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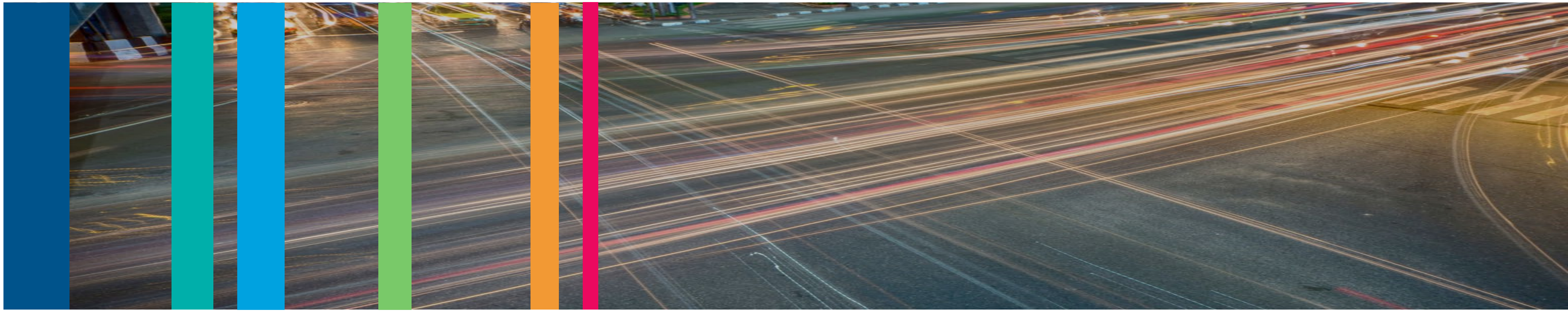


Benefits and Challenges for Governments Applying UNFC – The Hydrogen Puzzle

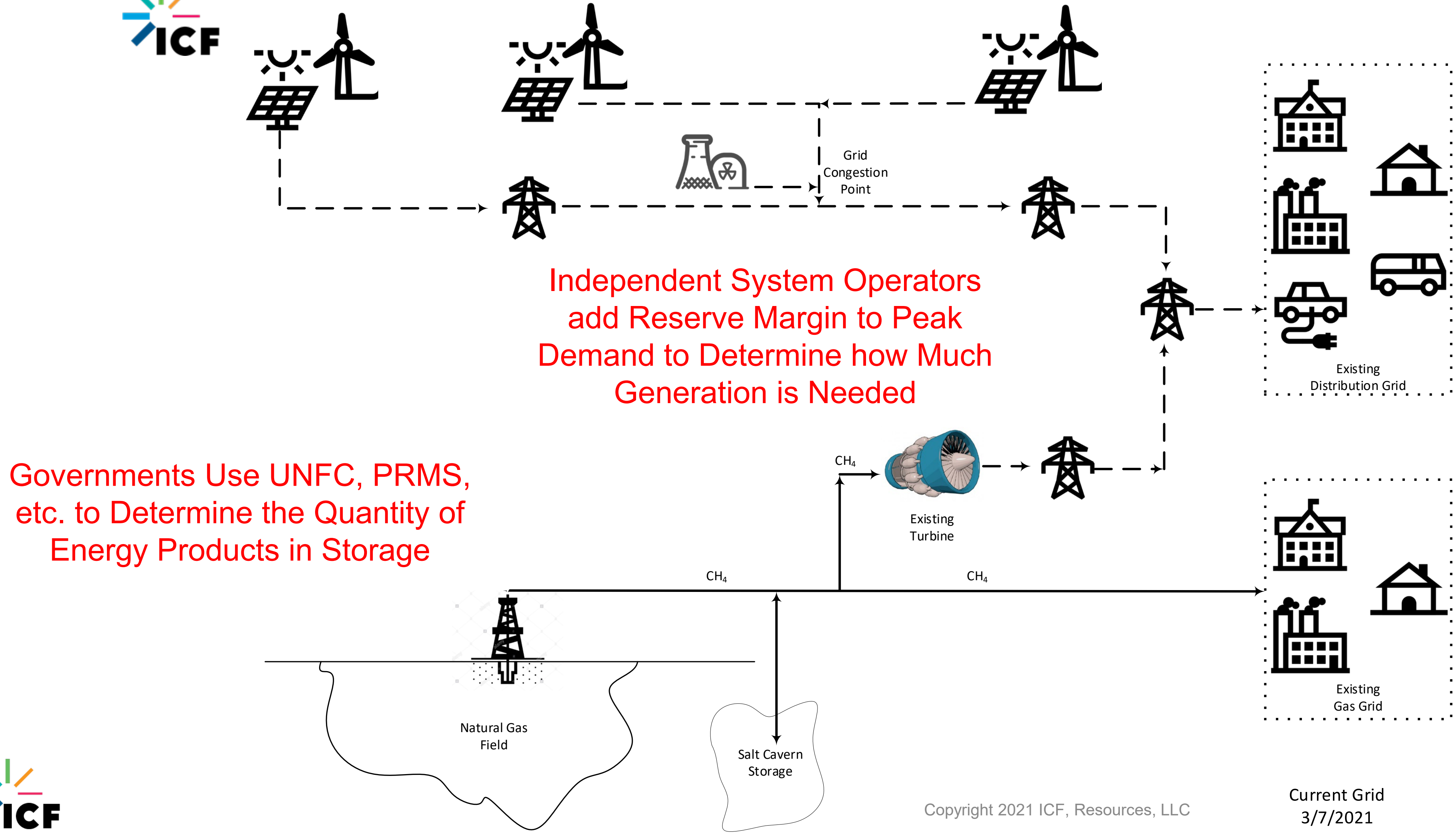
Mike McCurdy, Managing Director, Fuels & Power

