Chemical Looping Technology for Hydrogen Production: Commercialization Prospect

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Ohio Hydrogen Technology Forum

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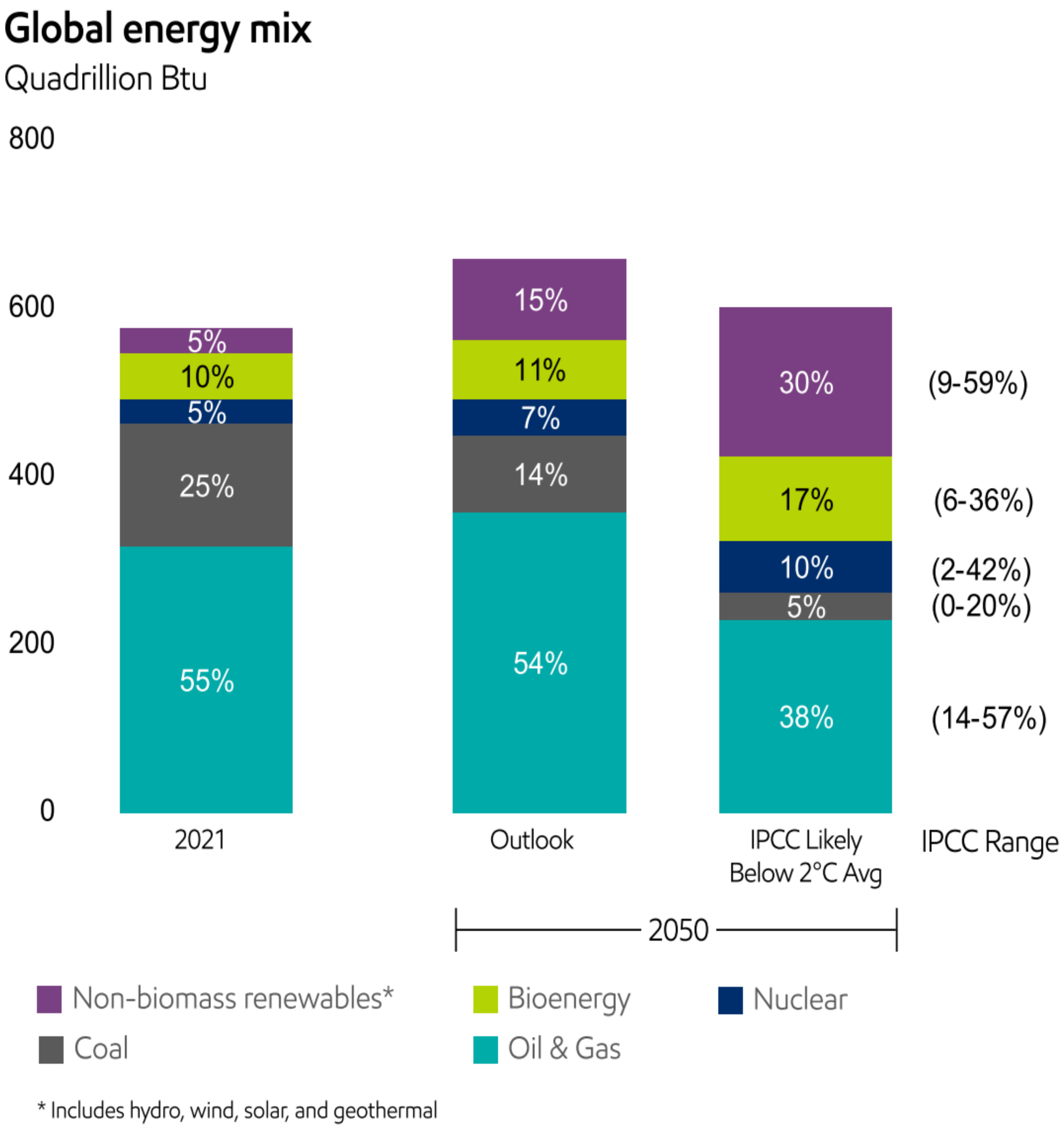
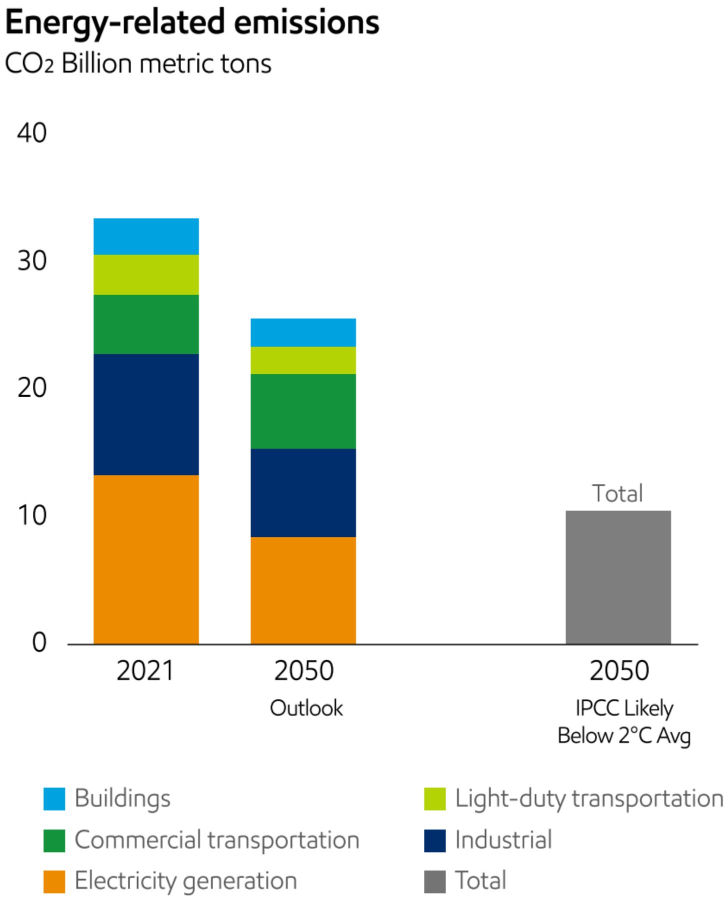
- World population →**10 bn** by 2050, requiring **15% higher energy**
- Low-carbon energy technologies
- Three main technologies that have been identified to curb climate change to 2°C by 2050 are **Carbon Capture and Storage, Hydrogen, Biofuels**
- **Chemical Looping:** a promising technology for reducing CO_2 emissions

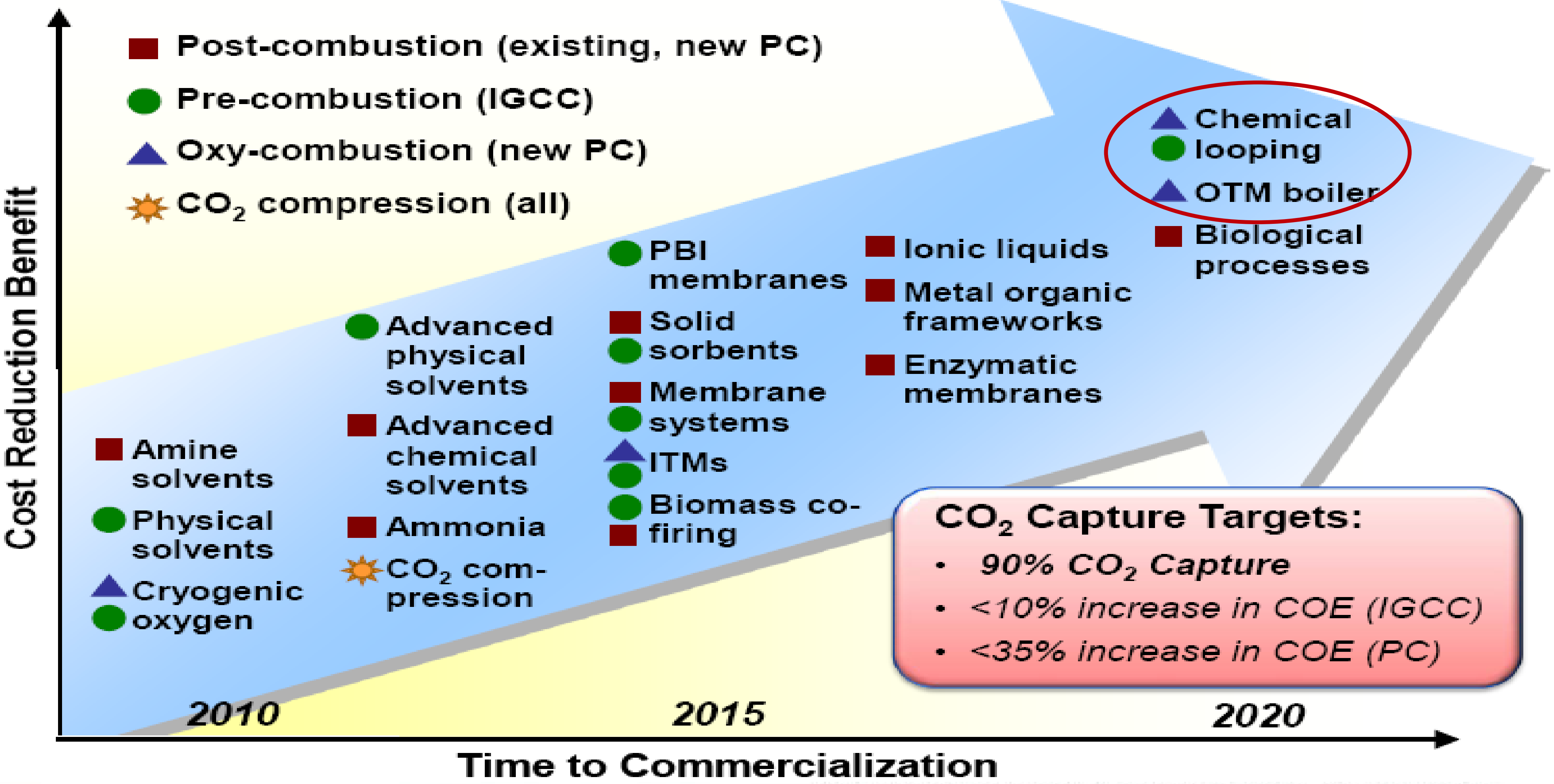




Ref: ExxonMobil Energy Outlook

CO_2 Capture from Fossil Energy

Technological Solutions



Figueroa, J.D., Fout, T., Plasynski, S., McIlvried, H., Srivastava, R.D., *International Journal of Greenhouse Gas Control.* 2008.

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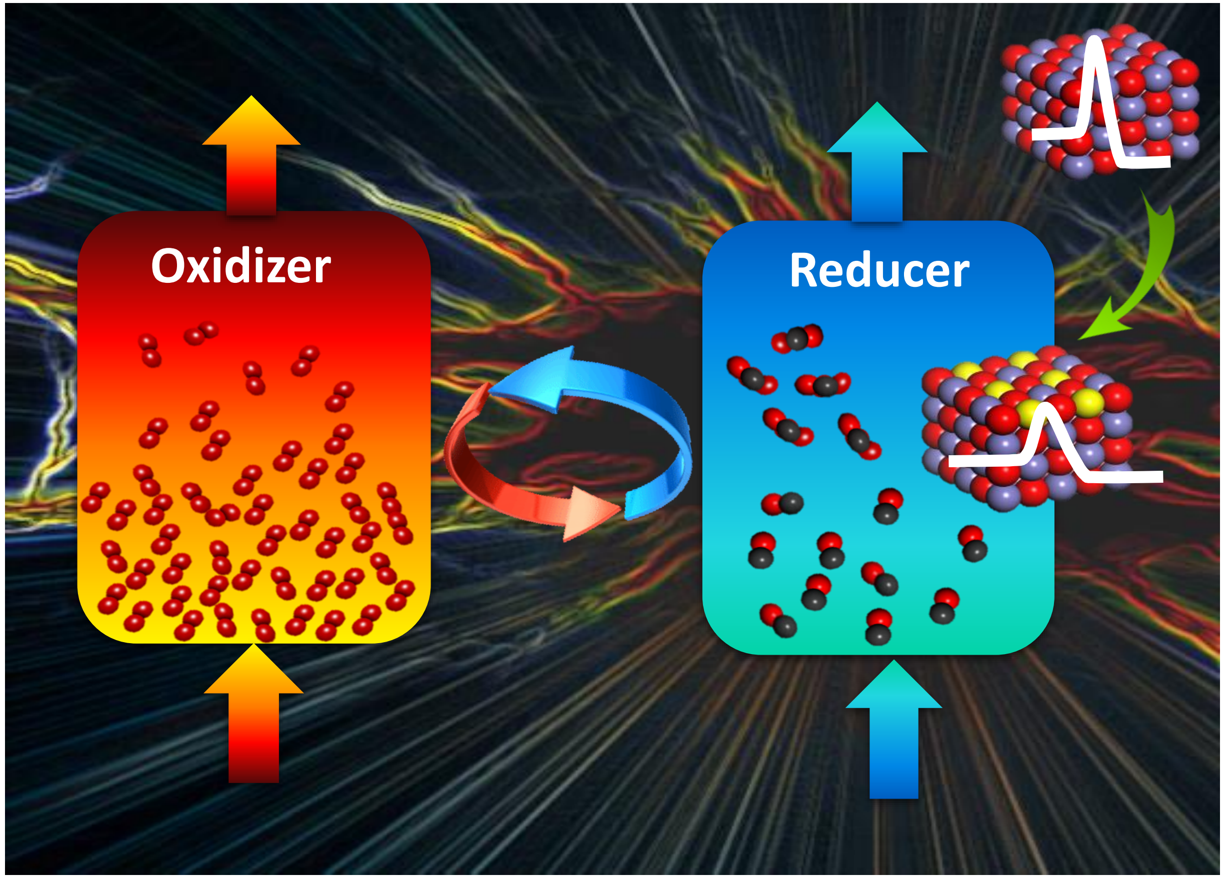


ROYAL SOCIETY OF CHEMISTRY

Publishing

Journals, books and databases

As featured in Journal of Materials Chemistry A, Advance Article, 2017
DOI:10.1039/C7TA04228K

Showcasing a new approach on improving the reactivity of iron oxide oxygen carriers using a very small concentration of the lanthanum dopant by Professor Liang-Shih Fan's research group at the Ohio State University.

