Decarbonization Options for the Future

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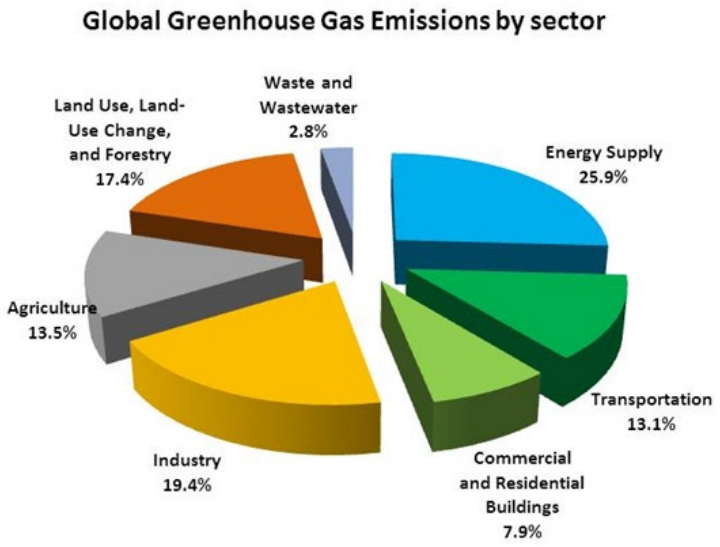
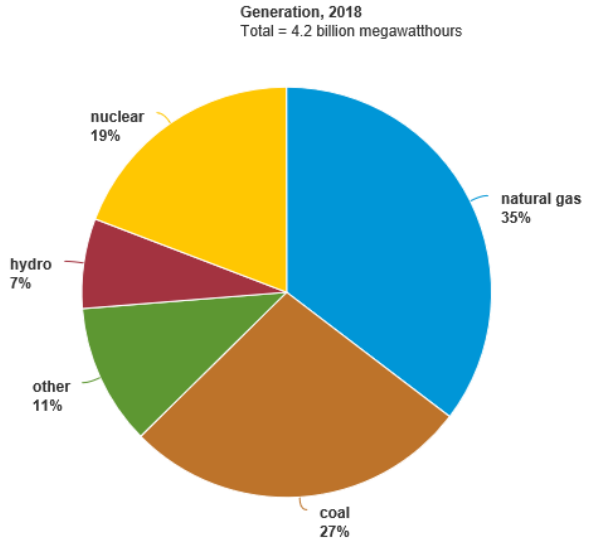
Solar® Turbines
A Caterpillar Company

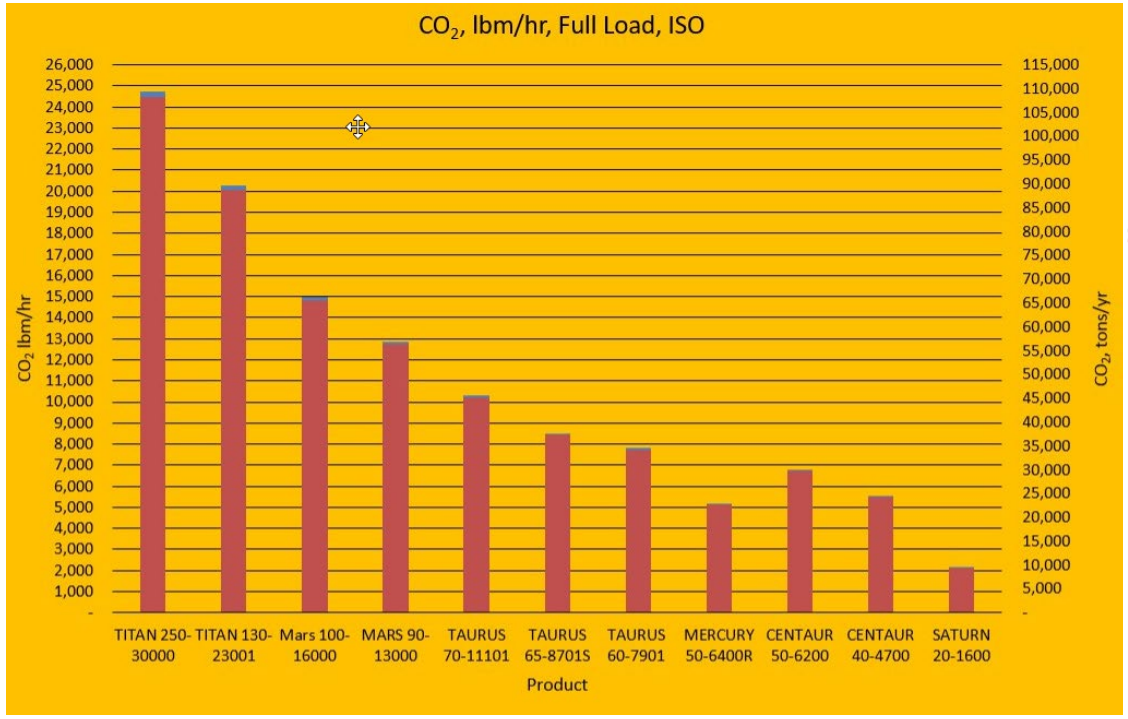
Addressing the Concern of Climate Change

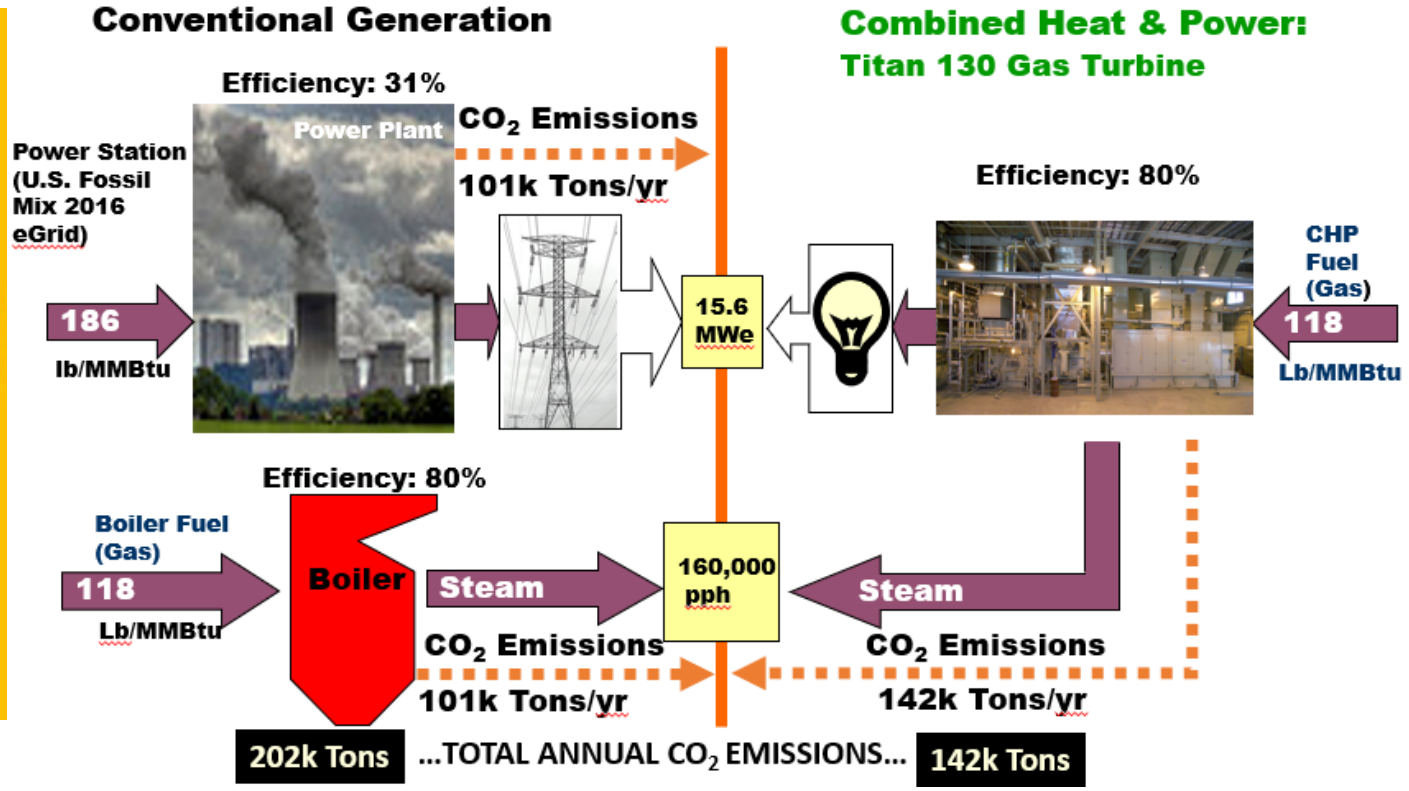
- CO2 from burning fossil fuels is contributing to global warming and climate changes
- Renewable energy sources are helping mitigate this impact, but is far from the ultimate solution
- Using intermittent renewable energy does not always keep buildings powered, warm and cool
- Using electrification for transportation and building heating will require significant increase in electricity supply and upgrades to T&D
- A wide variety of solutions will be required based on location and local resources