10/5/2021

Agenda

- Existing Fossil Systems Use UNFC to Establish Energy Product Quantities in Storage
- Low Carbon Systems are More Complex, Both Dispatchable Power and Storage Requirements
- Hydrogen Potential is Vast in Quantities and Who Can Produce It
- The First Disappearing Energy Product?

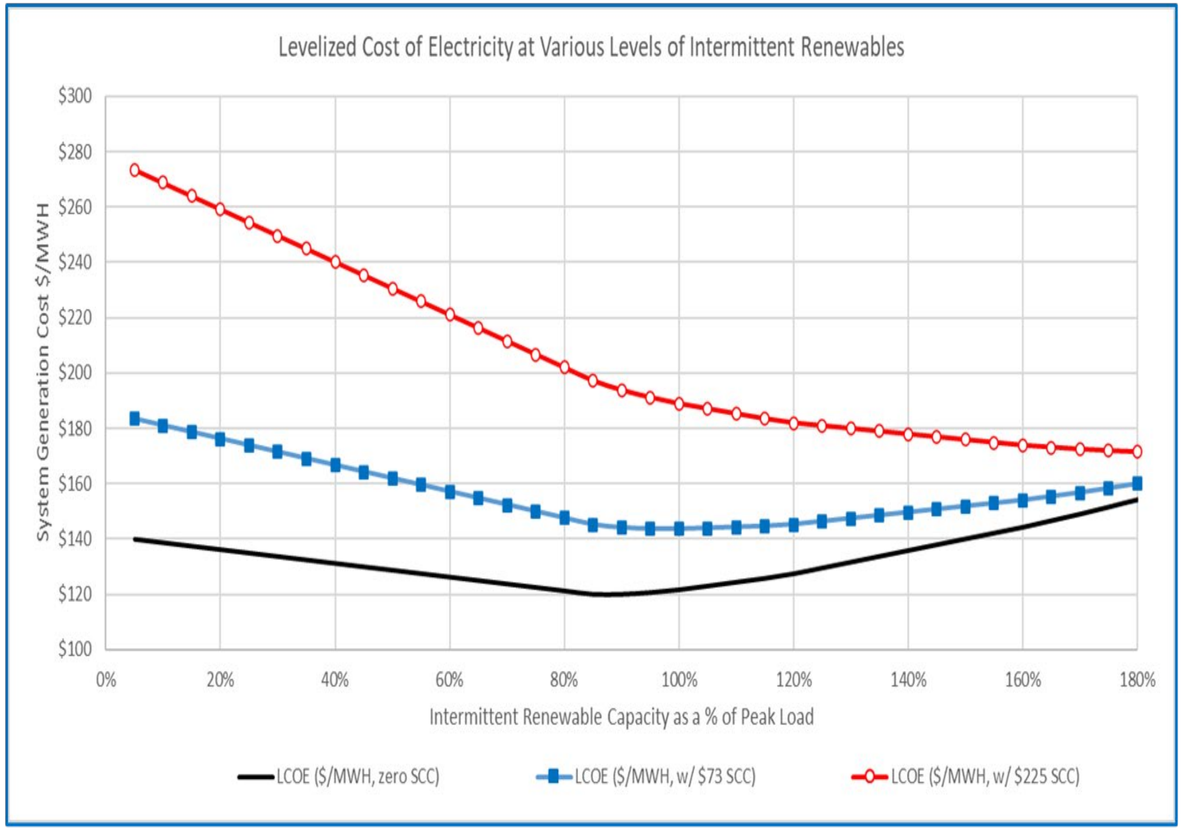
Existing Energy System Uses Reserve Ratio and UNFC to Quantify Resiliency