Title: Improved cyclic redox reactivity of lanthanum modified iron-based oxygen carriers in carbon monoxide chemical looping combustion

Oxygen carriers are required to have high reactivity and recyclability with low cost. A very low concentration of the lanthanum dopant can dramatically increase the reactivity of oxygen carriers in chemical looping combustion with carbonaceous fuels by reducing the reaction barriers. This methodology provides substantial performance improvements of oxygen carriers that are relatively simple to fabricate, and it will have an impact on chemical looping particle design and modification.

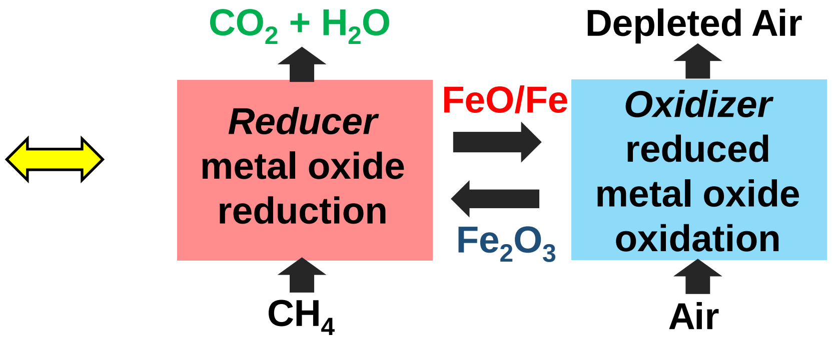
Redox Chemical Looping Technology

Metal Oxide as Oxygen Carrier

Combustion: Complete Fuel Oxidation

Reducer: Fe_2O_3 (oxidized) + CH_4 → FeO/Fe (reduced) + $CO_2 + H_2O$

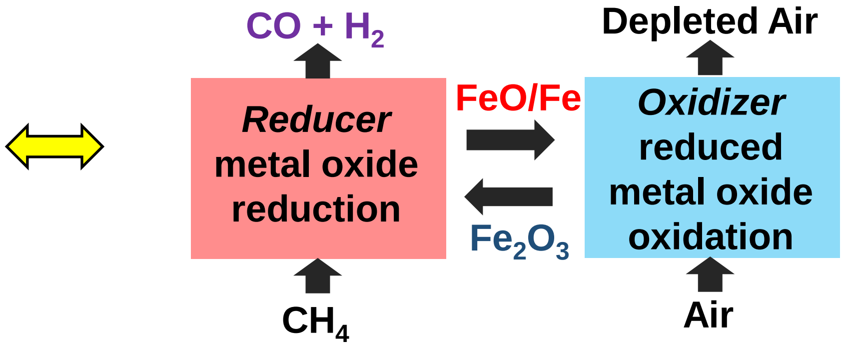
Oxidizer: FeO/Fe + Air (O_2) → Fe_2O_3

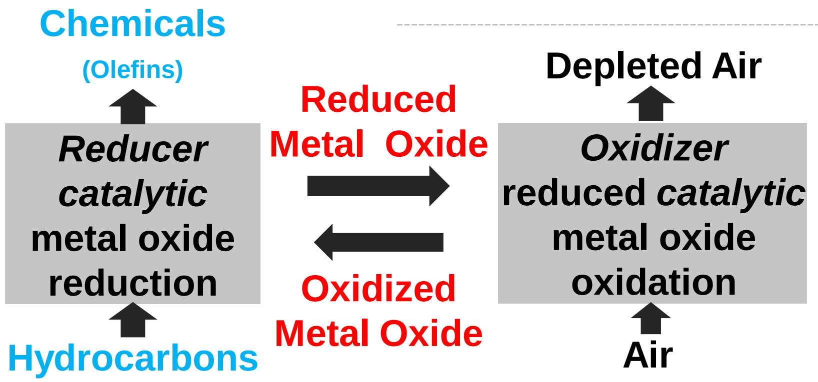


Gasification: Partial Fuel Oxidation

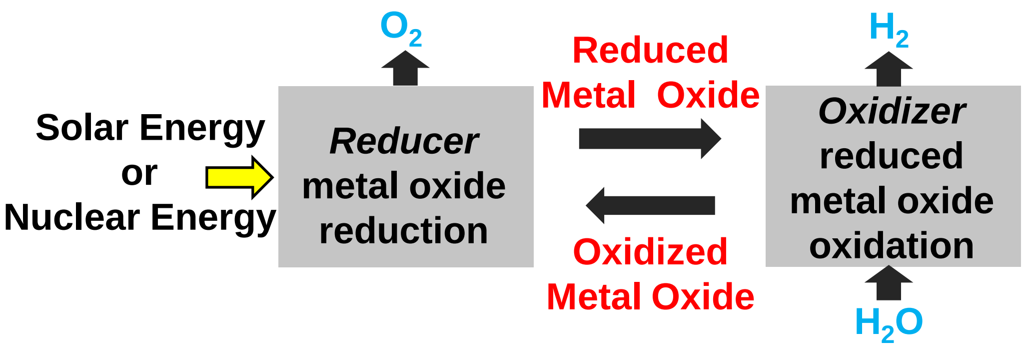
Reducer: Fe_2O_3 (oxidized) + CH_4 → FeO/Fe (reduced) + $CO + H_2$

Oxidizer: FeO/Fe + Air (O_2) → Fe_2O_3





Chemicals Production: Selective Oxidation

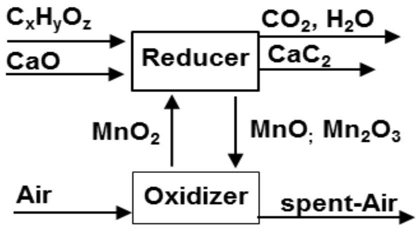


Solar/Nuclear Chemical Looping: Water Splitting

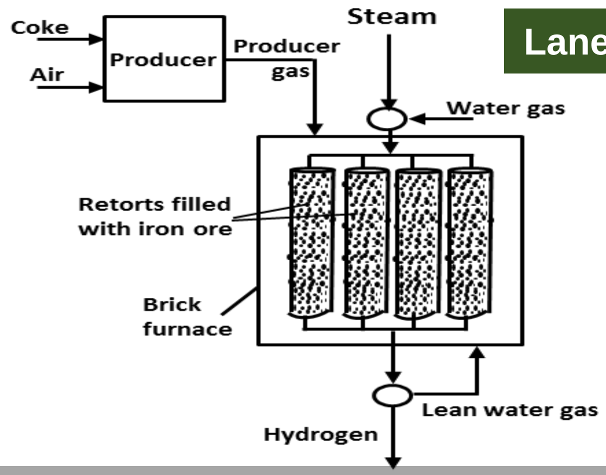
Luo, S., Zeng, L., Fan, L.-S., *Annual Review of Chemical and Biomolecular Engineering*. July 2015.
Chung, E.Y., Wang, W.K., Alkhatib, H., Nadgouda, S., Jindra, M.A., Sofranko, J.A., Fan, L.-S. 2015 AIChE Spring Meeting. April 2015.
Chueh, W. C., Falter, C., Abbott, M., Scipio, D., Furler, P., Haile, S.M., Steinfeld, A. *Science*. 2010.

History of Redox of Chemical Looping Technology development

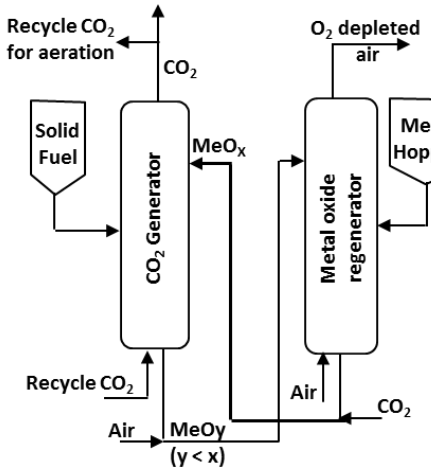
Technologies	Bergmann Process	Lane Process & Messerschmitt Process	Lewis and Gilliland Process	IGT HYGAS Process	CO_2 Acceptor Process
Time	1897	1910	1950s	1970s	1970s
Looping Media	$MnO_2/MnO/Mn_2O_3$	$Fe/FeO/Fe_3O_4$	Cu_2O/CuO	FeO/Fe_3O_4	$CaO/CaCO_3$
Reactor Design	Blast Furnace	Fixed Bed	Fluidized Bed	Staged Fluidized Bed	Fluidized Bed



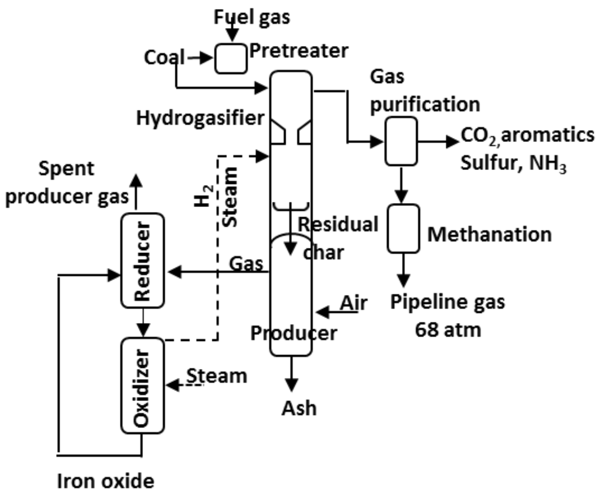
Bergmann Process



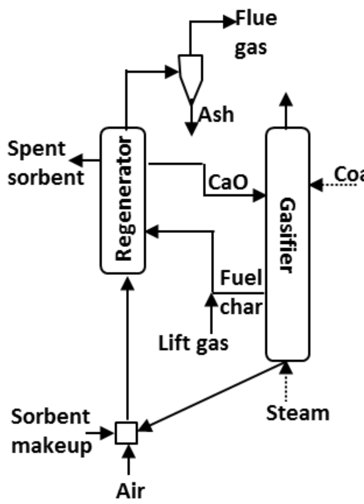
Lane Process



Lewis and Gilliland Process



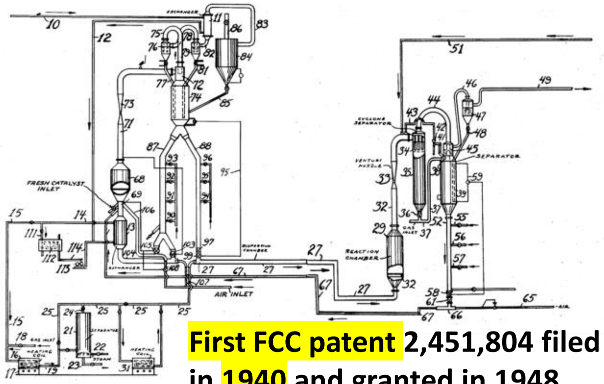
IGT Process



CO_2 Acceptor Process

Bergmann, F. German Patent 29,384, 1897;
Messerschmitt, A. U.S. Patent 971,206, 1910.; Lane, H. U.S. Patent 1,078,686, 1913.
Dobbyn, R.C., Ondik, H.M., et al . U.S. DOE Report DOE-ET-10253-T1, 1978.
Lewis, W.K., Gilliland, E.R. U.S. Patent 2,655,972, 1954.
Institute of Gas Technology. U.S. DOE Report EF-77-C-01-2435, 1979.

Fluid Catalytic Cracking (FCC) Process Development[2,3]



First FCC patent 2,451,804 filed in 1940 and granted in 1948

First comm FCC (13KBD) in 1942[1]

Evolution on Catalyst and Reactor

Reference:
1. A National Historical Chemical Landmark – The Fluid Bed Reactor, 1998
2. Fluid Catalytic Cracking Handbook
3. Wikipedia – Fluid Catalytic Cracking

Δt =~20 years for first plant

1920 · 1930 · 1940 · **1942** · 1950 · 1960 · 1970 · 1980 · 1990 · Today

Discovered Friedel-Crafts aluminum chloride for cat cracking (1915)

Standard Oil research on FCC in 1920's

Houdry lab study on cat cracking and found Fuller's earth+ (1922)

Socony-Vacuum and Houdry 200bpd fixed bed pilot (1933)

Discovered natural clays as cat greatly improve efficiency (1936)

Socony-Vacuum and Houdry 2000bpd fixed bed demo (1936)

Sun Oil 12KBD fixed bed comm (1937)

Standard Oil resumed FCC research with consortium (1938)

MIT Profs suggested powder fluidization

Houdry fixed bed comm 140KBD by 1940

Pilot FCC in 1940

TCC* moving bed demo (1941)

Grace Davison's first synthetic FCC cat (1942) and microspheroidal cat (1948)

10BKD TCC comm (1943)

TCC comm 300KBD by 1945

Air-lift TCC started up (1950)

UOP side-by-side design (1950s)

Shell Riser cracking (1956)

Mobil comm spray-dried zeolite cat (1964)

Mobil reported 1st use of ZSM-5 (1983)