First, Our CO2 Footprint w/CHP is Not so Bad





Possible Options with our Gas Turbines

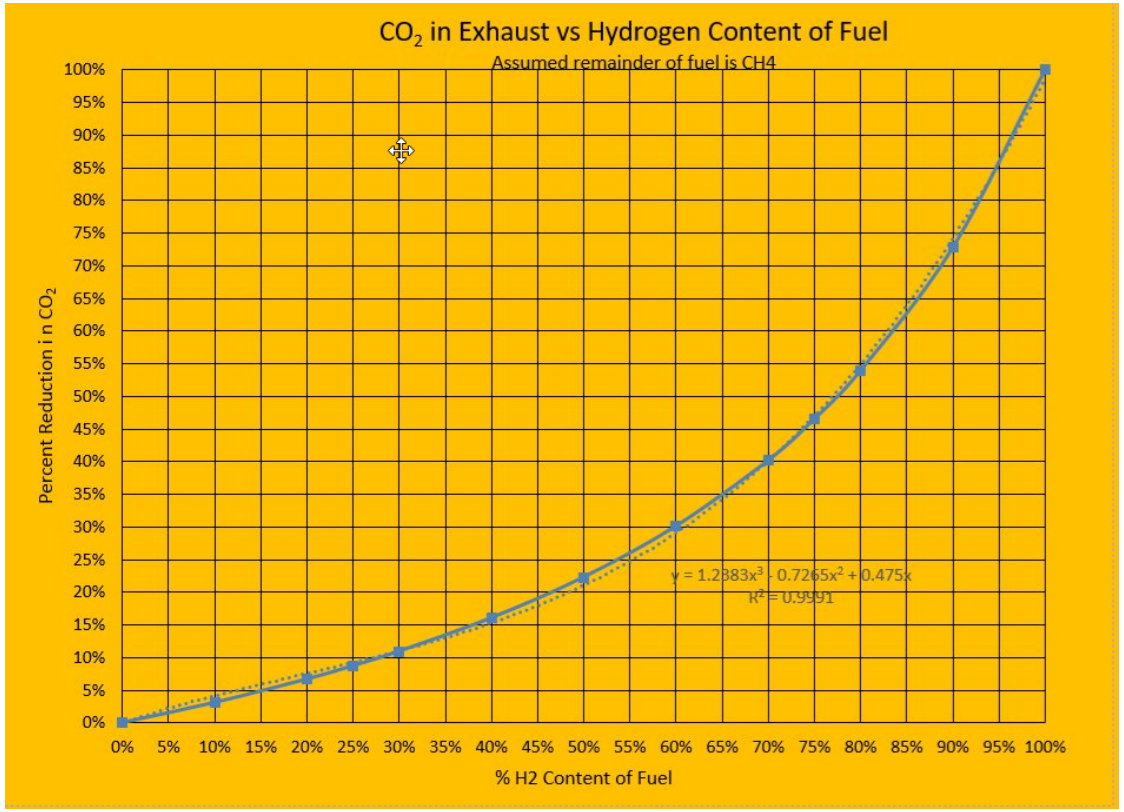
- Use of carbon neutral fuels
- Sequester CO2 from exhaust
- Convert exhaust CO2 to other products
- Improve efficiencies

Possible Carbon Neutral Fuel (CNF) Options

- Hydrogen* (Blue and Green)
- Renewable Diesel (From waste sources, meets ASTM D6751 specs)
- Biodiesel* (Mono Alkyl Esters mostly from soybeans)
- Dimethyl ether (CH3-O-CH3, renewable if made from biomass or waste)
- Gasified biomass or municipal waste*
- Renewable natural gas*
- Digester or landfill gases (CH4 and CO2, issue is high CO2 concentrations)
- Ammonia (Hydrogen carrier, major NOx producer)

*More information in subsequent slides

Hydrogen has Potential as CNF

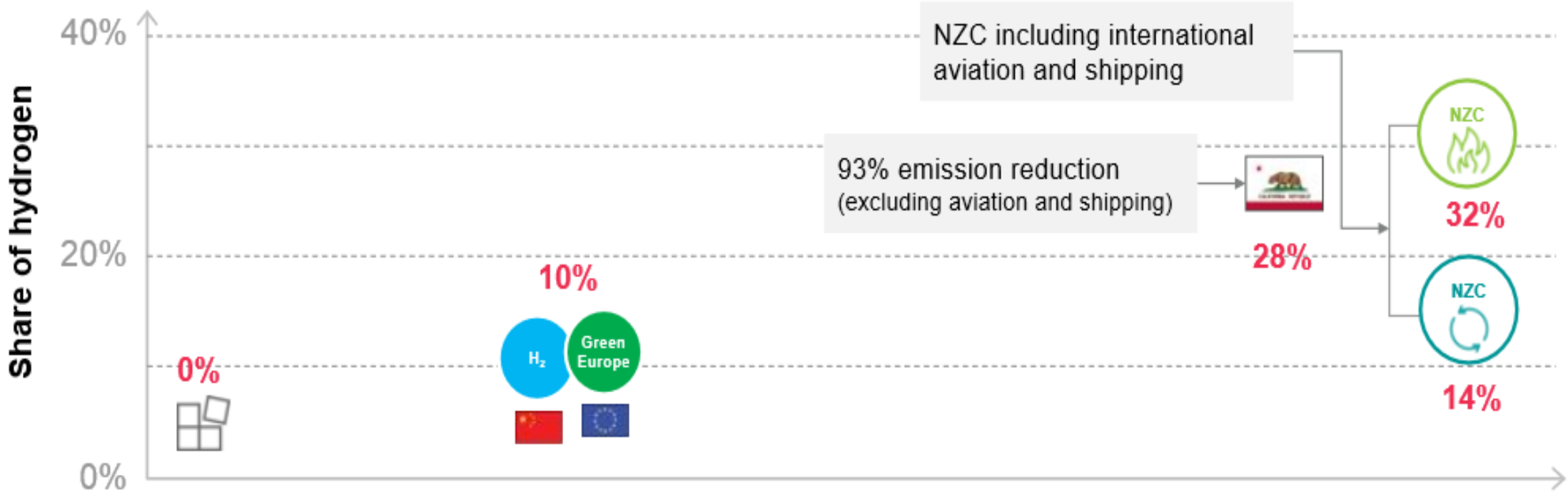


But:

- Where will it come from: SMR, electrolysis, etc.
- Safety concerns, storage, flammability, NOx, LEL, etc.
- Large water and electricity requirements for electrolysis
- Need high H2 volume % to make significant CO2 reductions
- Cost can range from $20/MMBTU to $35/MMBTU