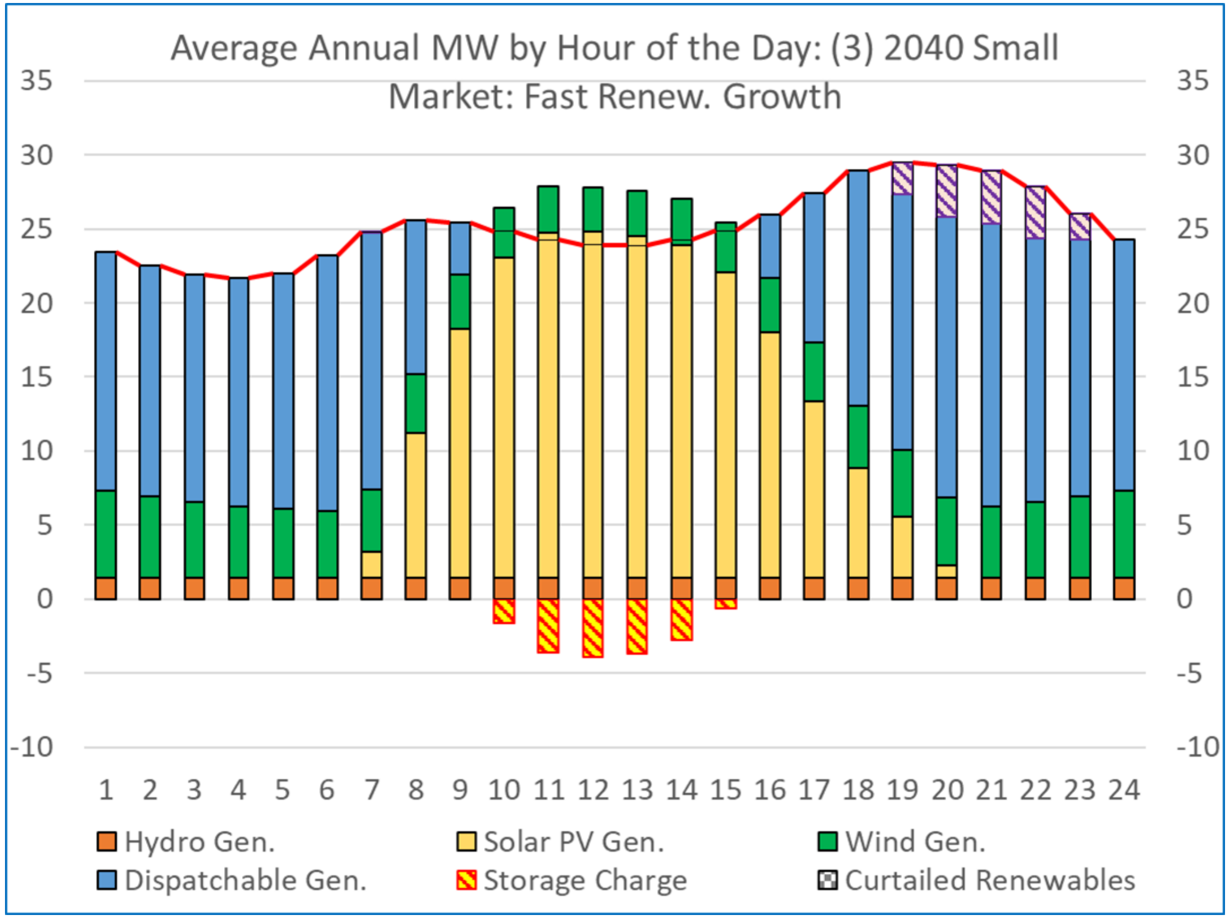


Current Grid
3/7/2021

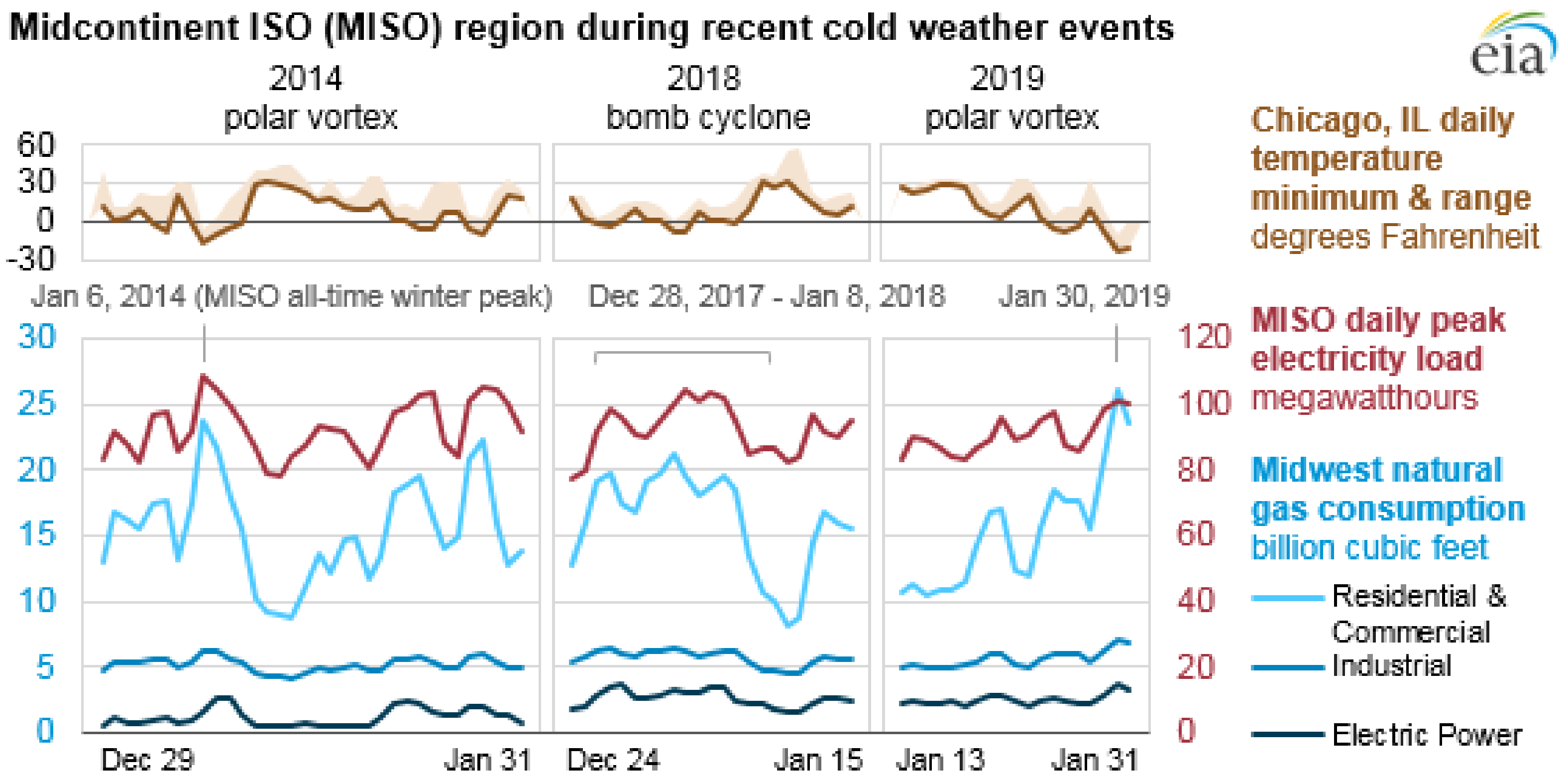
Future Systems Are More Complex, and You Can't Just Add More Renewables….