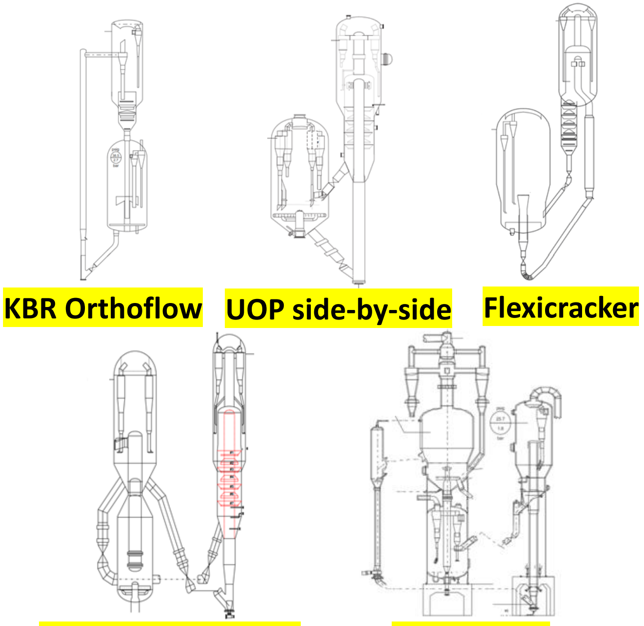
All fixed bed and most moving bed units shut down

Focused on catalyst improvement and additives development

+ A clay mineral containing aluminosilicates, could convert oil derived from the lignite to gasoline

* TCC - a moving bed process used a bucket conveyor elevator to move the catalyst from regenerator to reactor

Evolution of FCC Process (Examples)



KBR Orthoflow · **UOP side-by-side** · **Flexicracker** · **UOP High Efficiency** · **Technip FCC**

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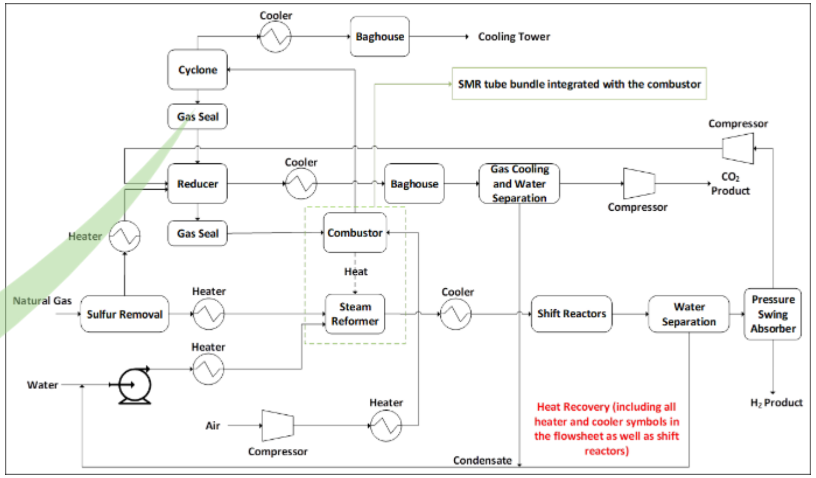
Multi-Scale, Multiphase Technology Development Approach

Powder Technology 439 (2024) 119654; LS Fan et al., "Multiphase Entrepreneurship: An Academic Reflection"

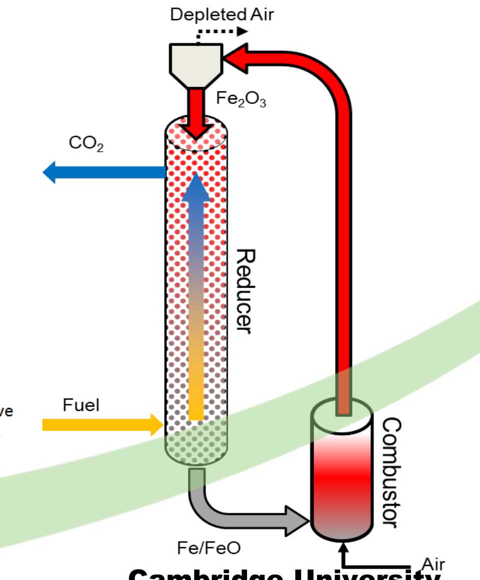
System scale (> 100m)

Chemical Looping H_2 Process system



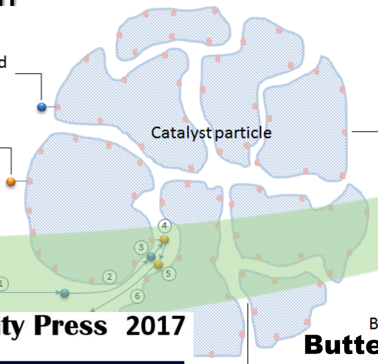
Reactor scale (m)

coupling of momentum, heat, mass transport

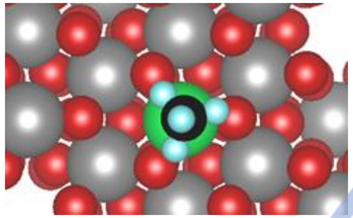


Particle, Droplet or Bubble scale (μm~mm)

external/internal diffusion, reaction, size and shape design

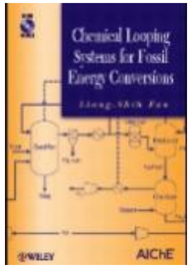


Molecular scale (Å)

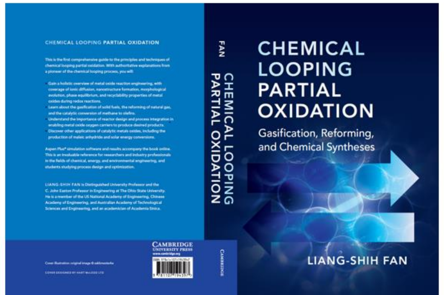


Surface chemistry, e.g., how chemical bonds are formed and cleaved. reaction mechanism, energetics, charge flow

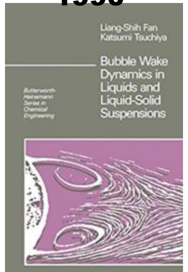
Wiley/AIChE 2010



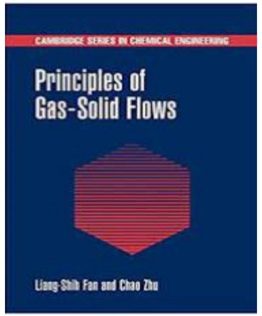
Cambridge University Press 2017



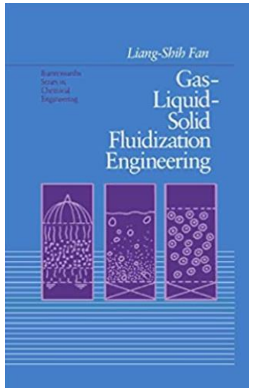
Butterworth, 1990



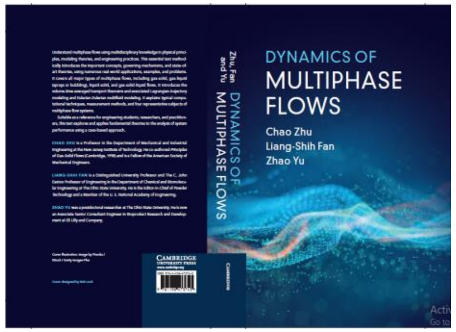
Cambridge University Press 1998



Butterworth, 1989



Cambridge University Press 2021



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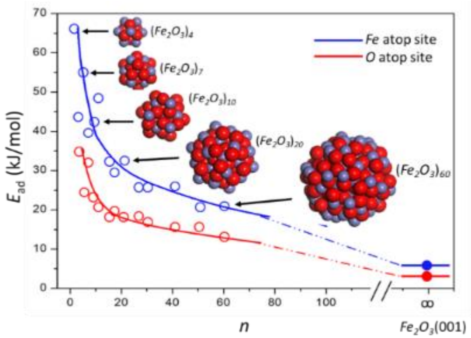
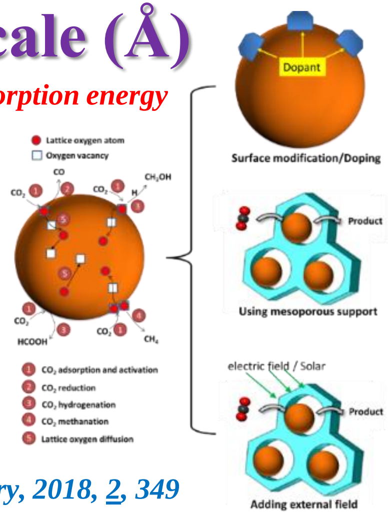
Molecular scale (Å)

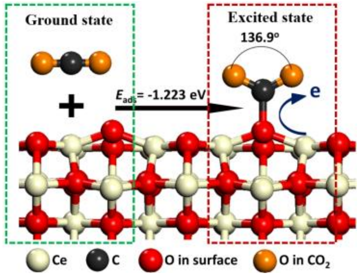
Nanoparticle oxygen carrier adsorption energy

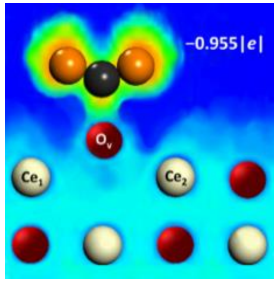




Nature Review Chemistry, 2018, 2, 349

Molecular adsorption and charge transfer

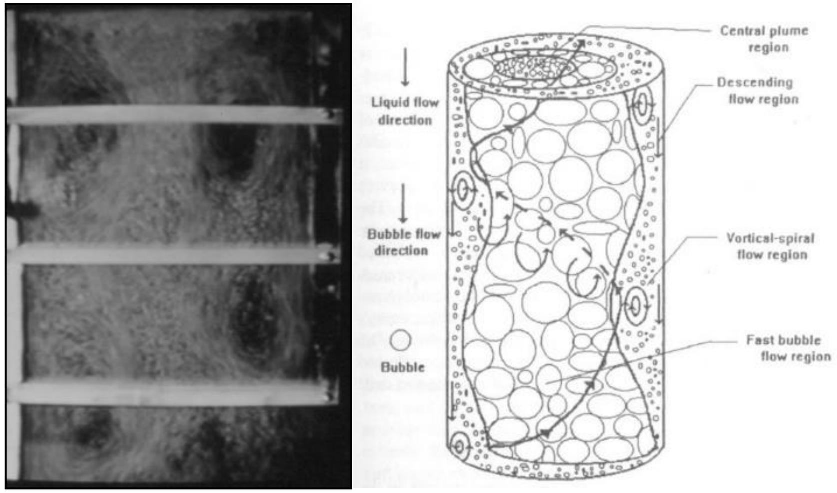




Nature Communications, 2019, 10, 1

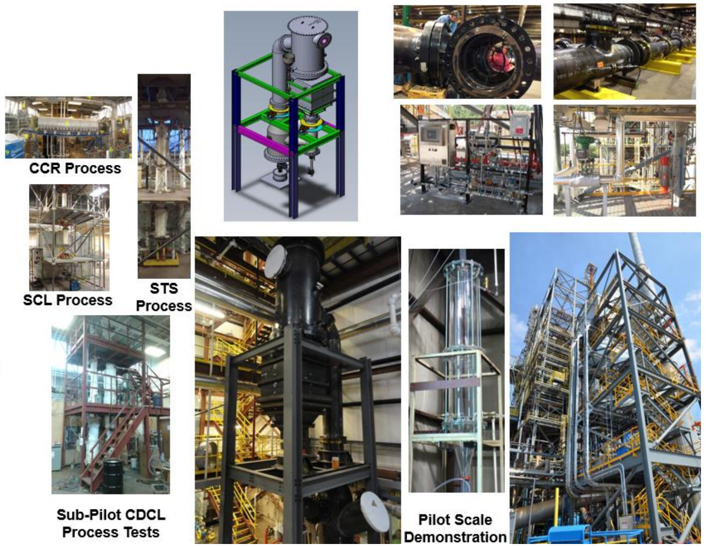
Reactor scale (m)

Flow structure of a 3D bubble column and 3D fluidized bed



AIChE Journal, 1994, 40, 1093

Sub-pilot and pilot scale demonstrations



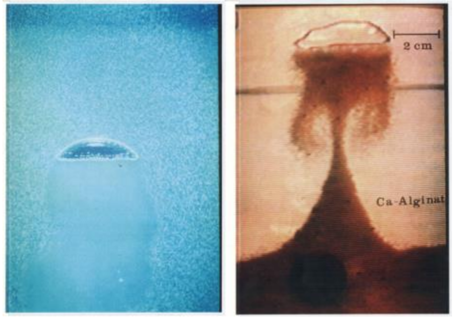
AIChE Journal., 2015, 61, 2

Particle, Droplet or Bubble scale (μm~mm)

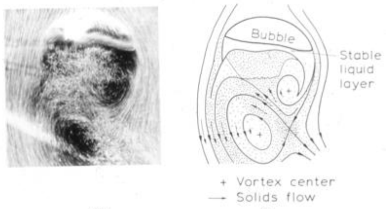
Metal oxide redox chemistry

Nature Reviews Chemistry, 2018, 2, 349

Bubble wake dynamics



N_2 – Water – GB774

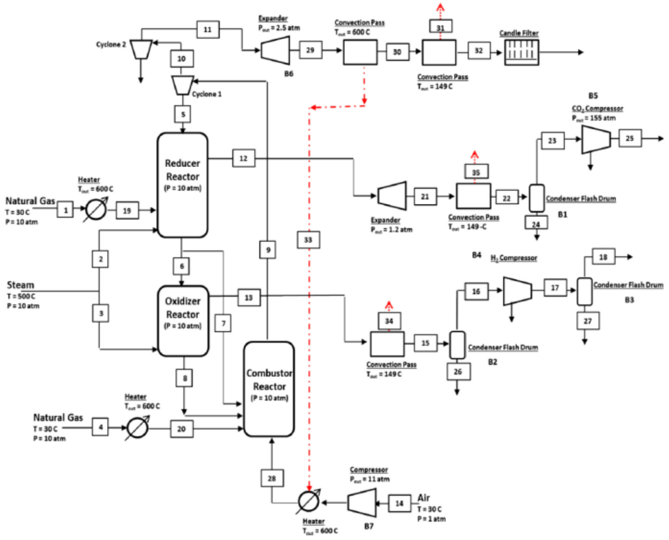


(a) (b)
Wake structure (asymmetric vortex pair) in a two-dimensional system.