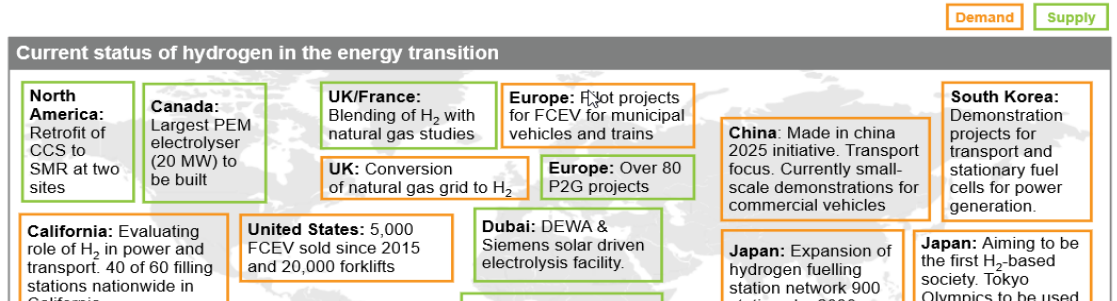
Hydrogen and low-carbon gas has the potential to provide as large a share as natural gas today

Share of hydrogen in final energy in the IHS Markit outlooks - 2050



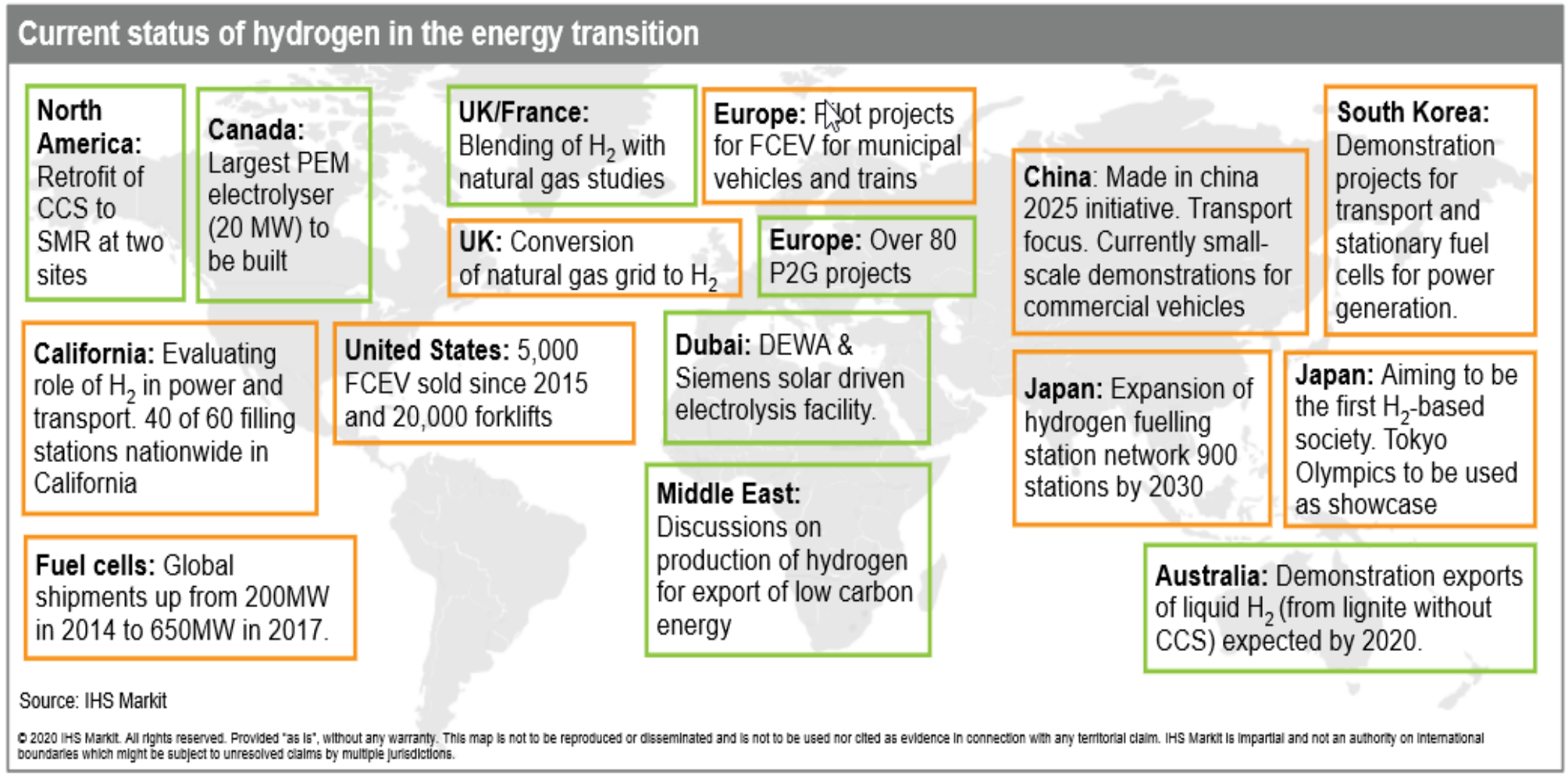
Source: IHS Markit

Low-carbon hydrogen is being developed globally



Low-carbon hydrogen is being developed globally

Demand Supply

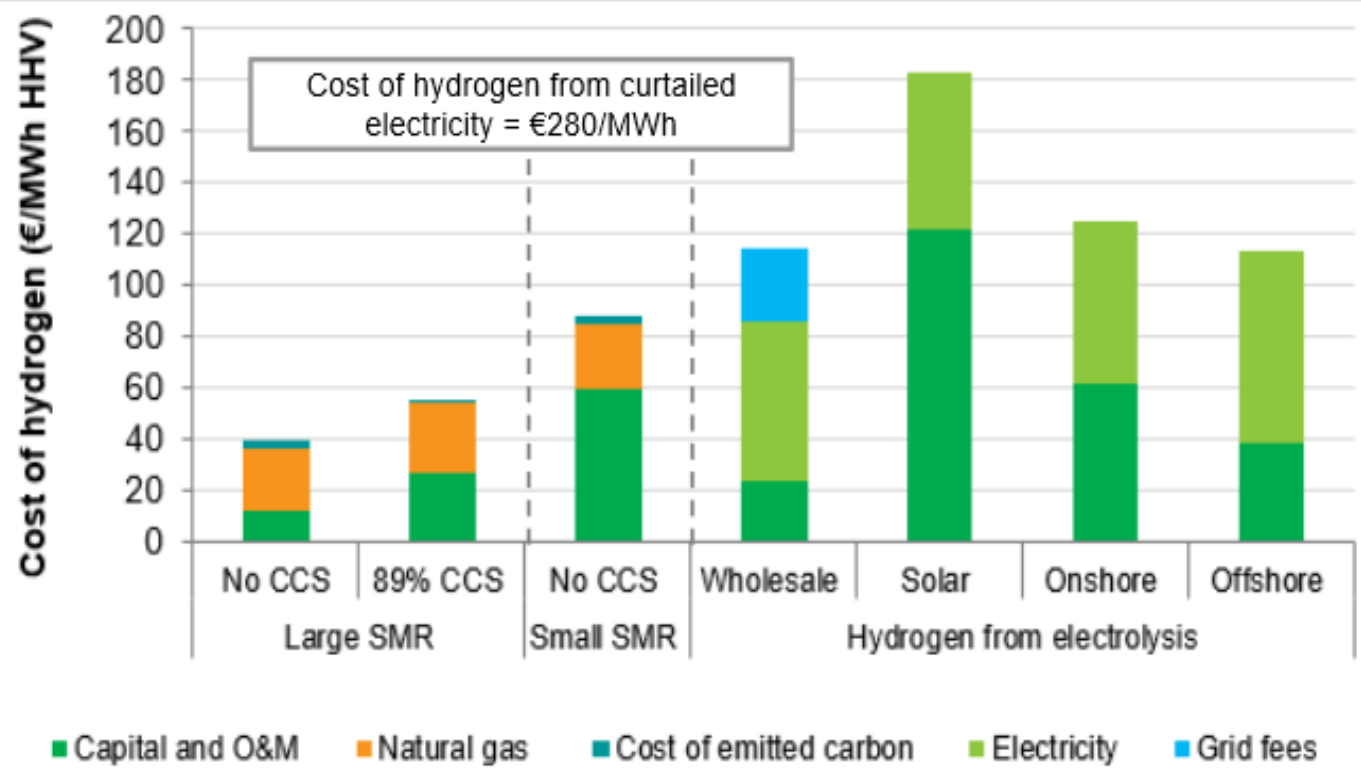


Source: IHS Markit

On an energy basis, hydrogen is approximately twice the cost of natural gas

Today, the lowest-cost hydrogen (outside China) is produced from natural gas…

Levelized cost of hydrogen at the boundary of the production facility in Germany, 2020



