation and sequestration. Because CO2 avoidance is insensitive to the minor costs of CO2 transportation and sequestration, there is room for CO_2 pipeline transportation to be quite profitable. It is not cost but permits and legislation that will enable this (most likely) least expensive route of reducing GHG emissions to be deployed soon. Additional comments on this infrastructure topic will be submitted separately.is attributable to

Finally, reduction of NG leakage is imperative for all uses of NG, including hydrogen production. Poli to reduce natural gas leakage is addressed in a separate submission. Note, however, that no such leakage is associated with the ZH2-Bio solution described above.

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