Renewable Penetration in Isolated Island Grid





Natural Gas System (Chemical Storage) Currently Provides Peaking and Long-Term Storage Capacity

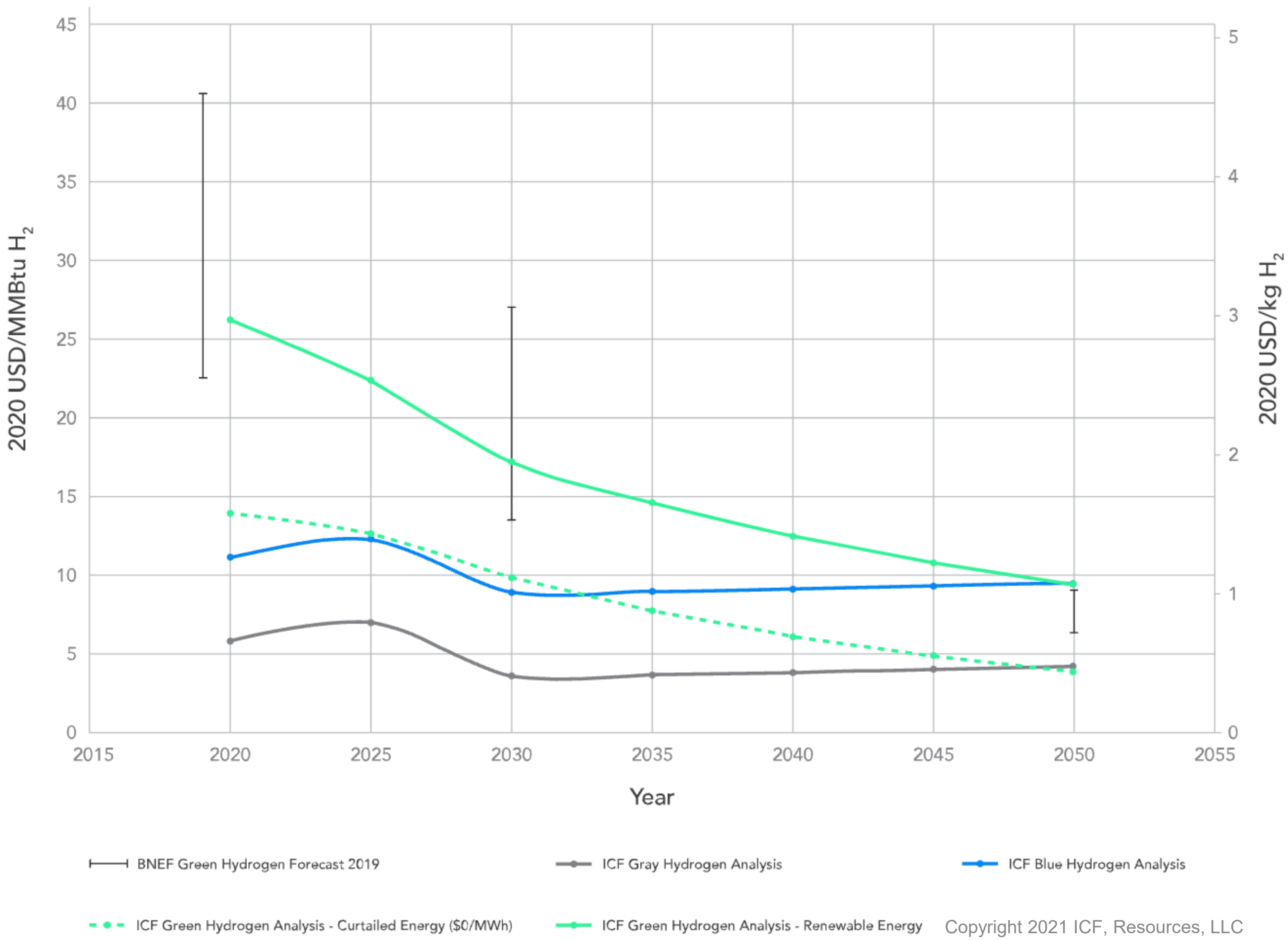


https://www.eia.gov/todayinenergy/detail.php?id=38472

- Demand can double or even treble in days, difficult for battery storage
- Battery storage economically viable for 4-8 hours
- ERCOT would have needed ~90 hours this spring

https://www.icf.com/insights/energy/economics-hydrogen-energy

Hydrogen production cost



ICF analysis assumptions:

- 3% annual maintenance as percentage of Capex
- Used 2018 DOE case studies for initial Capex costs