Note: October 2019. SMR = steam methane reformer; O&M = operations and maintenance; HHV = higher heating value.
Source: IHS Markit

Year	2020
Location	NW Europe
Electrolyser capacity (MWe)	20 MW
Large SMR capacity (Nm^3/h)	100,000
Small SMR capacity (Nm^3/h)	2,000
Carbon price (€/tonne)	25

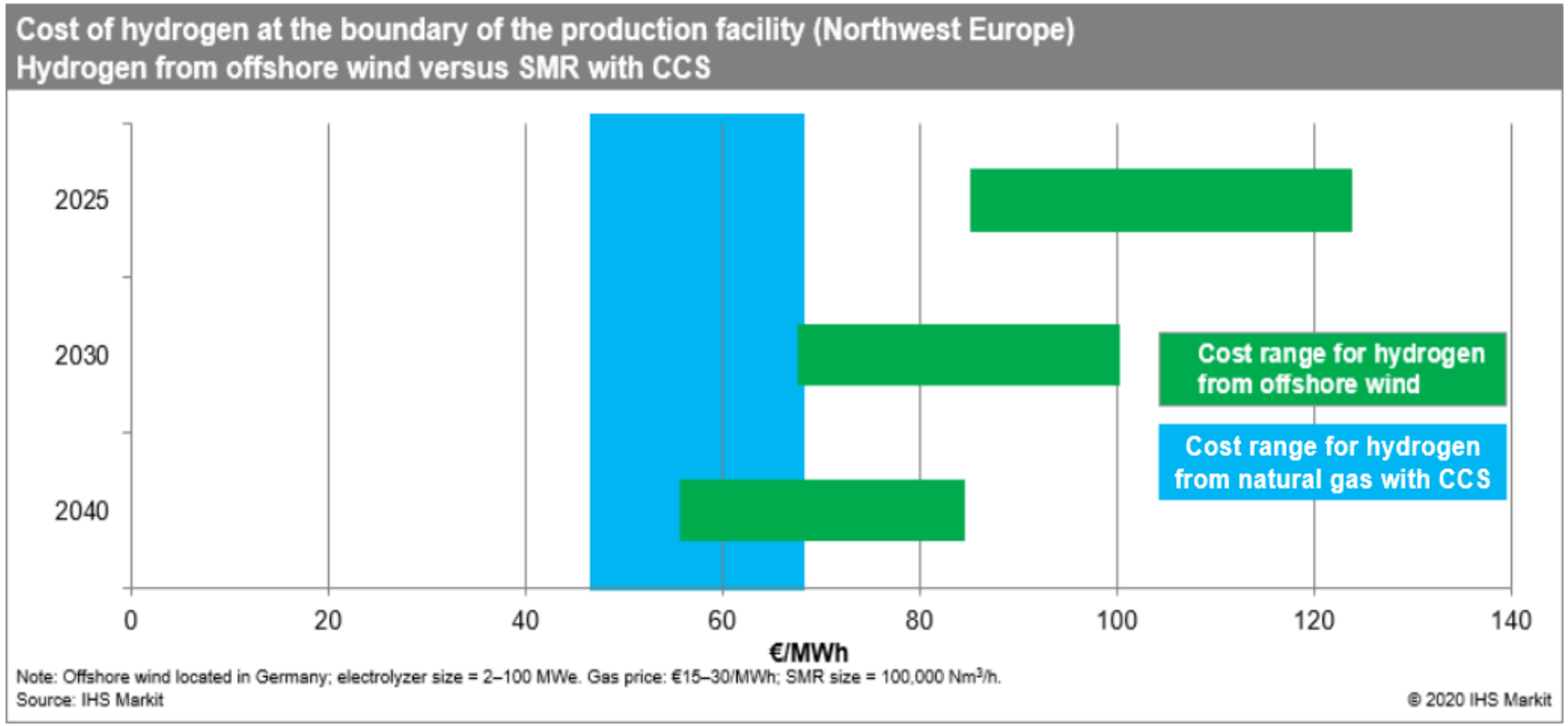
Feedstock assumptions

	Fuel price (€/MWh)	Capacity factor (%)
Natural gas	20	95%
Curtailed electricity	0	5%
Grid electricity	45 + 20 fees	95%
Solar	45	12%
Onshore wind	46	26%
Offshore wind	54	47%

Source: IHS Markit

Can Hydrogen Cost Decline

…but costs of electrolytic hydrogen are expected to fall rapidly



What is Future for Biodiesel

Reacting: In the presence of a catalyst Yields:

100 Lbs. Vegetable Oil or Animal Fat

+

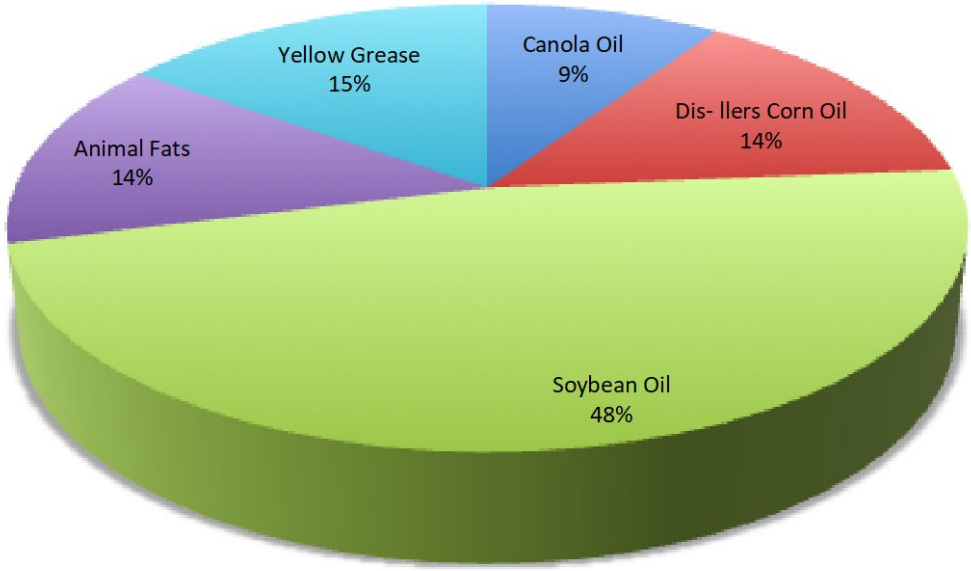
10 Lbs. Alcohol

100 Lbs. Biodiesel

+

10 Lbs. Glycerine

Produces mono-alkyl esters – chemically similar to diesel fuel



More supplies becoming available when co producing proteins for use with oils as a byproduct

More on Biodiesel

Biodiesel's Low Carbon Footprint

Biodiesel Reduces Global Warming

- **80% Overall Reduction in Full Life Cycle Carbon Emissions (Direct Impacts):**
  - Meets EPA RFS 'Advanced Fuel' Definition
  - B20 Provides 16% Carbon Reduction

- **Biodiesel Generates RFS2 RINs**
  - Biomass Based Diesel Category
  - Advanced Category

Cost today are still a bit high,
but will come down w/ CO2 credits, etc.?