International J. of Multiphase Flow, 1990, 16, 187

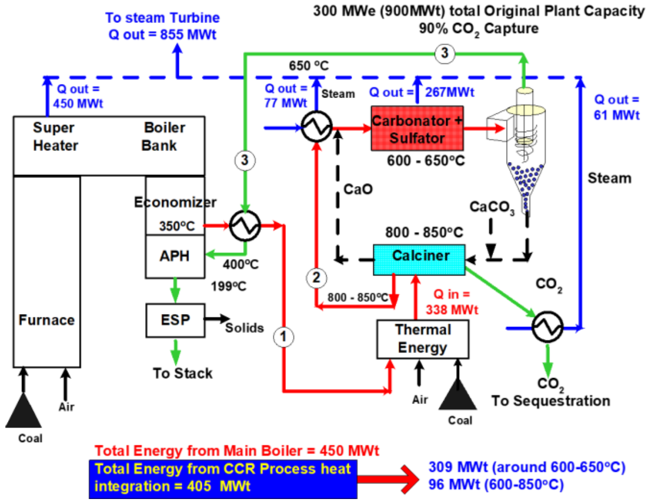
System scale (> 100m)

Process system analysis for H_2 production



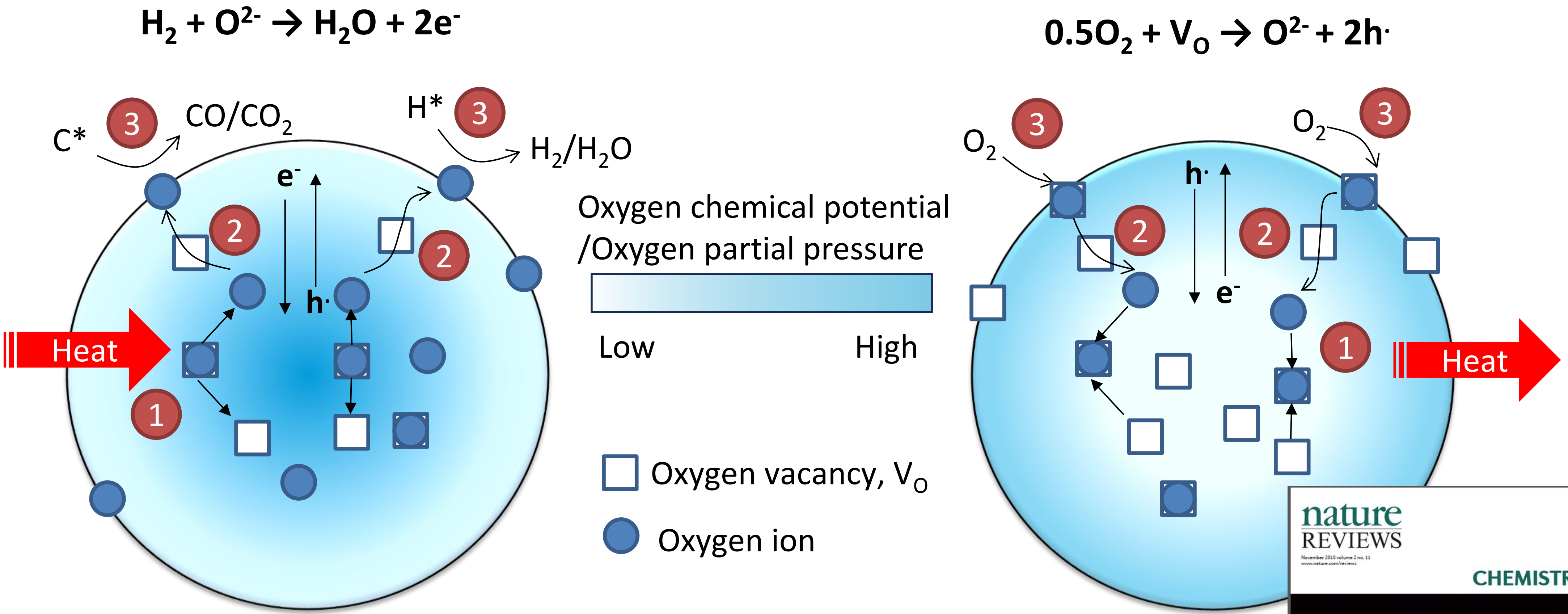
Applied Energy, 2016, 165, 183

Calcination-Carbonation-Reaction Process for CO_2 Capture



Fuel, 2013, 104, 561

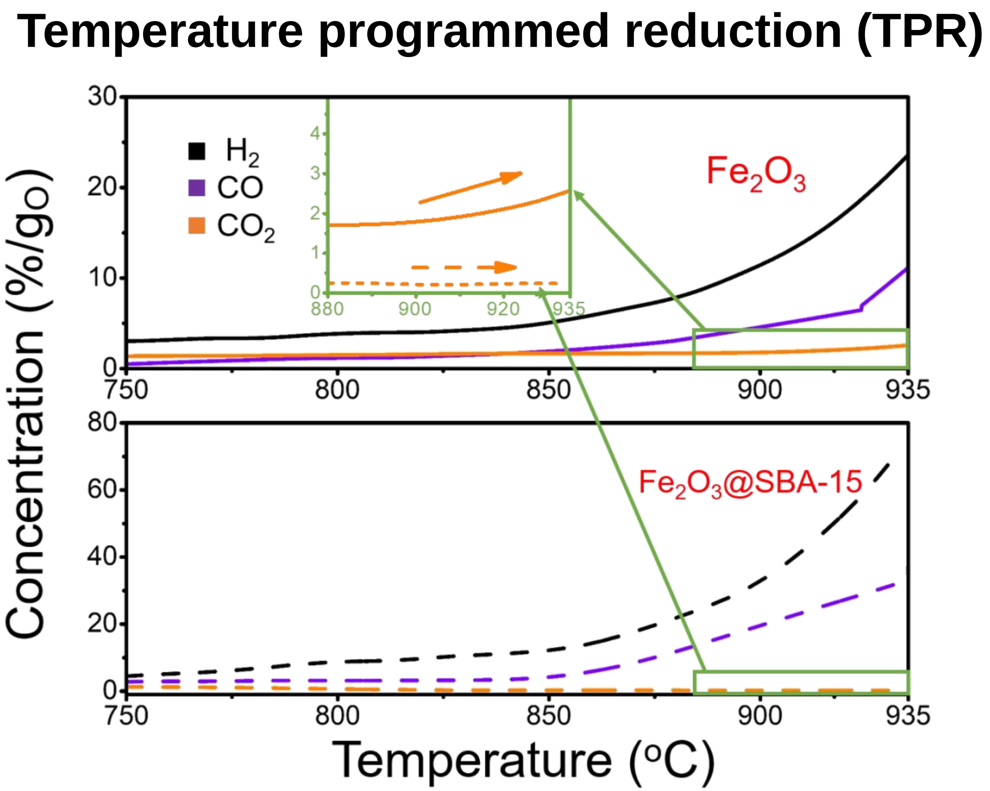
Metal Oxide Redox Chemistry

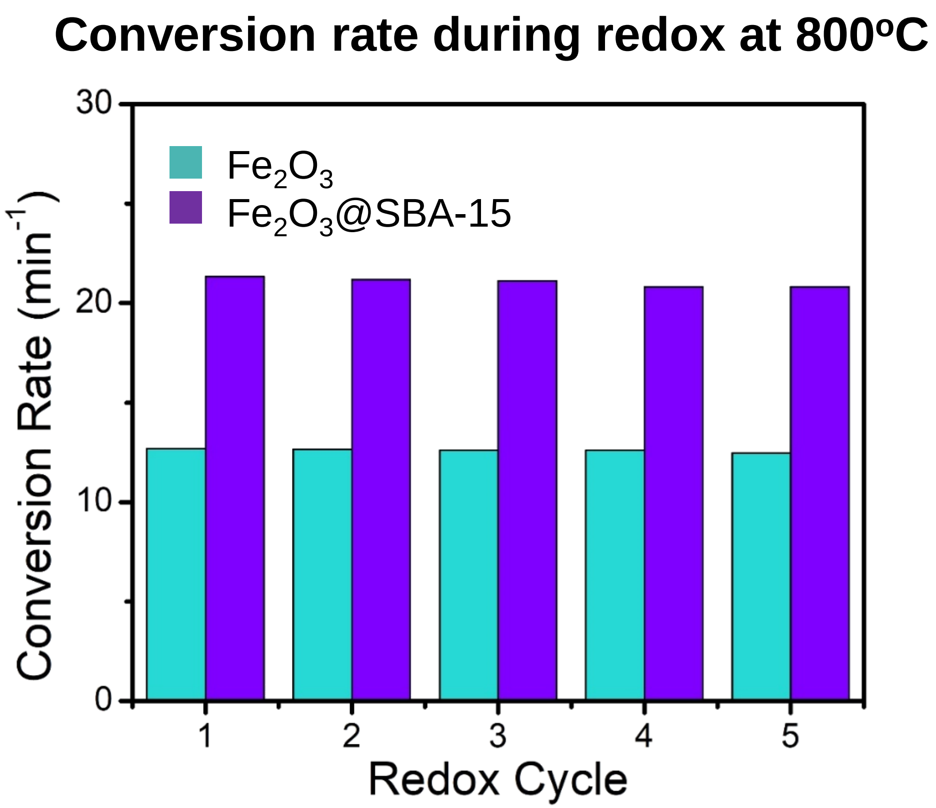


1. Oxygen ion/vacancy generation
2. Bulk phase diffusion
3. Surface reaction

As featured in Nature Review Chemistry, Metal oxide redox chemistry for chemical looping processes, L Zeng, Z Cheng, JA Fan, LS Fan, J Gong, Nature Reviews Chemistry, 2018, 2 (11), 349-364

Oxygen Carrier Nanoparticles - Fe_2O_3@SBA-15





Fe_2O_3 nanoparticles@SBA-15 has a high CO selectivity of ~100%, as well as a high reactivity, which is 66% higher than Fe_2O_3 particles.

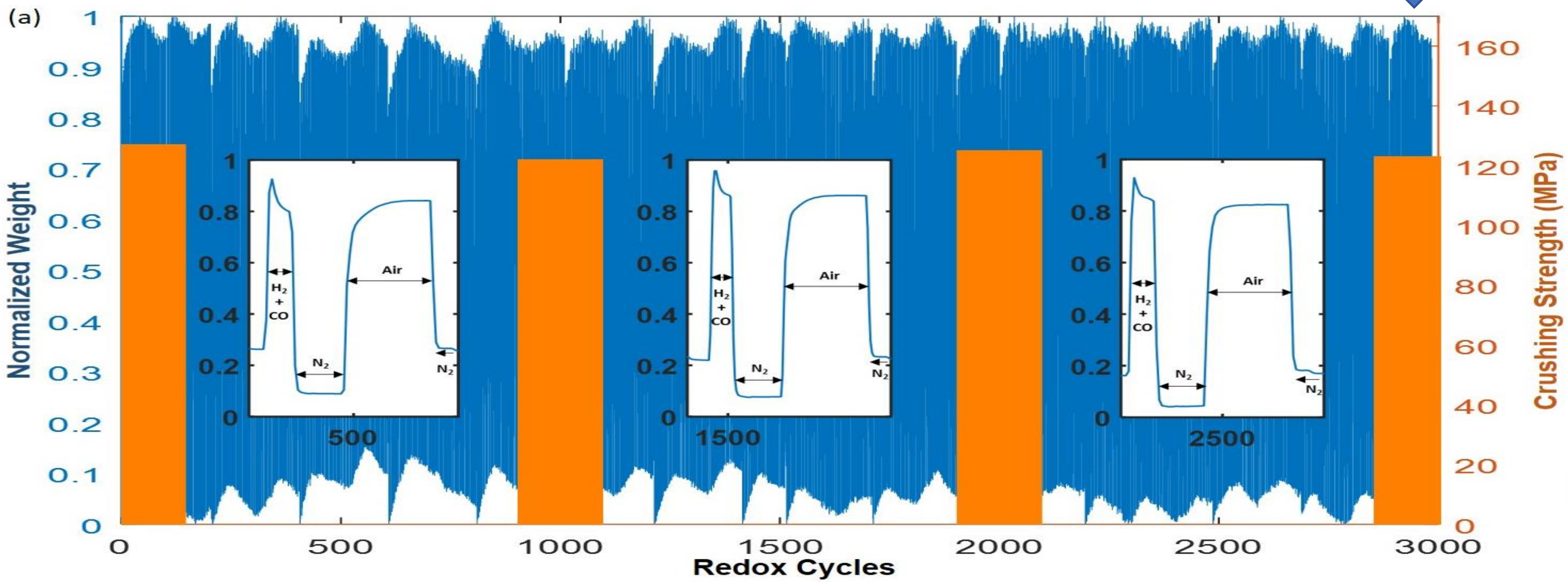
Y. Liu, L. Qin, Z. Cheng, J. W. Goetze, F. Kong, J. A. Fan, L.-S. Fan, Nature Communications, 2019, 10, 1-6

Chemical Stability of OSU Oxygen Carrier – 3000 Redox Cycles

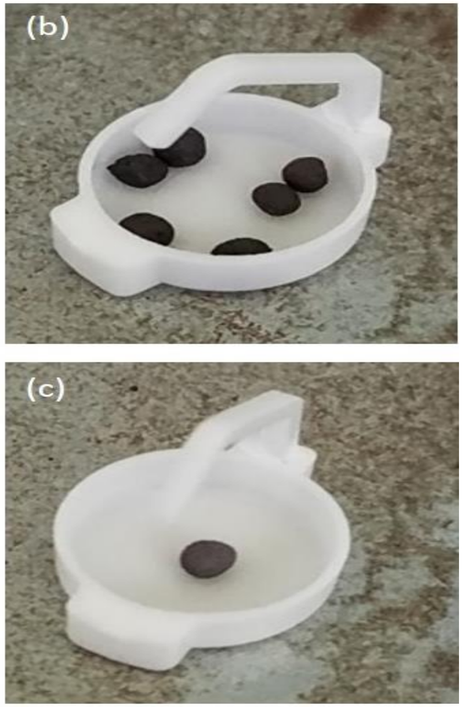
Both reactivity and strength (120 MPa) are sustained over 3000 redox cycles at 1000 °C with constant particle size of 1.5 mm

Chung, C., Qin, L., Shah, V., and Fan, L.-S., *Energy & Environmental Science*, 10, 2318-2323, (2017).