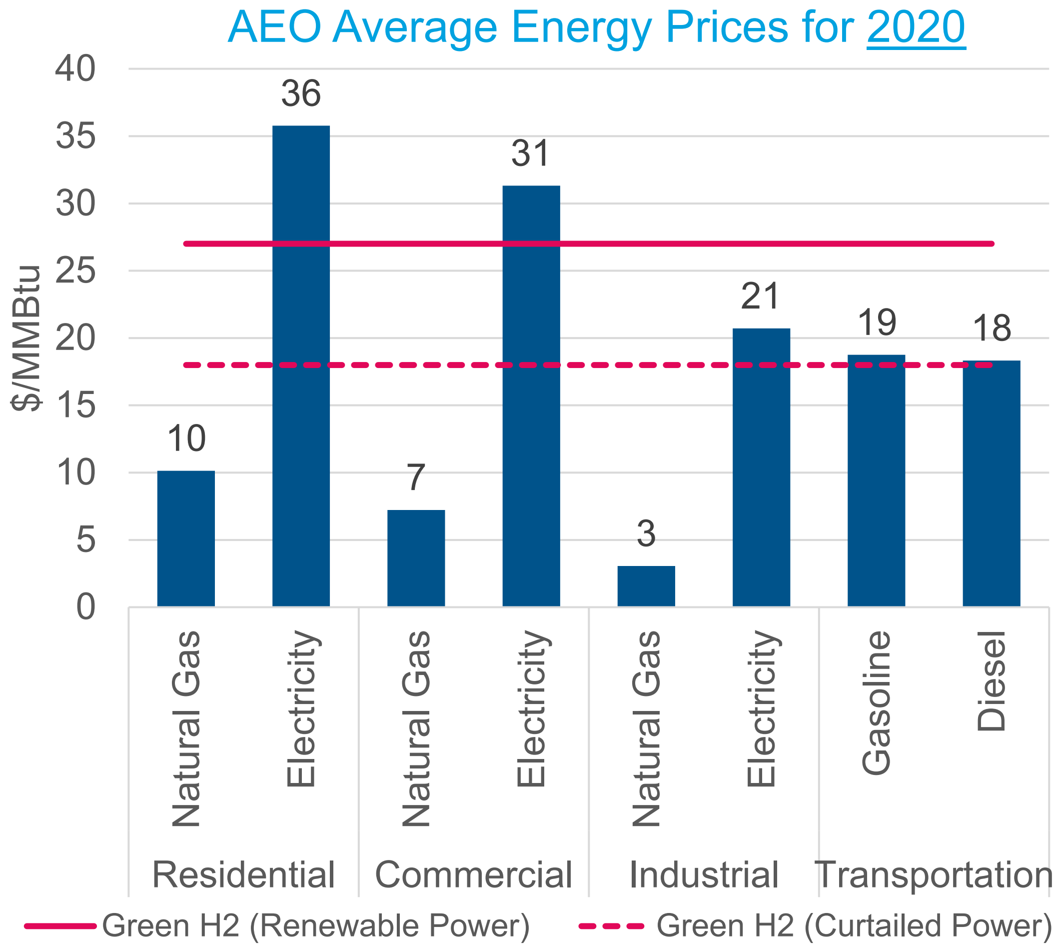
Green Hydrogen

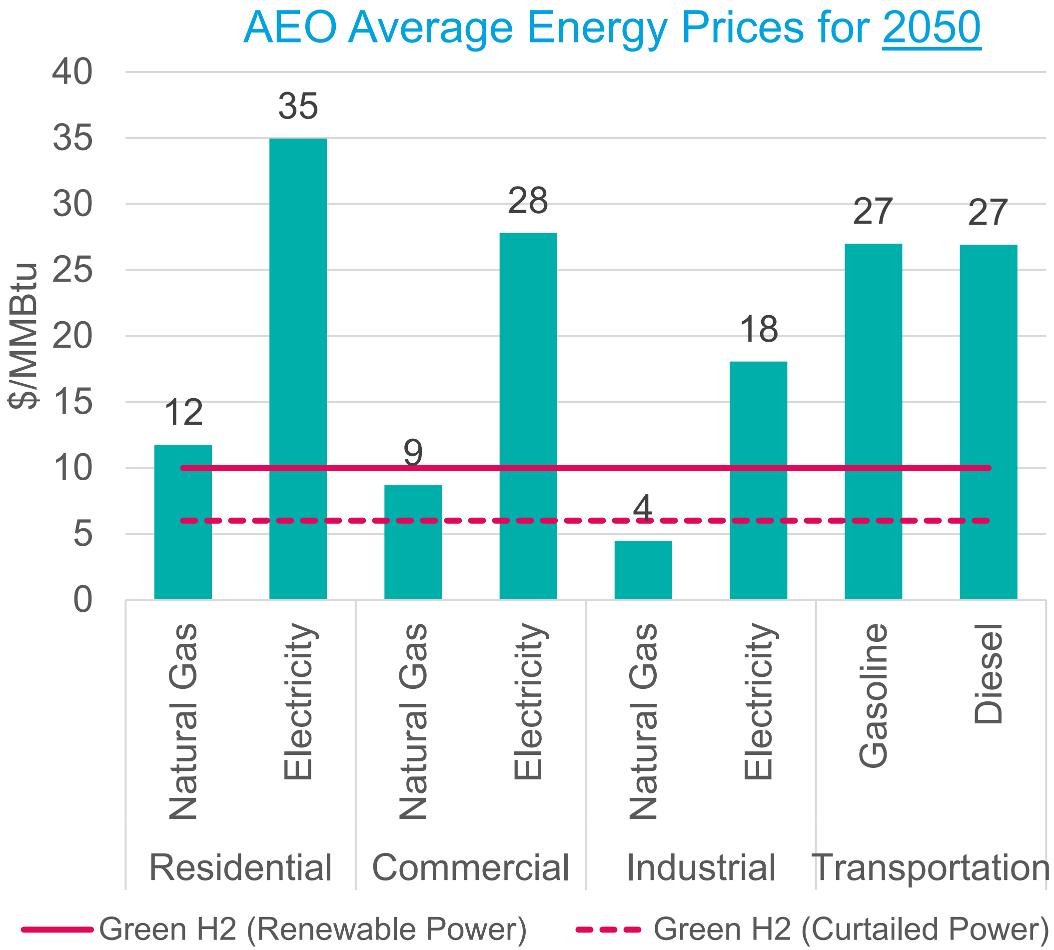
- Renewable power costs projected from ICF modeling
- Solar capacity factor of 27%
- Energy consumption ranged from 55 to 49 kWh/kg from 2020 to 2050
- 7-10 years of stack membrane replacement; 15% of direct cap cost
- Learning Rate of 12% used for PEM Electrolyzers

Gray Hydrogen

- Additional CapEx for SCR NOx Control on Stack for Gray Hydrogen (SMR only)
- Additional CapEx for CO2 removal for process and at stack for Blue Hydrogen (SMR + CCS)

Hydrogen production costs in context of delivered energy prices





Notes:

- Delivered energy prices/costs are national averages from EIA's 2021 Annual Energy Outlook (AEO)
- Hydrogen production costs are an ICF calculation for green hydrogen, based on assumptions on previous slide
- These bars do not account for relative efficiency of equipment using different fuel types

Hydrogen as Long Duration Storage Using Existing Energy System

- **Existing GT's can be Retrofit for High Hydrogen Service**