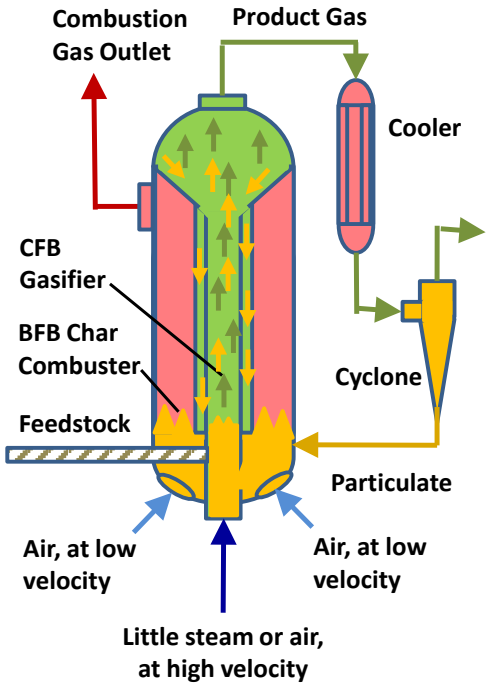
Biodiesel Improves Diesel Properties

- Blends with petrodiesel in any percentage
  - Once it is blended it does not separate back out
- Higher Cetane
  - Over 50 vs. average petrodiesel around 44
  - Smoother, more complete burn
- Higher Lubricity
  - 2% biodiesel 'fixes' even bad diesel
- Virtually Zero Sulfur
  - Meets ULSD limits of 15 ppm or less
- Zero Aromatics Reduces Toxicity and Burns Cleaner
- 11% Oxygen Provides Superior Lubricity and Reduces Black Smoke (Particulates)
- High Flash Point Makes it Safer
  - Non hazardous shipping (over 200 F)

Bidiesel emission compared with DF#2			
	B20	B50	B100
NOx	+2%		+13%
CO	-20%		-50%
UHC	-30%		-93%
Smoke			

Gasified Biomass or MSW is a Possibility

50 MWe MSW Gasification Project in UK

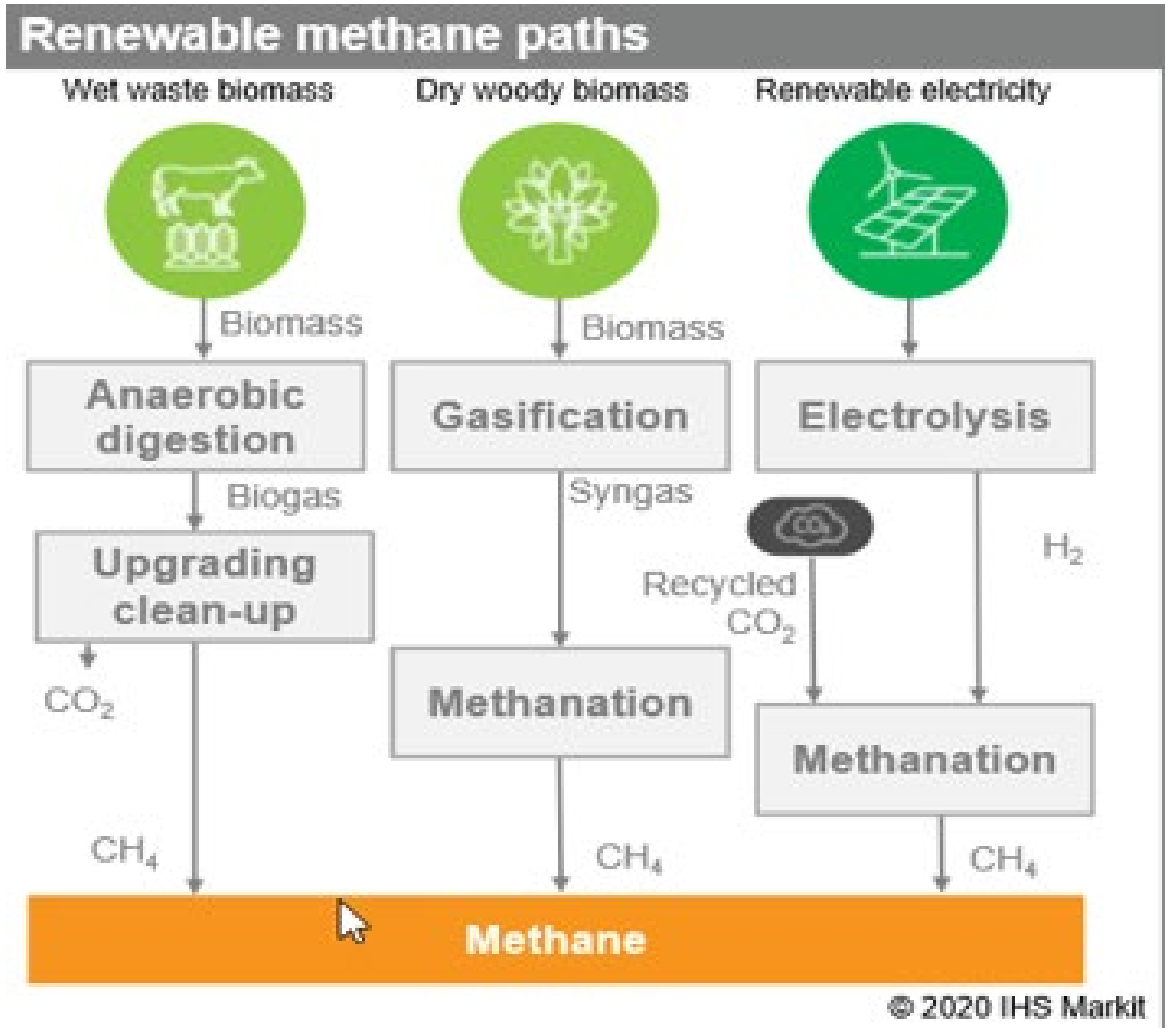


Milena Gasifier

But:

- Need reliable source of biomass or MSW
- Gasification to syngas has high initial capital cost
- Cost can be lowered with MSW tipping fees or waste biomass
- Good gas cleaning a requirement

Renewable Natural Gas is an Option



But:

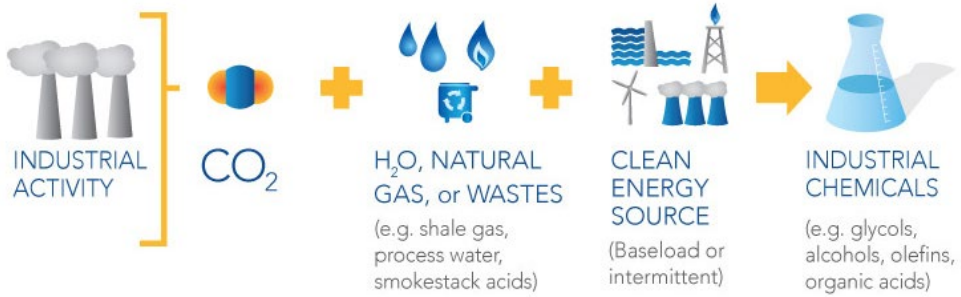
- It is defined as renewable, but supply is ltd
- Better if produced locally and used without expensive pipeline quality improvements when considering digestion or gasification
- Methanation requires CO2 source and is relatively expensive when taking into account electrolysis, etc.
- Premium today for RNG is 300%+ over NG