3000



Before

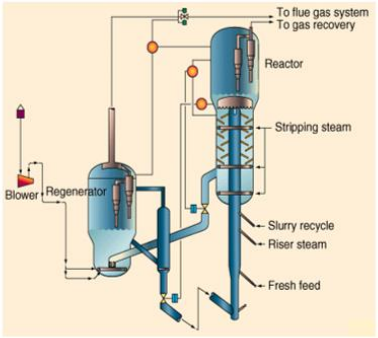


After

Latest results also indicates sustained physical and chemical stability at 1100 °C over 900 redox cycles

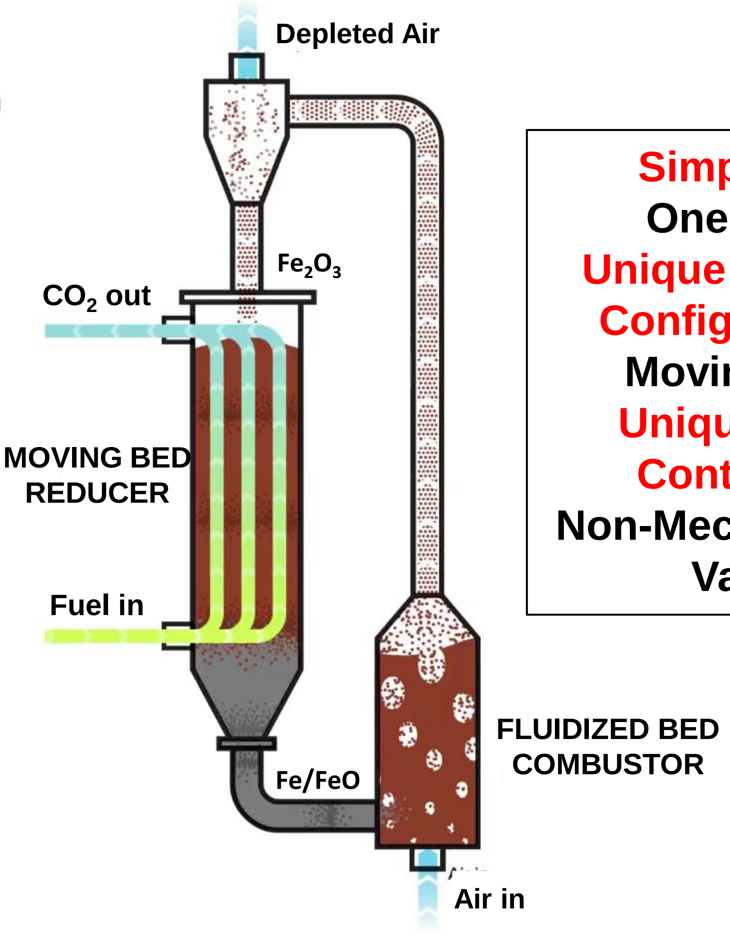
Understanding Chemical Looping Process – Reactor Configuration

Fluidized Catalytic Cracking (FCC)



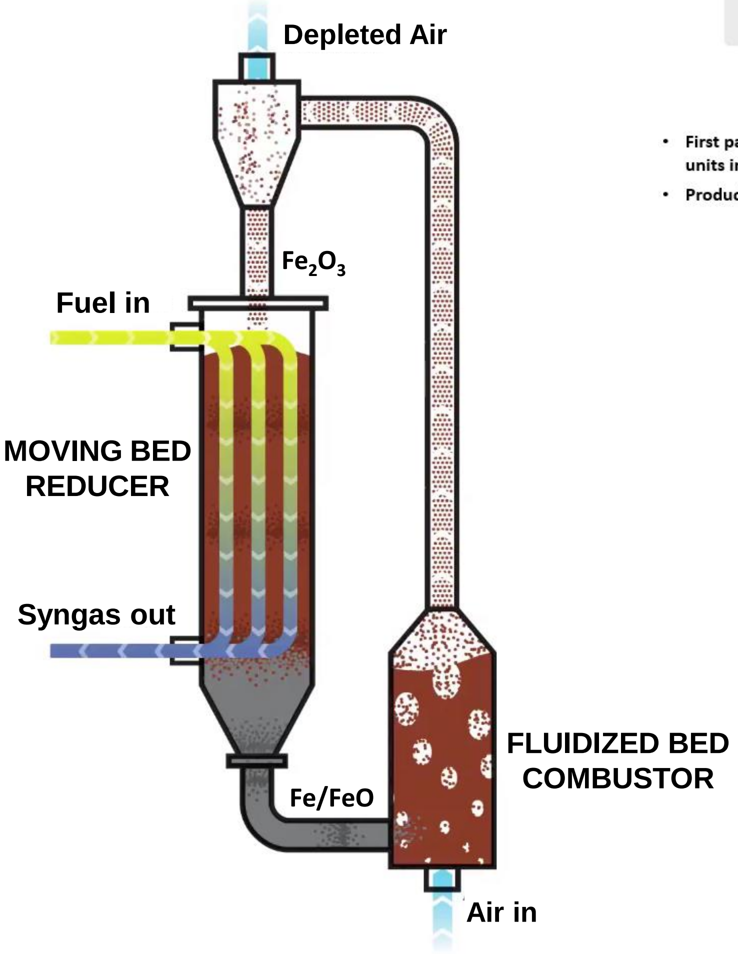
- First patent in 1940 with more than 350 commercial units in operation now
- Accounts for >50% of all transportation fuel and >30% gasoline production

Counter-current: Full Combustion

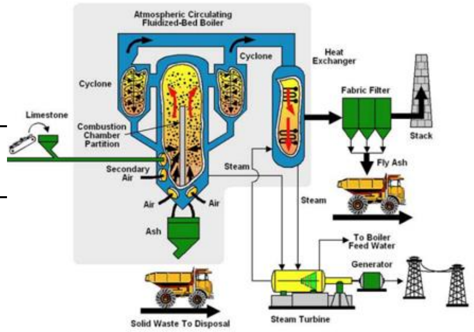


Simplicity: One Loop
Unique Reducer Configuration: Moving Bed
Unique Flow Controller: Non-Mechanical L-Valve

Co-current: Full Gasification



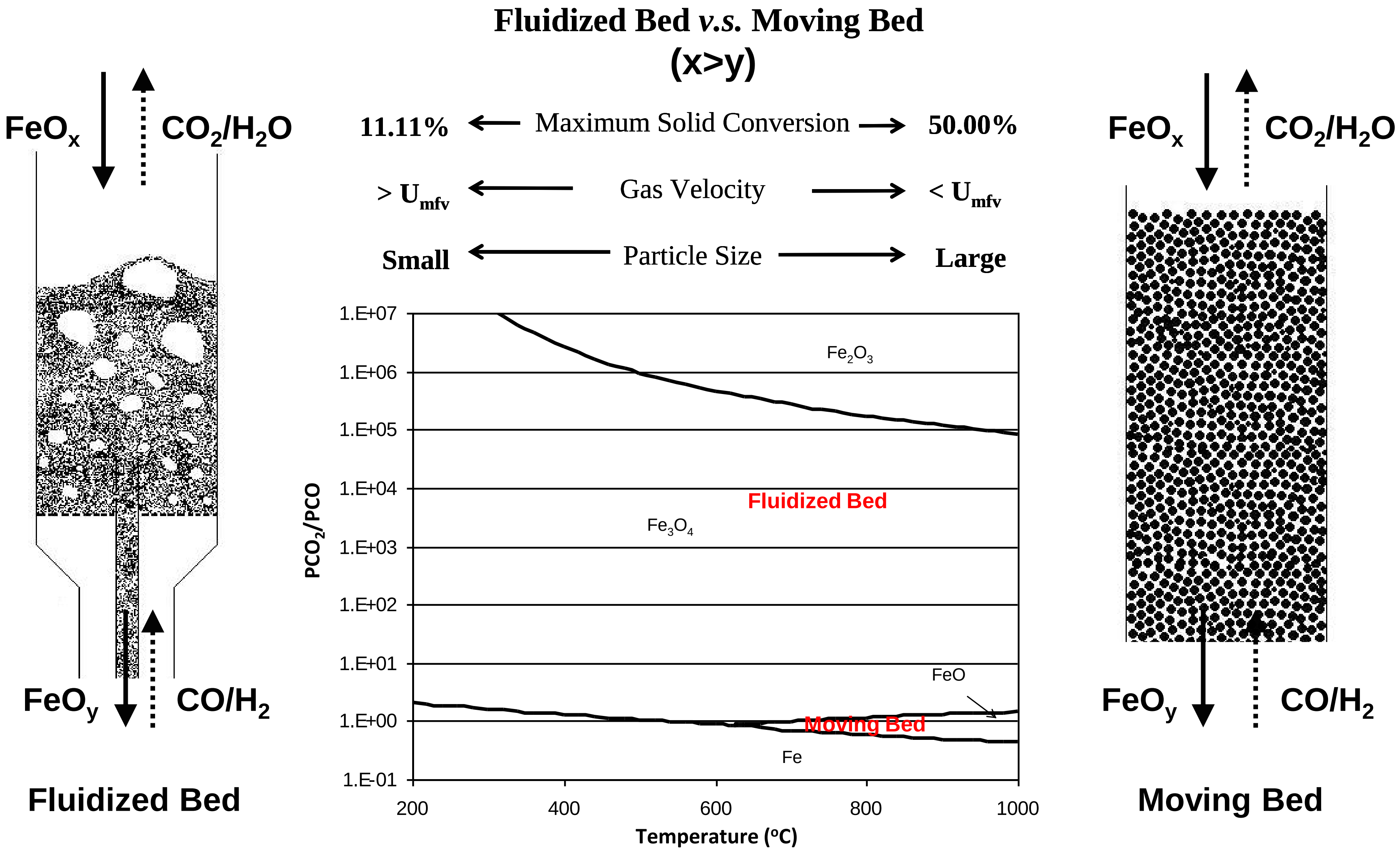
Coal Combustion



- First patent in 1976 with more than 600 commercial units in operation now
- Producing electricity with low sulfur dioxide emission

Fan, L.-S., Zeng, L., Luo, S. *AIChE Journal*. 2015.

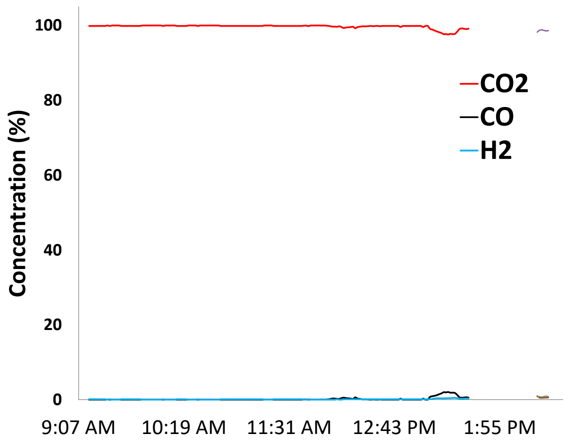
Reducer Design Concept: Combustion



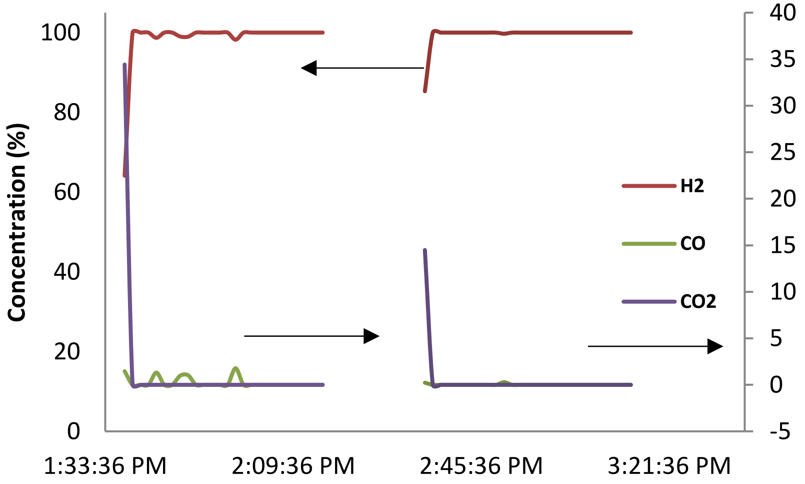
Fan, L.-S. Chemical Looping Systems for Fossil Energy Conversions. Wiley, 2010.