  - Hydrogen combustors
  - Larger fuel piping and valves
  - Safety sensors and flame detectors
  - Control system changes
- **Major OEMs (GE, Mitsubishi, Siemens) Targeting 100% Hydrogen Compatibility between 2025 and 2030**
- **No Change in Heat Rate (J/kWh or Btu/kWh)**
- **Slight Derate in Power (About 8% for 100% H_2)**

GE lists 75 turbines with 6MM+ operating hours, the Deasan Refinery 6B's in South Korea have been running on 70-95% hydrogen since 1997 (guaranteed at 95%)

6B.03

Source: https://www.ge.com/power/gas/gas-turbines/6b-03

Hydrogen Storage – Liquid Tanks

- **Gaseous hydrogen is liquefied by cooling it to below −253°C (−423°F)**

- **Liquid hydrogen tank storage costs:**
  $3.65/MMBTU H_2 in 2020
  →$2.40/MMBTU H_2 in 2050
  - Almost 80% of the costs are due to the energy required for liquification (10.4 kWh/kg H_2)

- **Boil off losses are typically between 1-3% per day**

NASA, 3800 m^3, 270 t

JAXA (Kawasaki), 540 m^3, 38 t

Source:https://www.utwente.nl/en/tnw/ems/research/ats/chmt/m13-hendrie-derking-cryoworld-chmt-2019.pdf