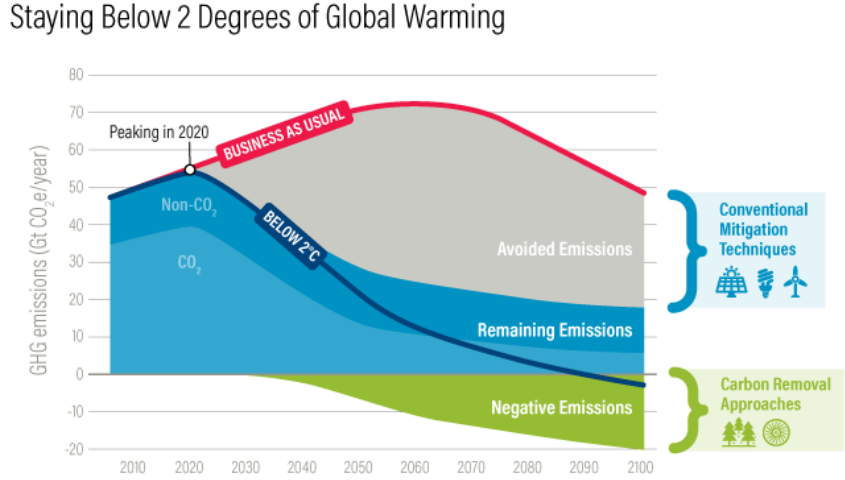
Gas Source	Carbon Intensity (g CO_2e/MJ)
California Natural Gas (Traditional)	78.37
Landfill Gas	46.42
Dairy Digester Gas	-276.24
Wastewater Treatment	19.34
Municipal Solid Waste (MSW)	-22.93

Source: California Air Resources Board

Future of Post Combustion Carbon Capture

- First Step - CO2 sequestration
- Second Step – Viable use of sequestered CO2





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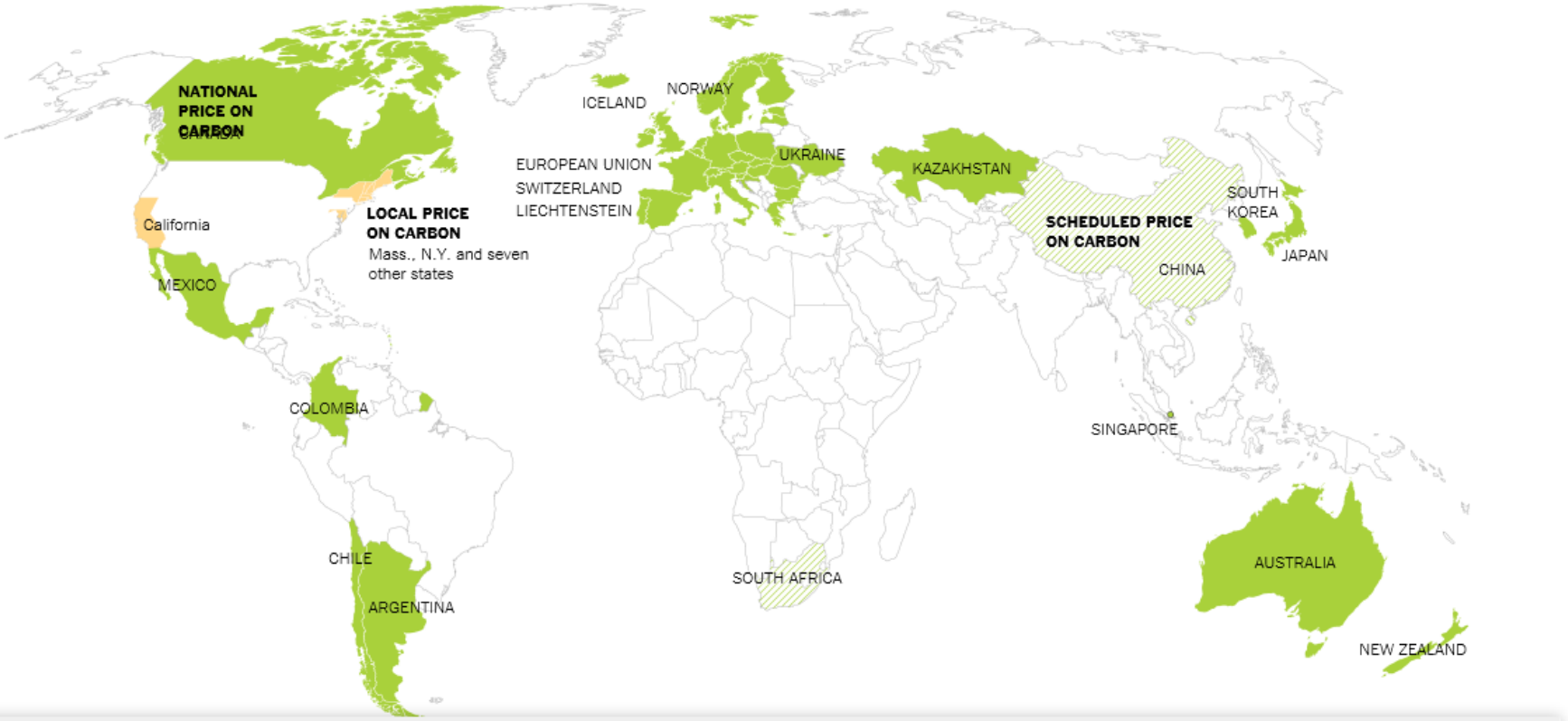
INTERNATIONAL DISTRICT ENERGY ASSOCIATION

Caterpillar: N

CO2 Sequestration will be Needed

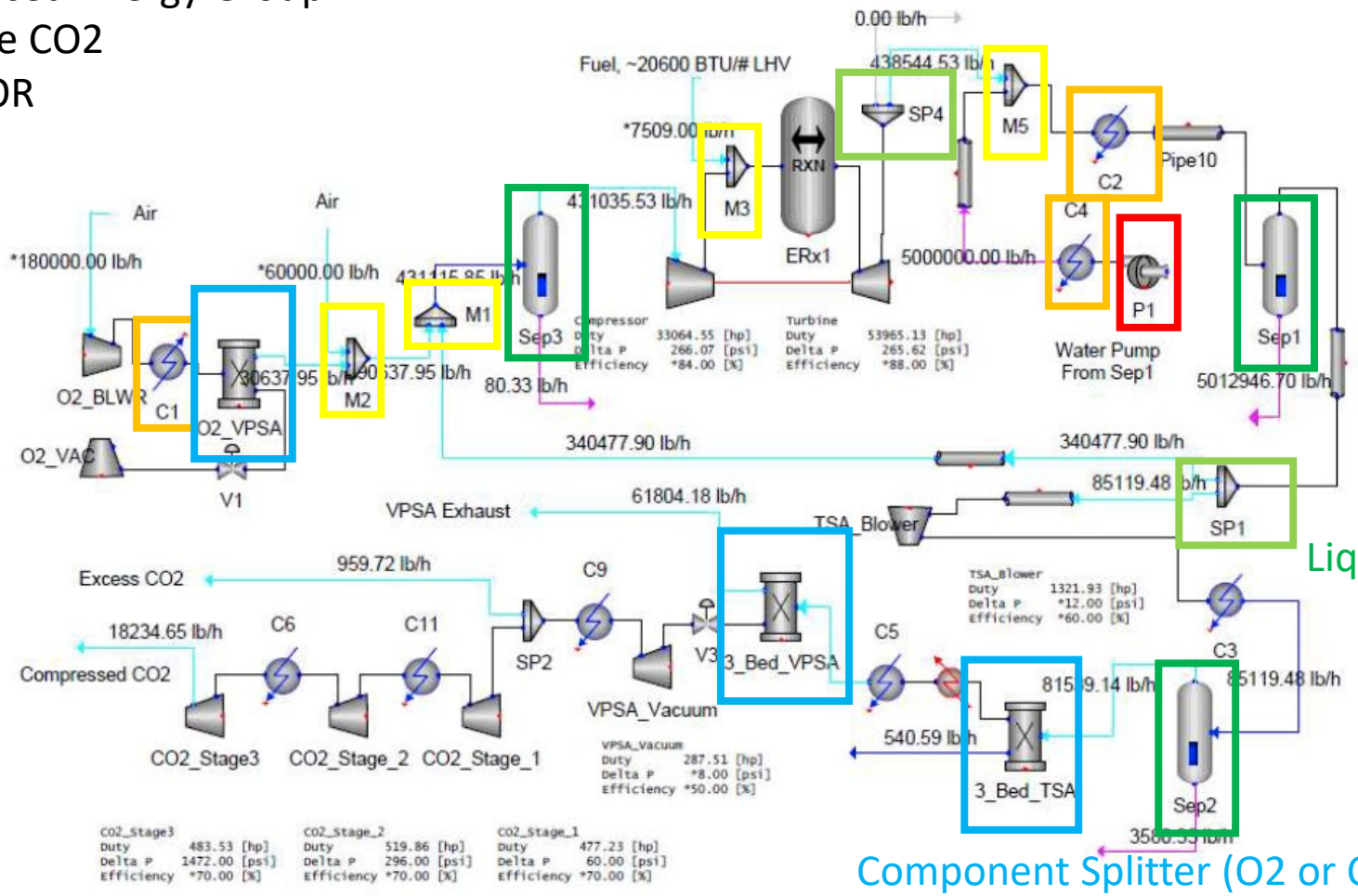
These Countries Have Prices on Carbon. Are They Working?