OSU 3-Reactor System for Hydrogen Production

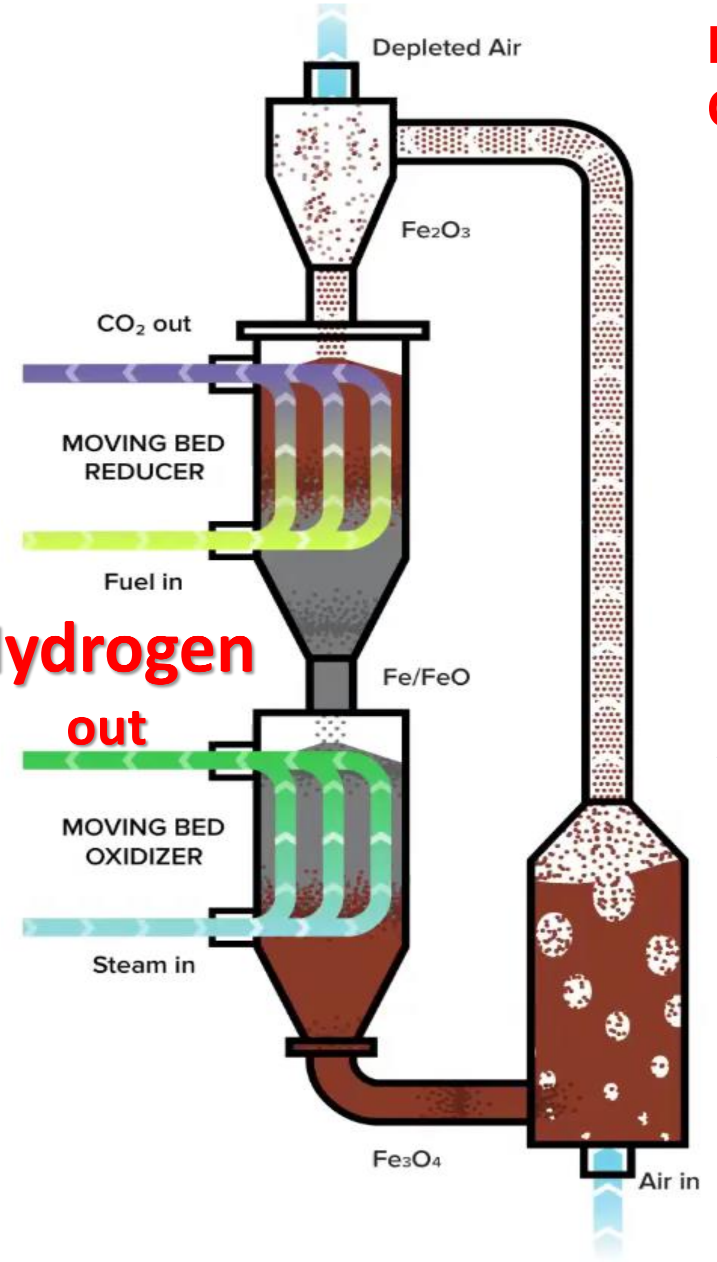
> 99% CO_2 purity in Reducer



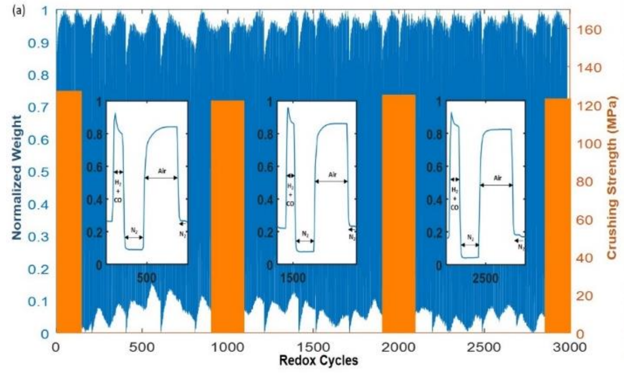
>99.99% H_2 purity in Oxidizer



Hydrogen out



Pilot demonstration at National Carbon Capture Center, AL

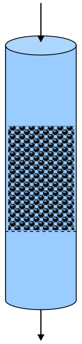


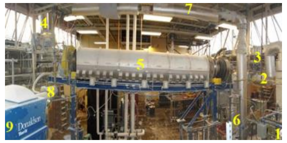
Cost of Low Pressure H2 Production with CO_2 Capture Can be less than \$1.5/Kg H_2

Hsieh and Fan et al., Applied Energy, 2018.
Li and Fan et al., AIChE Journal. 2010
Tong and Fan et al., Fuel. 2013.
Kong and Fan et al., Fuel. 2020

Evolution of Ohio State University Redox Chemical Looping Technology

TGA Tests





CCR Process

SCL Process

STS Process

Particle Synthesis — 1993

Fixed Bed Tests — 1998

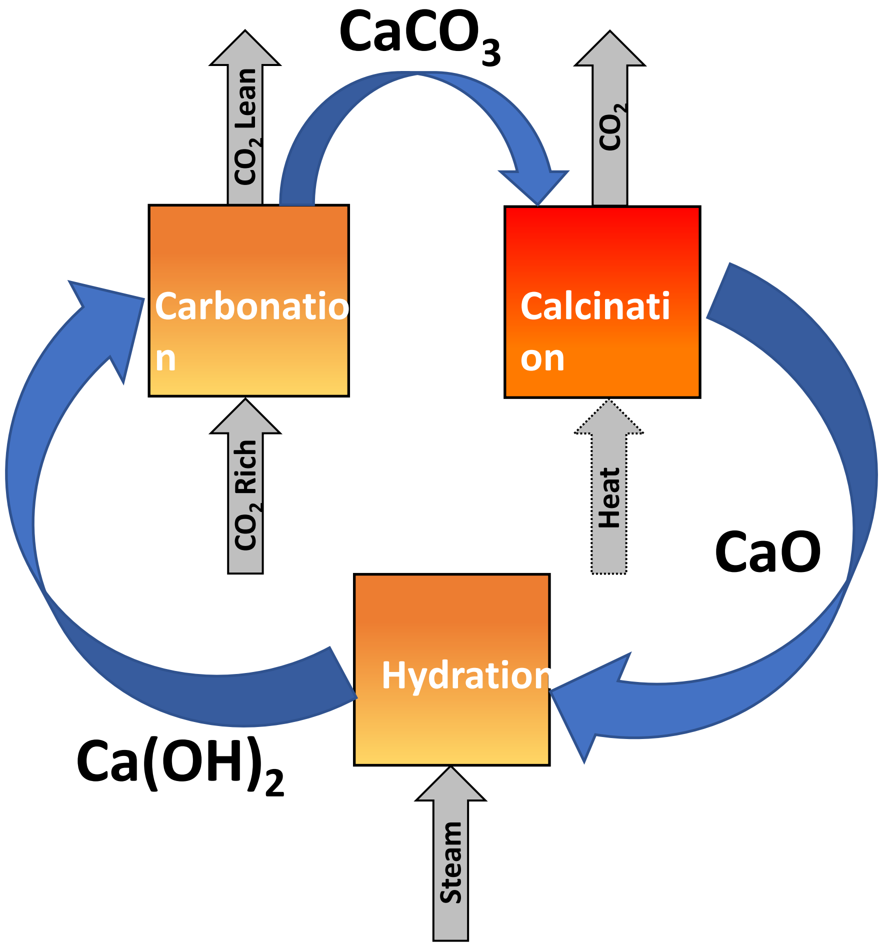
Bench Scale Tests — 2001

Sub-Pilot CDCL Process Tests — 2007

Pilot Scale Demonstration for **Hydrogen production** — 2010 to date

Fan, L.-S., Zeng, L., Luo, S. *AIChE Journal*. 2015;
Zhang, Y., L.-S. Fan et al, Applied Energy 282, 116065, 2021.
Hsieh, T.-L., L.-S. Fan et al., Applied Energy 230:1060-1072, 2018.

Calcium Chemical Looping Technology



OSU Carbonation-Calcination (1990s onwards) and Carbonation-Calcination-Hydration Looping Systems

ITRI Demonstration Plant (2015)

H. Gupta, L. S. Fan, U.S. Patent 7.067,456
M. V. Iyer, H. Gupta, L. S. Fan: U.S. Patent 7,618,606
S. Ramkumar, L. S. Fan: U.S. Patent 8,496,909
R. Statnick, W. Wang, S. Ramkumar, L. S. Fan: U.S. Patent 8,512,661
N. Deshpande, N. Phalak, L. S. Fan: U.S Patent US 8,877,150

BrightLoop™ Technology Evolution & Commercialization

1994-2004

Research & Development

Laboratory and Bench Scale Experiments

2008

Sub-Pilot

Hosted at The Ohio State University

2014

Pilot

National Carbon Capture Center
Wilsonville, Alabama

2017

Pilot

Coal Direct Chemical Looping
Barberton, Ohio

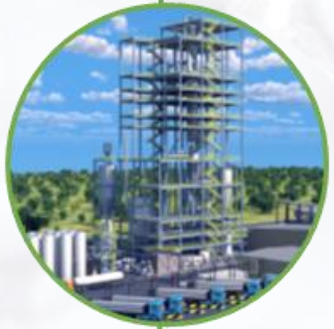
Innovation and Testing

2025

Commercial Demonstration

1-5 tonnes H_2 per day
Massillon, Ohio

2027



Medium Scale Commercial

10-50 tonnes H_2 per day

Detailed Engineering In Progress

2029

Large Scale Commercial

100-250 tonnes H_2 per day

Scale Up

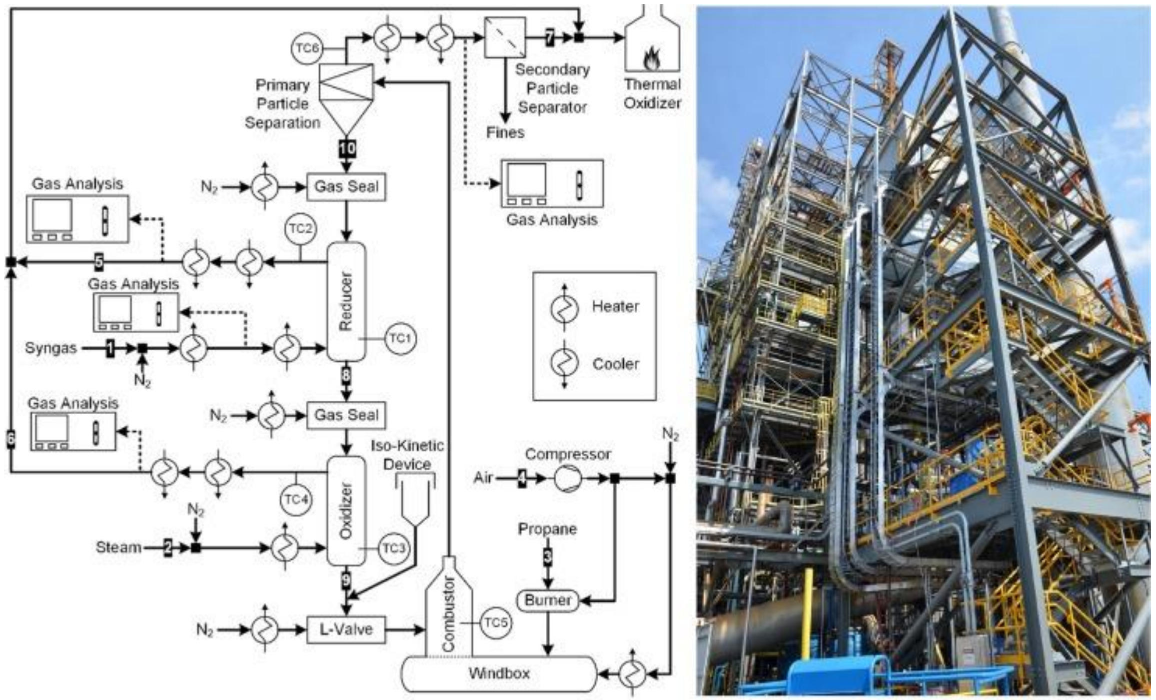
BrightLoop™ Project: Massillon, Ohio, USA

Natural Gas to Hydrogen

OUTPUT	
H_2 from Natural Gas	**1-5 tonnes/day**
H_2 production use	**Industrial, Transportation**

PROJECT DEVELOPMENT PLAN – Approximate Timeline	
Off-take agreement finalized	**2Q 2024**
Funding Commitment	**3Q 2024**
Permits issued	**4Q 2024**
Target first H_2 production	**1Q 2026**

OSU 3-Reactor System for Hydrogen Production

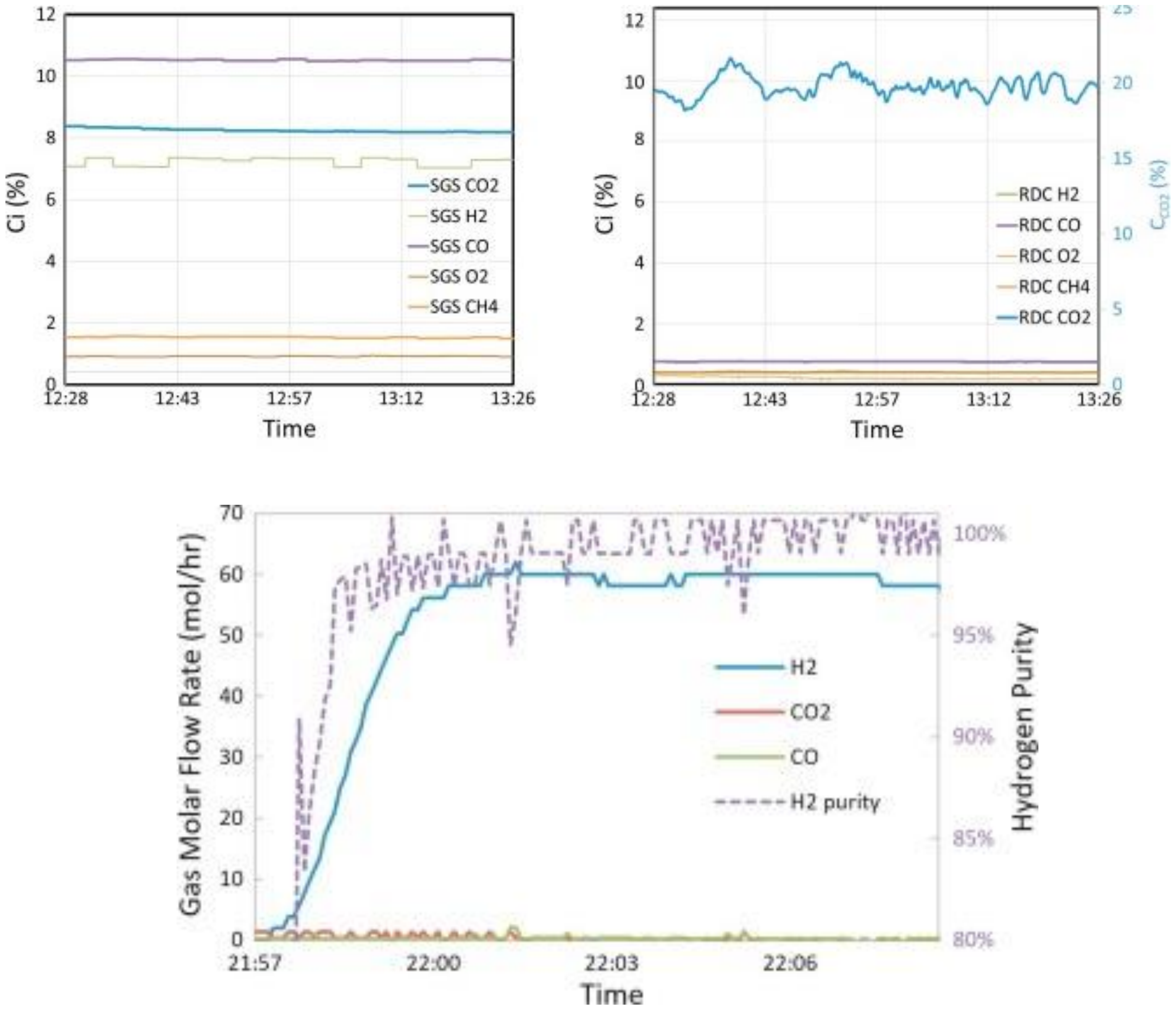


(a) (b)