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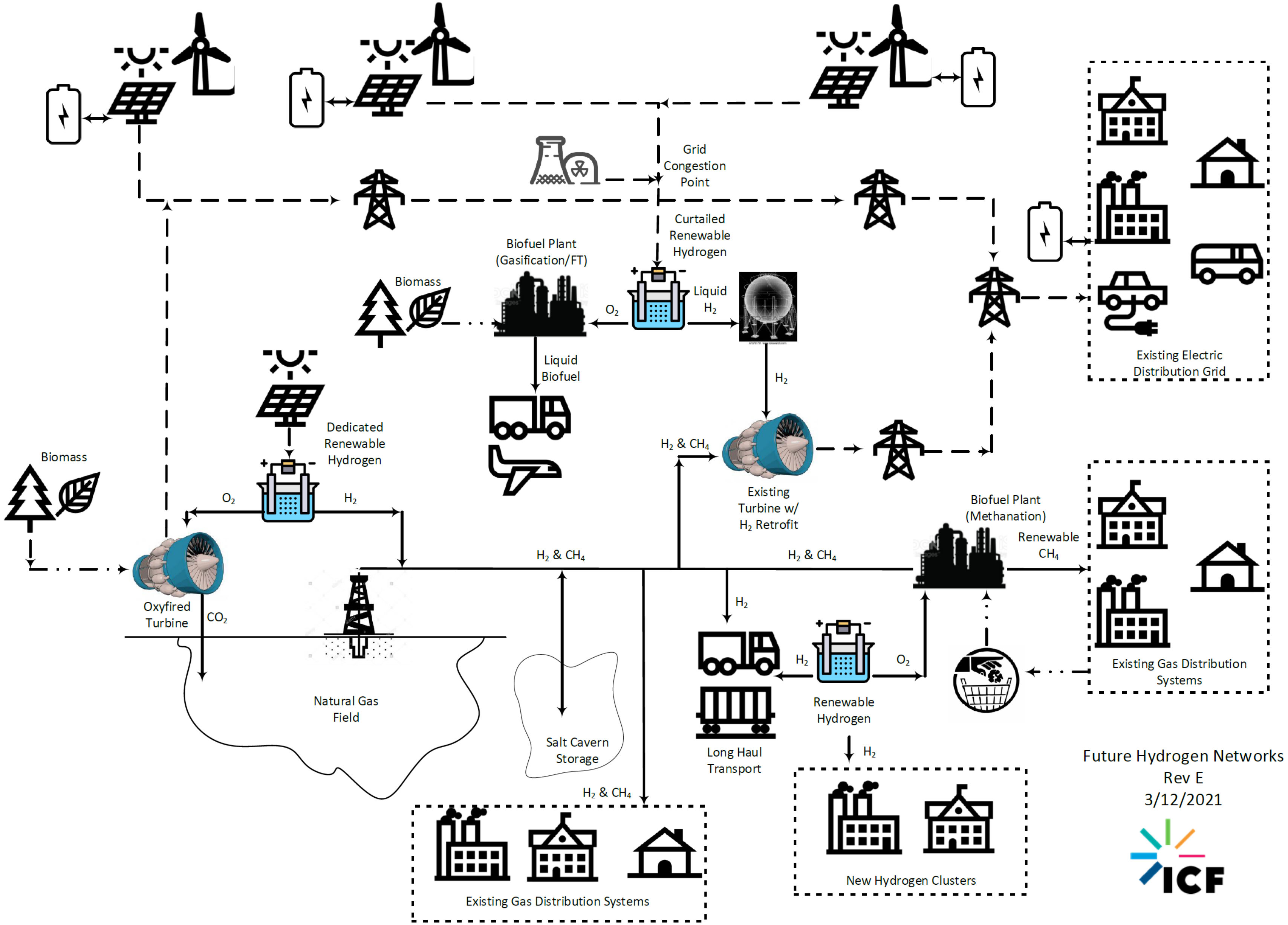
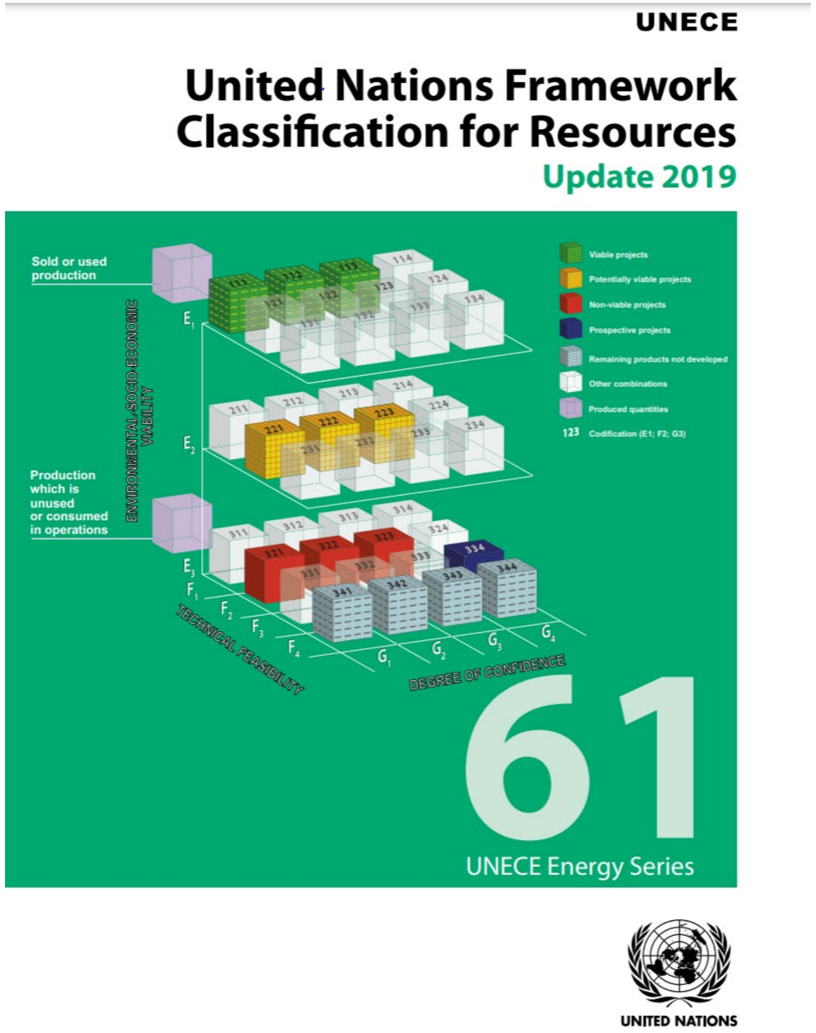
Hydrogen may be used in a wide variety of applications…