By BRAD PLUMER and NADJA POPOVICH APRIL 2, 2019



EGR and Carbon Capture with Titan 130

Working with Enhanced Energy Group on Semi Closed Cycle CO2 Sequestration for EOR



Pump

Cooler

Mixers

Splitter

Liquid Separators

Component Splitter (O2 or CO2 separation)

Potential Uses for Sequestered CO2

Phytonix Process

using

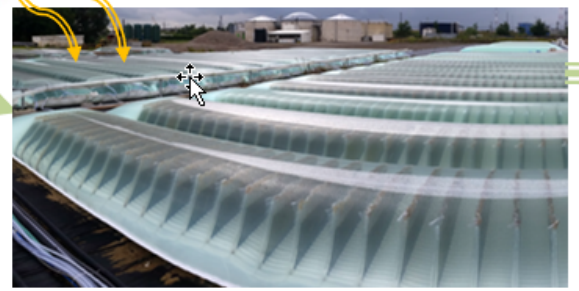
modified photosynthesis

Phytonix Solar Chemicals

❶ Flue Gases Containing CO_2 Emissions

Sun

❷



(Photobioreactor)

(Industrial Plant)

❸ Phytonix Butanol

Produces

❺ Target Production Cost

≈ $2.00/gallon

(± 25%)

Wholesale Price

≈ $6.75/gallon

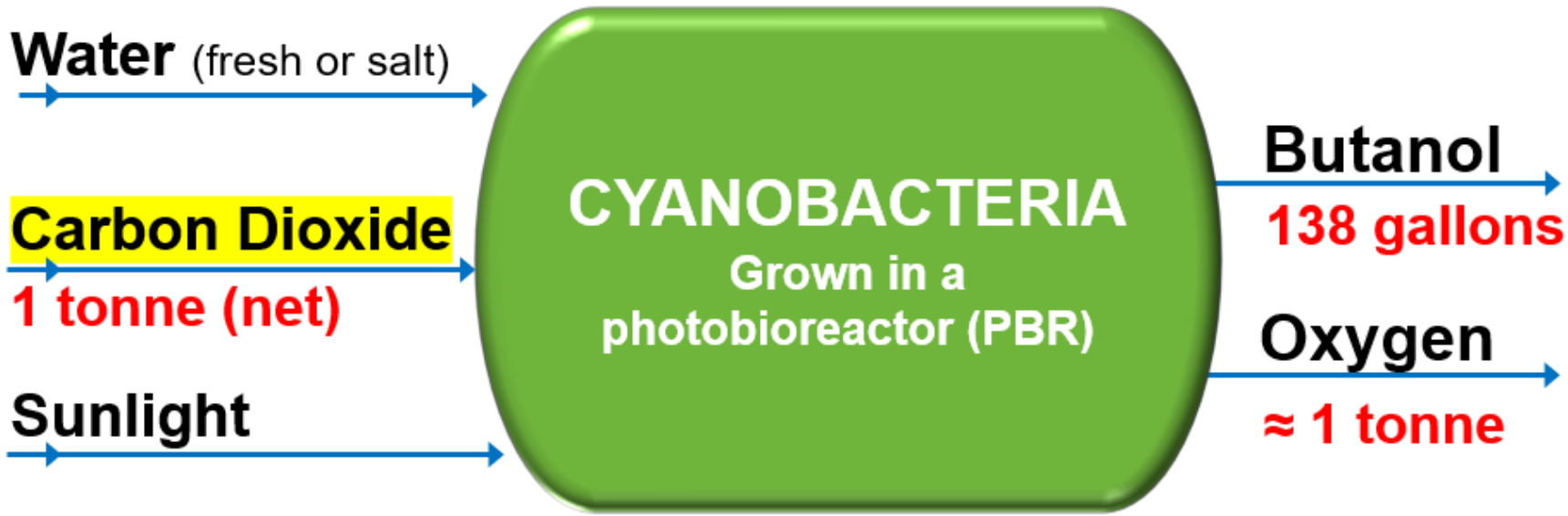
❹

High-Value, High-Margin Product

Production cost of incumbent producers to make butanol from propylene ≈ $4.75/gallon

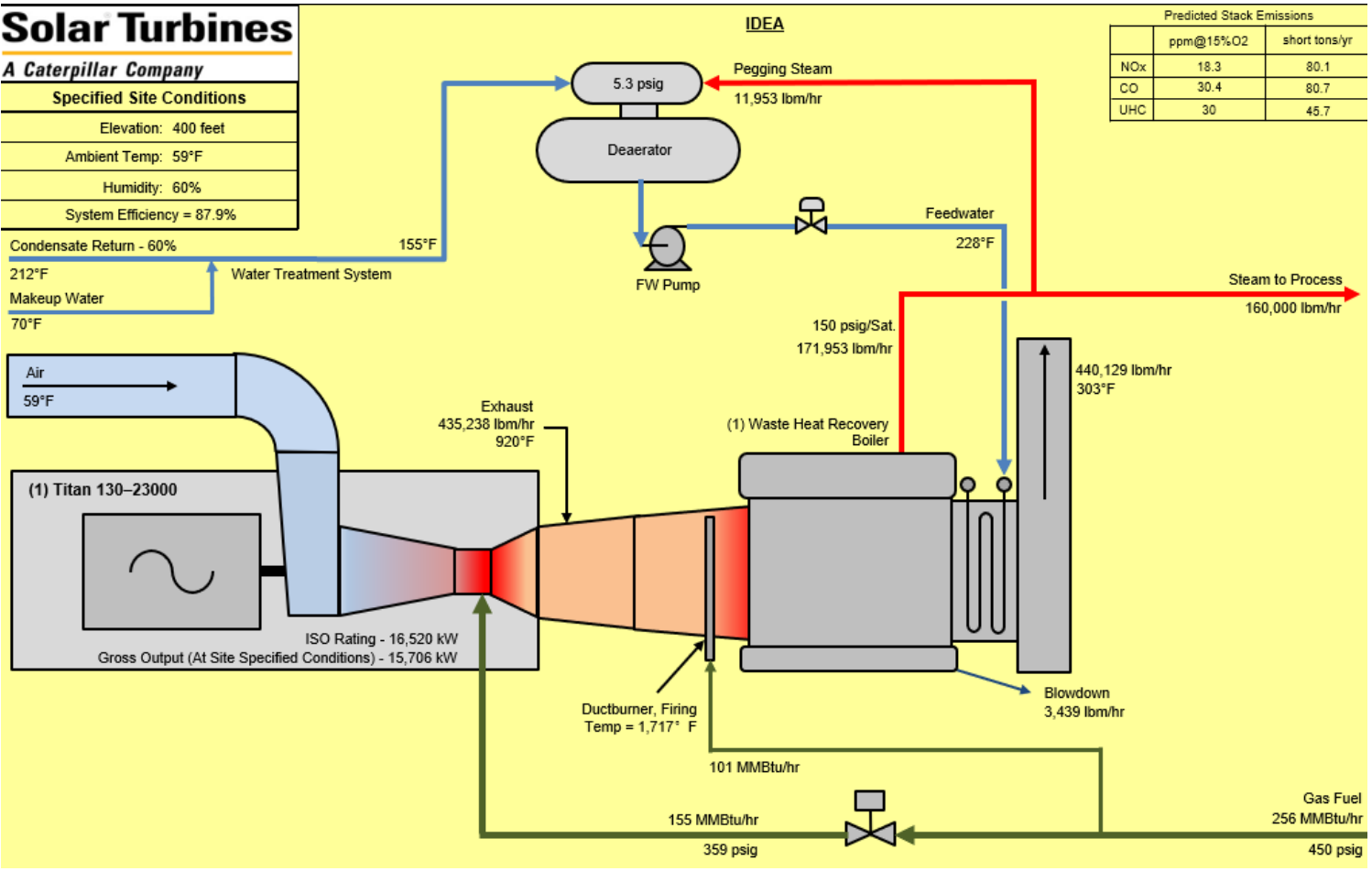
Phytonix uses genetically modified cyanobacteria, a tiny aquatic plant, to convert CO_2 and water into butanol using photosynthesis. ***Each microbe functions as a "miniature chemical factory".*** *Cyanobacteria are cultivated outdoors in the sun, in photobioreactors containing water and nutrients.*