250 kW$_{th}$ Pilot demonstration at National Carbon Capture Center, AL

Operating parameters:

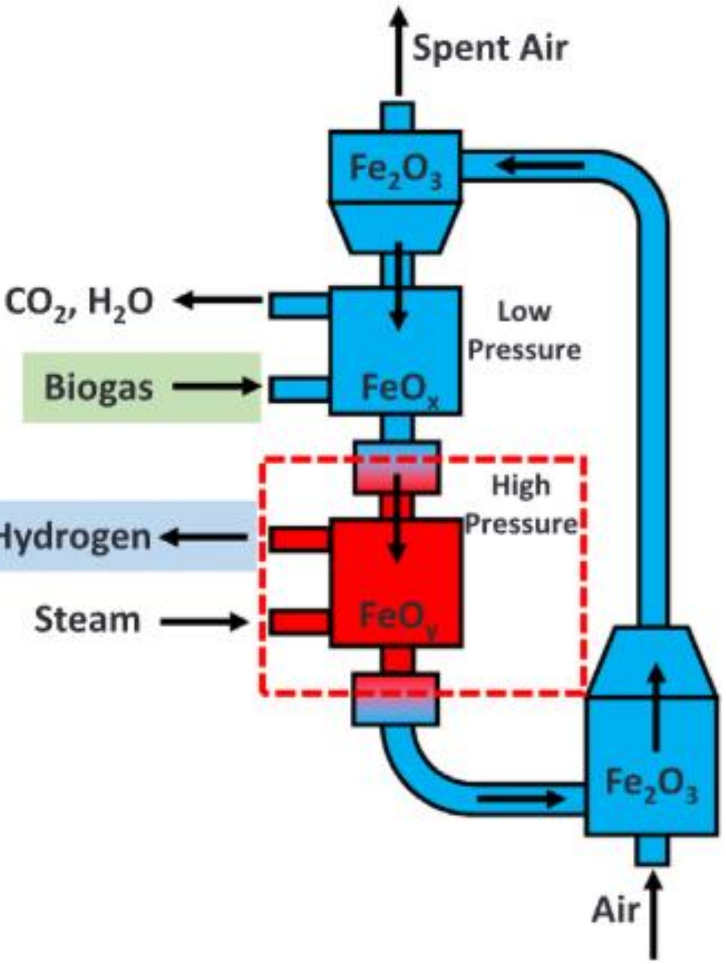
1. OC flow rate = 1320 kg/hr
2. Syngas inlet flow rate = 324.8 kg/hr
3. H2 outlet flow rate = 3.61 kg/hr

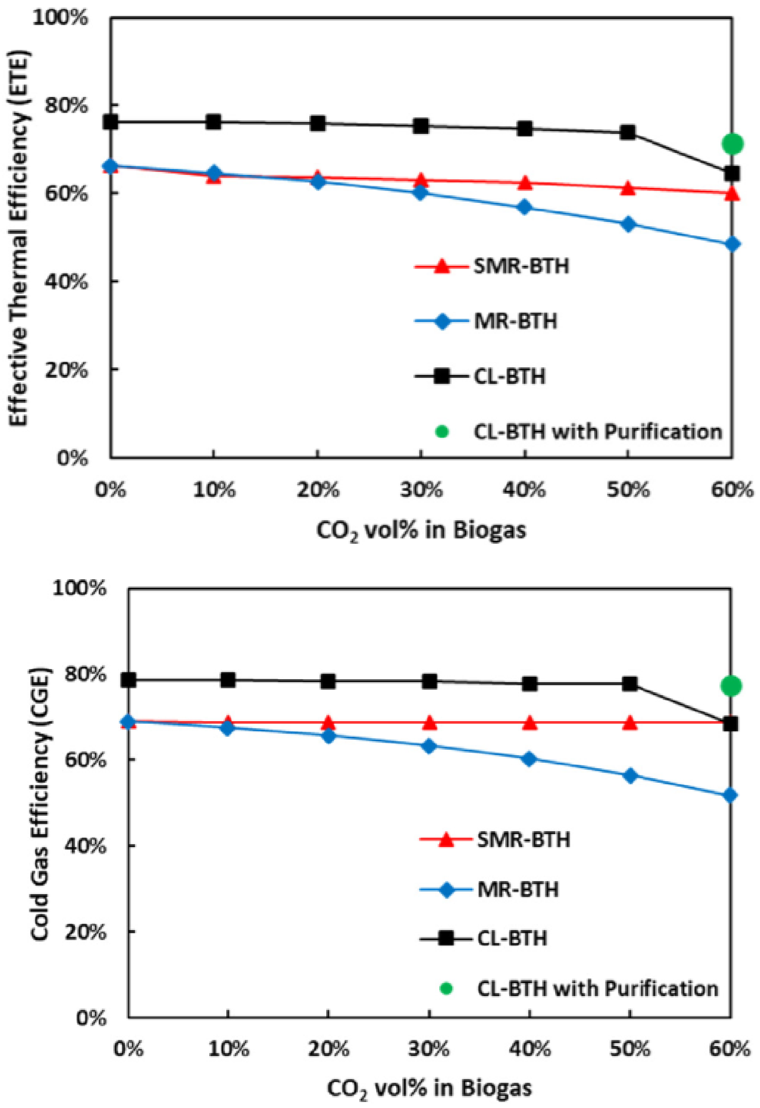


Gas profiles for pilot demonstration: Reducer (top) and Oxidizer (bottom)

Zhang, Y., L.-S. Fan et al, Applied Energy 282, 116065, 2021.
Hsieh, T.-L., L.-S. Fan et al., Applied Energy 230:1060-1072, 2018.

Biogas to H_2 conversion with CO_2 capture using chemical looping technology



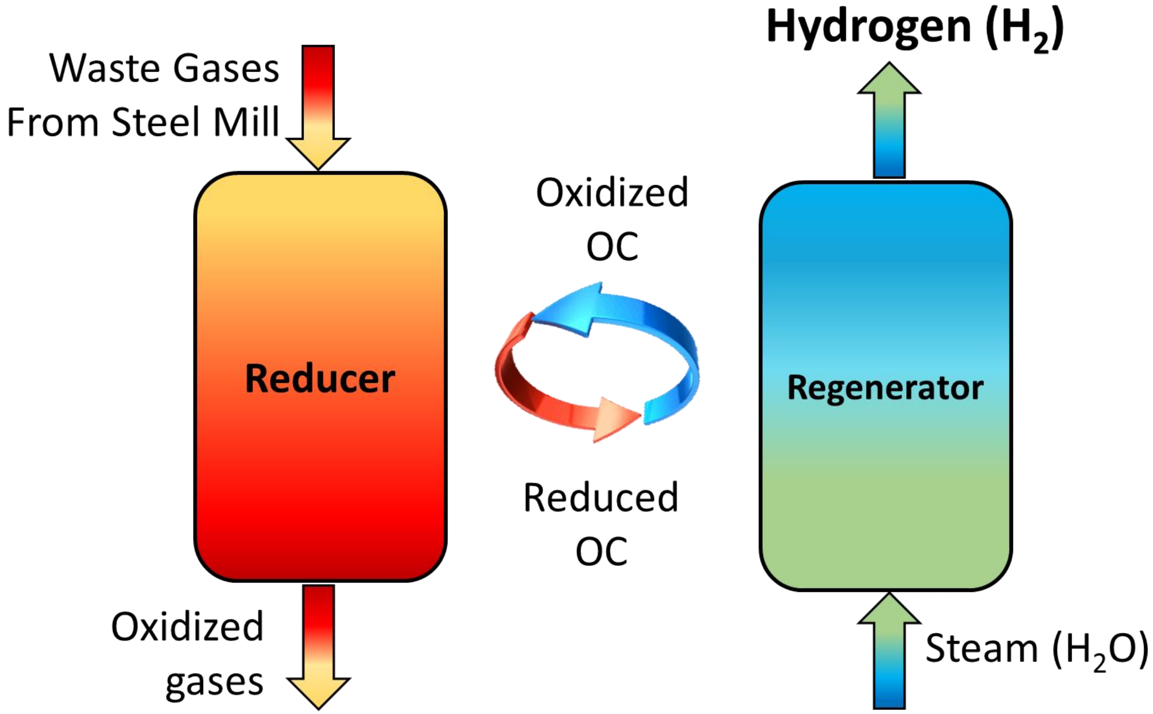


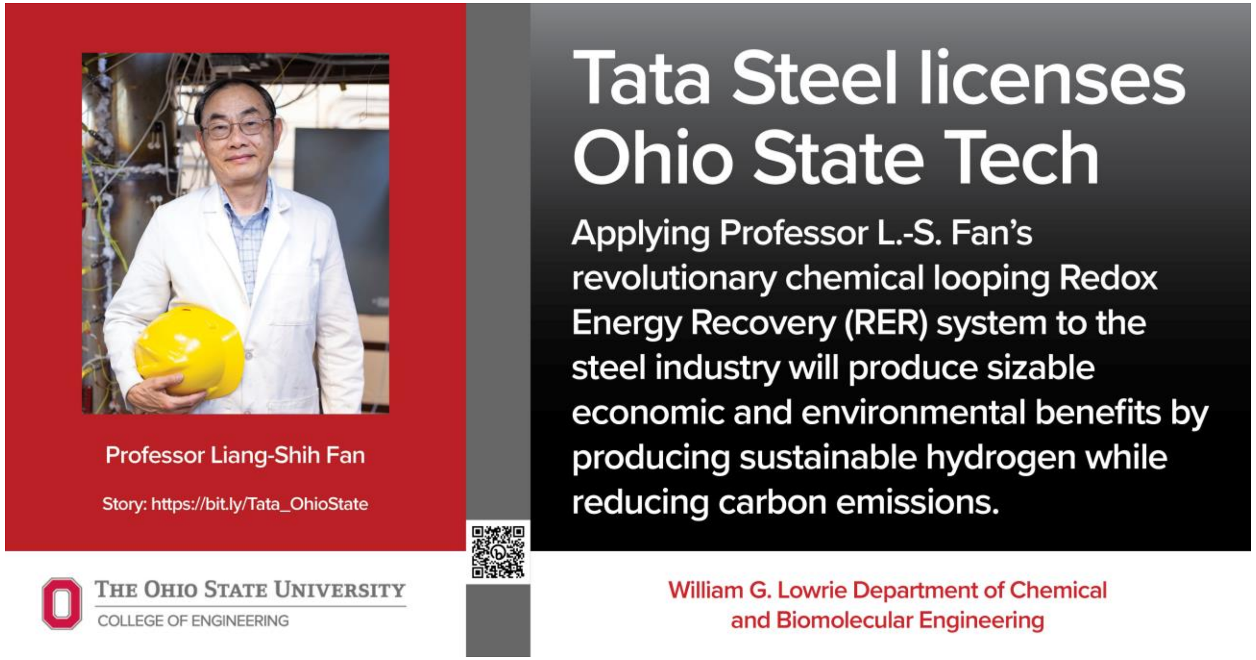
- The chemical looping process can directly handle biogas with 0-50% CO_2 volume ratio.
- Achieves 100% CO_2 capture, making it a carbon-negative hydrogen production method.

- Oxidizer pressure set at 3 MPa eliminates the need for hydrogen compression, reducing auxiliary power consumption.
- H_2 yield reaches 2.42 moles of H_2 per mole of CH_4, outperforming conventional methods.

- Cold Gas Efficiency (CGE) increases by 13-14% compared to conventional reforming processes.
- Effective Thermal Efficiency (ETE) improves by 15-20% demonstrating better energy utilization.

Kong, F., Swift, J., Zhang, Q., Fan, L. S., & Tong, A. (2020). Biogas to H2 conversion with CO2 capture using chemical looping technology: Process simulation and comparison to conventional reforming processes. Fuel, 279, 118479.