So how does a Government know that there is enough?

The UNFC!



So What's the Problem?



- Remember, liquid hydrogen boil off losses are typically ***between 1-3% per day***
- The UNFC's first disappearing energy product…

Conclusions

- UNFC is an excellent system to classify hydrogen as an energy product, and provides a good foundation for estimating quantities from various sources
- Future grids with intermittent renewables will need more robust classification and quantification systems
- Hydrogen can be a key energy storage medium for power gen, transport, heating
- Key Challenge *or Opportunity*, how to deal with the first disappearing energy product? Could this be a differentiator for the UNFC vs other systems….

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Questions?

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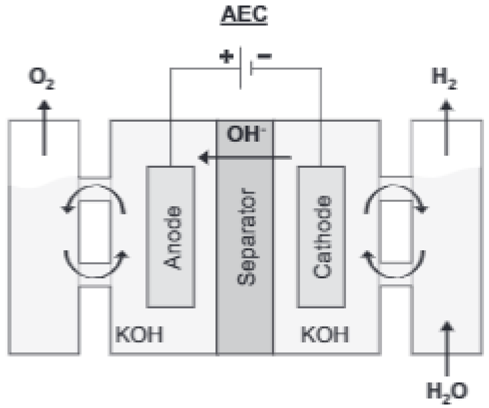
Sources:https://reader.elsevier.com/reader/sd/pii/S0360319917339435?token=9E70FEB9AFA100FDF19CCD5AF2AF193052BF92B1C3D9533FBDA878D75D1A468F17DD195646F71D75F5DE977C82D8CEDA

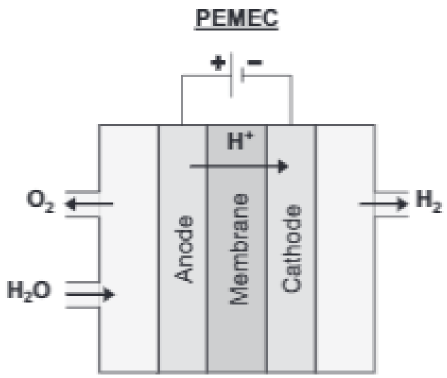
Electrolyzers

Alkaline



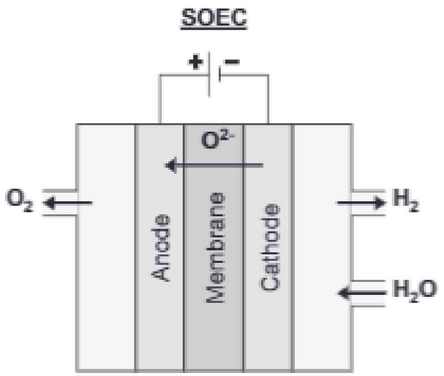
- Liquid electrolyte solution (i.e. KOH or NaOH)
- Operating temperatures: 60-80°C
- Production rate: <760 m^3 H_2/hr
- System energy: 4.5-6.6 kWh_{el}/m^3 H_2
- Cold start time: <60 mins
- Stack lifetime: 60,000-90,000 hrs
- Mature technology

Proton Exchange Membrane (PEM)



- Solid polymer electrolyte
- Operating temperatures: 50-80°C
- Production rate: <40 m^3 H_2/hr
- System energy: 4.2-6.6 kWh_{el}/m^3 H_2
- Cold start time: <20 mins
- Stack lifetime: 20,000-60,000 hrs
- Commercial technology

Solid Oxide



- Solid ceramic material for electrolyte
- Operating temperatures: 650-1000°C
- Production rate: <40 m^3 H_2/hr
- System energy: >3.7 kWh_{el}/m^3 H_2
- Cold start time: <60 mins
- Stack lifetime: <10,000 hrs
- Demonstration phase

PEM electrolyzers projected to cost less ($/$kW_{el}$) than alkaline electrolyzers through scale-up and R&D technology improvements