Phytonix engineered cyanobacteria converts CO_2 into sustainable butanol



Reduction in GHGs is 3X - 4X the CO_2 consumed as sustainable Phytonix butanol will displace butanol made from propylene, a petroleum derivative.

Improving Efficiency

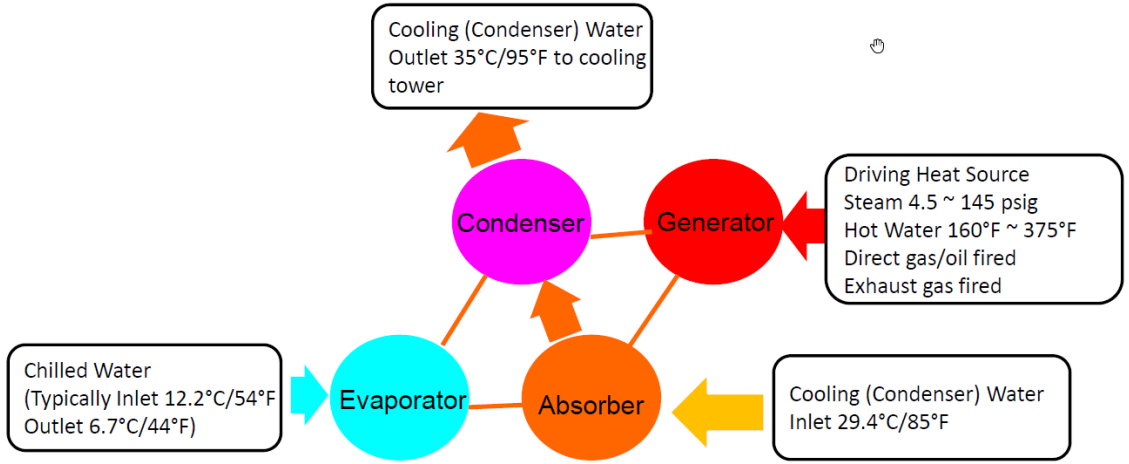


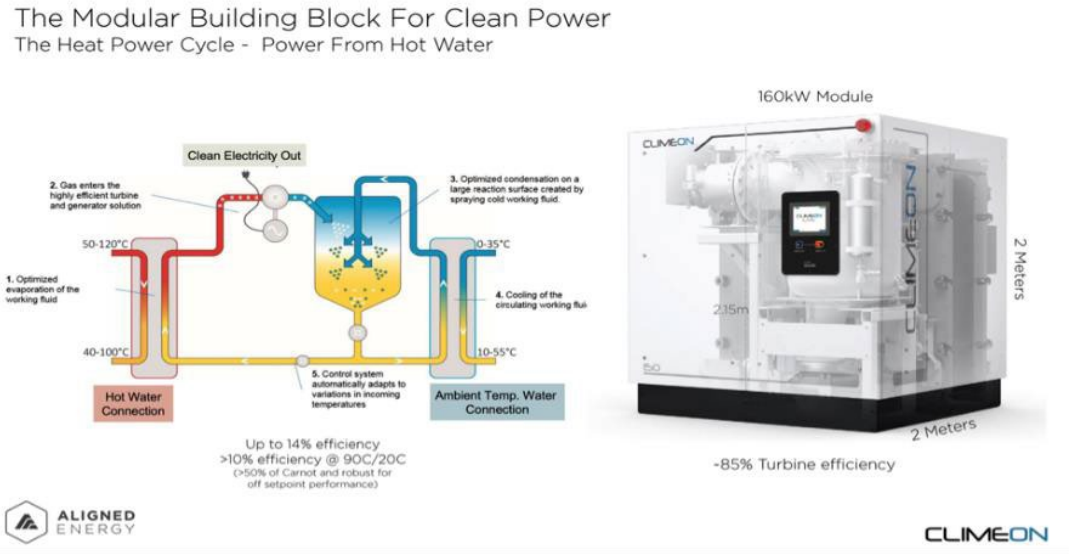
How:

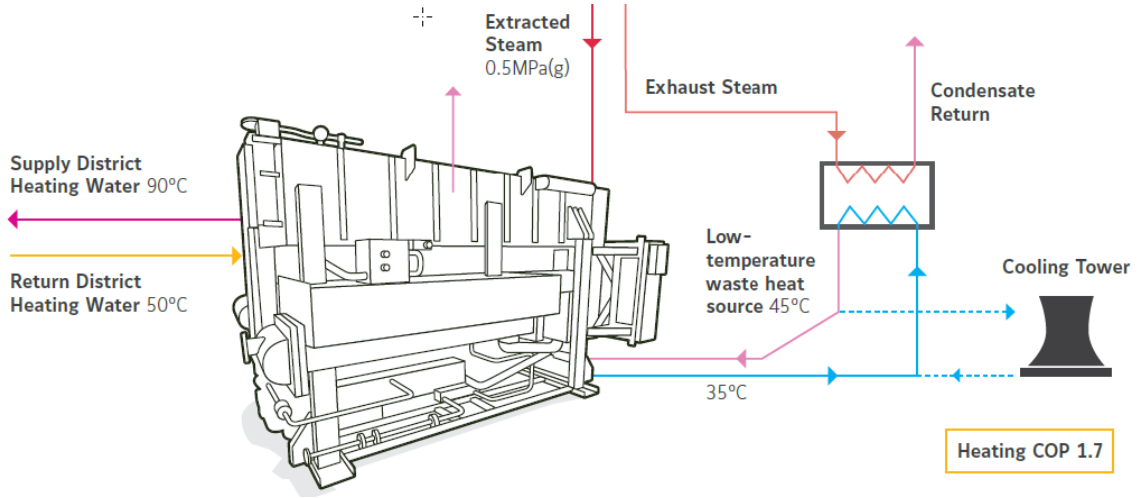
- Typical HRSG Exhaust 275 F to 300 F
- Titan 130 can provide an additional 16.3 MM BTU/h if using lower temperature media source
- Assume 80 F water supply could get the exhaust temperature to 150 F providing 16.3 MM BTU/h of additional heat
- Improves LHV efficiency to 91%
- Media temperature could be 180 F to 220 F hot water

What to do with this Low Grade Heat?

- Hot water for heating
- Absorbers for cooling
- Use with heat pumps
- Can make more power







Thank You, Any Questions?

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