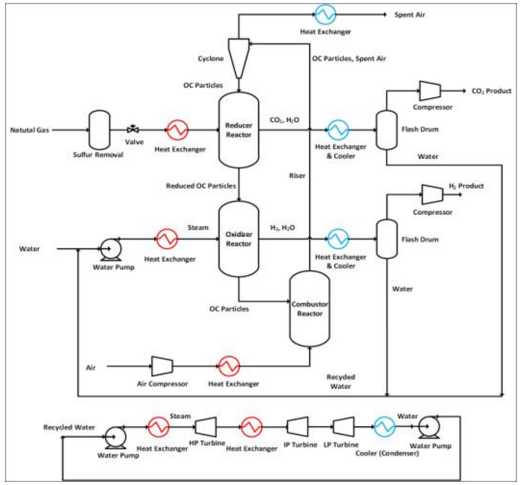




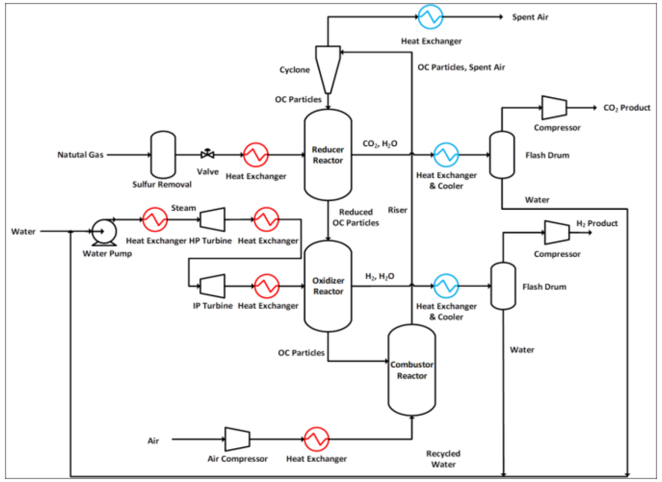
- Steelmaking: high contributions to GHG emissions
- Outlet gases contain H_2O, CO_2, along with some amount of H_2 and CO, typically flared
- Leveraging the reducing potential to generate H_2.
- Seamless integration into existing steel production processes with minimal modifications to plant infrastructure
- Lower carbon intensity steel production
- An effort towards a decarbonized steel production with Tata Steel, India.
- Current ongoing efforts for commercialization.

Co-generation of Electricity and Hydrogen Using OSU Chemical Looping Platform

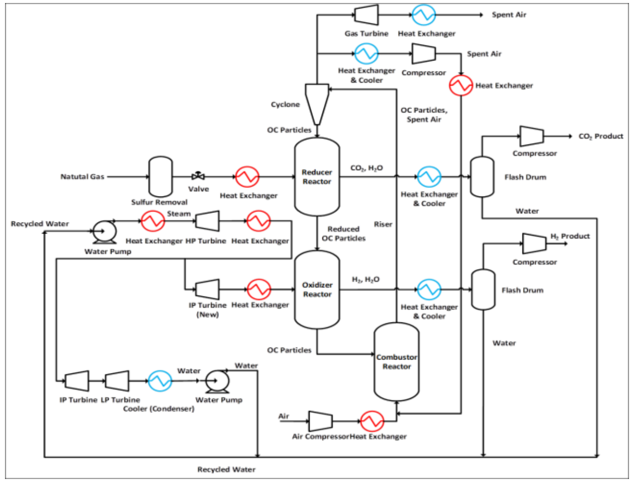
ITC-CLWS: integrated turbine combined chemical looping water splitting



Standard CLWS process & Rankine cycle (case 1)



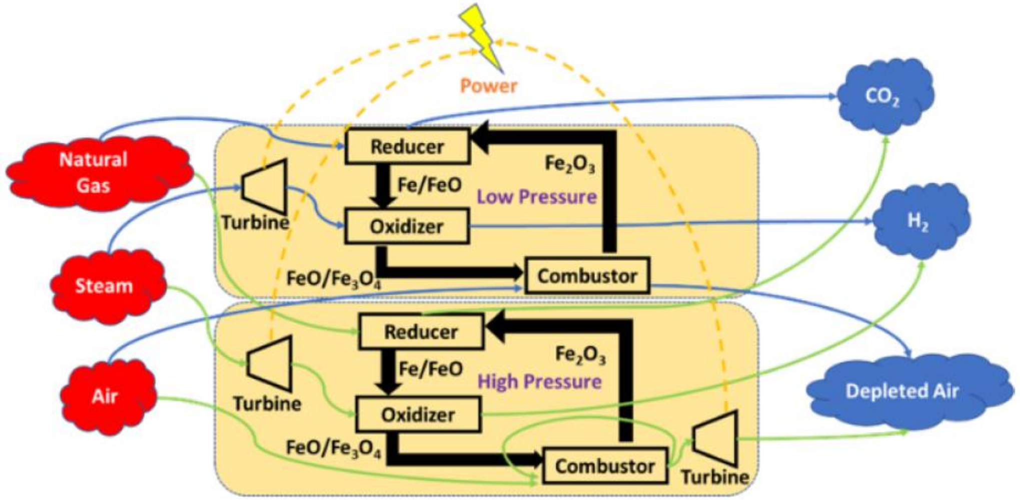
Basic ITC-CLWS process (case 2&3)



High-pressure ITC-CLWS processes (case 4&5)

Tax policies:

1. 45Q - The amount that a taxpayer may claim as a Section 45Q tax credit is computed per metric ton of qualified carbon dioxide captured and sequestered ($27.61/MT CO_2 in 2023).
2. 45V - Credit is calculated based on the amount of CO2 equivalent per kilogram of hydrogen. Used to incentivize clean H2 production. Maximum tax credit can be $3/kg H_2 if the process emits less than 0.45 kg CO_2 eq/kg H_2.
3. CO_2 emission tax - Penalty for emitting CO_2 into the atmosphere. It is considered to be $37.7/MT CO_2 in 2018.
4. For this study emission tax is considered instead of 45Q and 45V.



Ref: Hydrogen and Electric Power Cogeneration in Novel Redox Chemical Looping Systems: Operational Schemes and Tech-Economic Impact
Qiaochu Zhang, Andrew Tong, and Liang-Shih Fan
Industrial & Engineering Chemistry Research
DOI: 10.1021/acs.iecr.2c03834

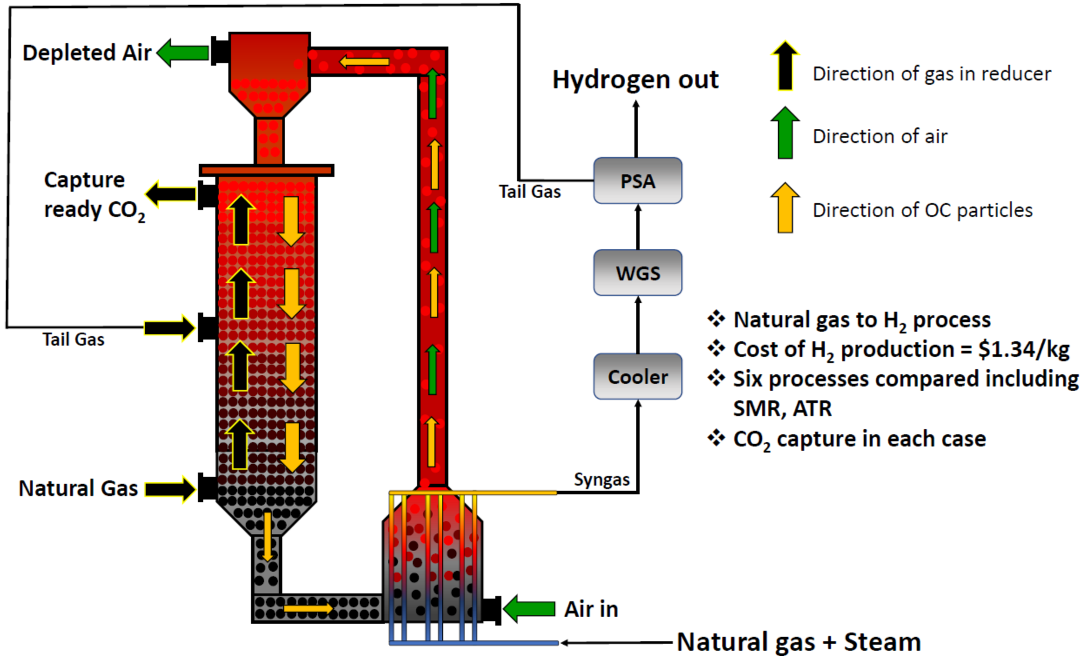
LCOH sensitivity diagrams for CLWS/ITC-CLWS Cases 0-5 (a-f)

Case index	0	1	2	3	**4**	5	**ATR**	**SMR**
Hydrogen Price, 2018 $/kg	1.48	1.48	1.42	1.44	**1.37**	1.78	**2.23**	**1.61**

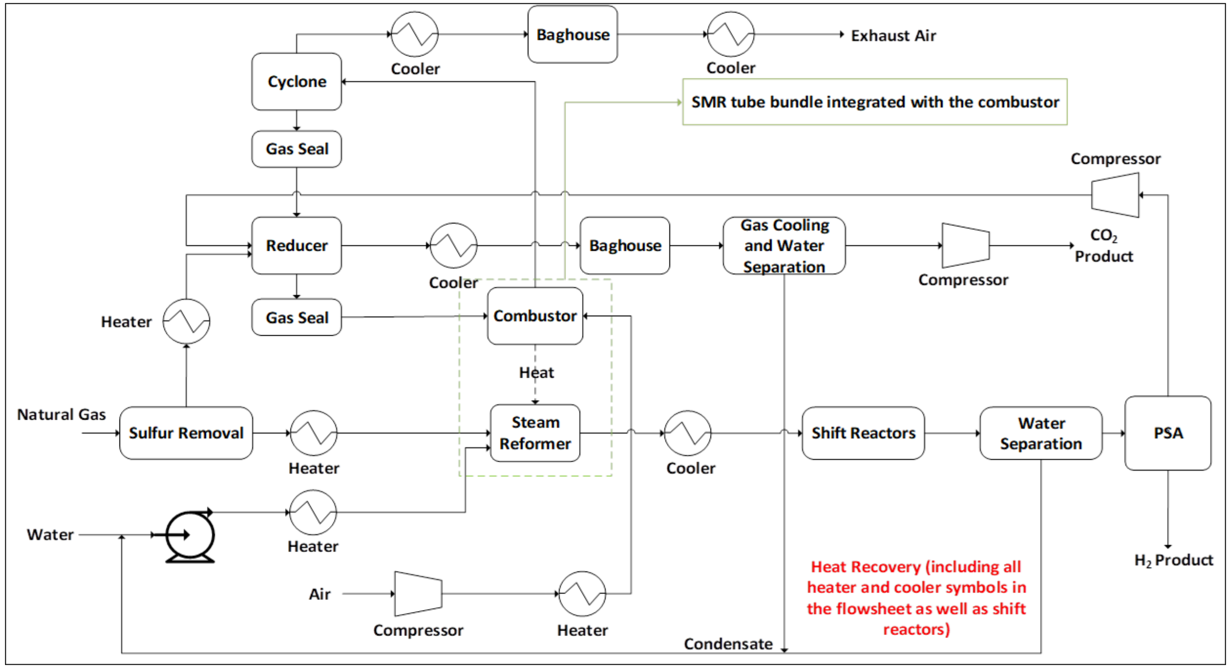
LCOH comparison of Cases 0-5 and ATR, SMR with 103.2 ton/hr natural gas as feedstock

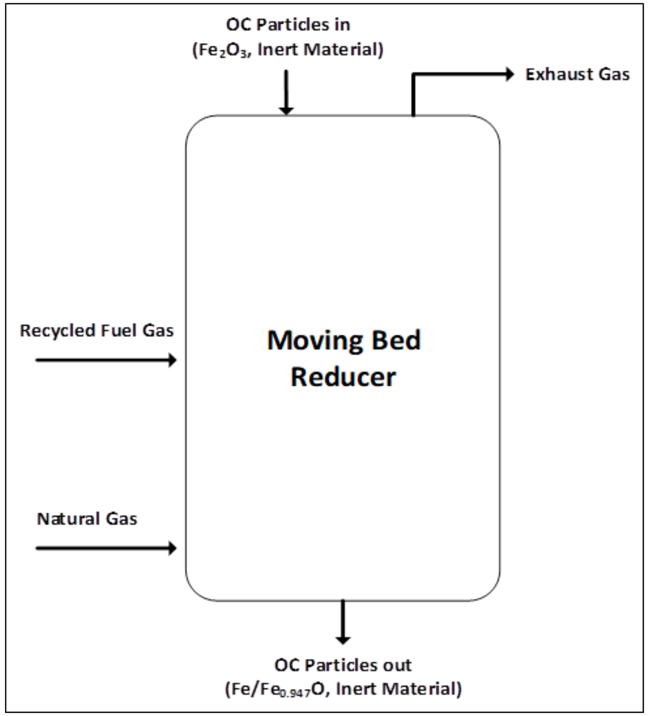
LCOH: Levelized Cost of Hydrogen

Zhang, Q., Fan, L.-S., et al, International Journal of Hydrogen Energy https://doi.org/10.1016/j.ijhydene.2023.07.300, (2023).



- Natural gas to H_2 process
- Cost of H_2 production = $1.34/kg
- Six processes compared including SMR, ATR
- CO_2 capture in each case



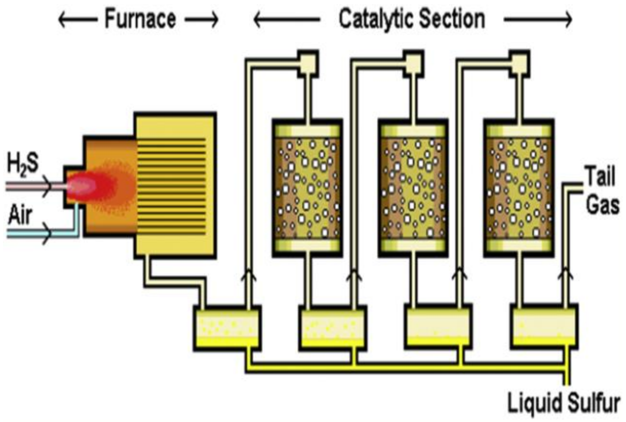


Stage injection strategy

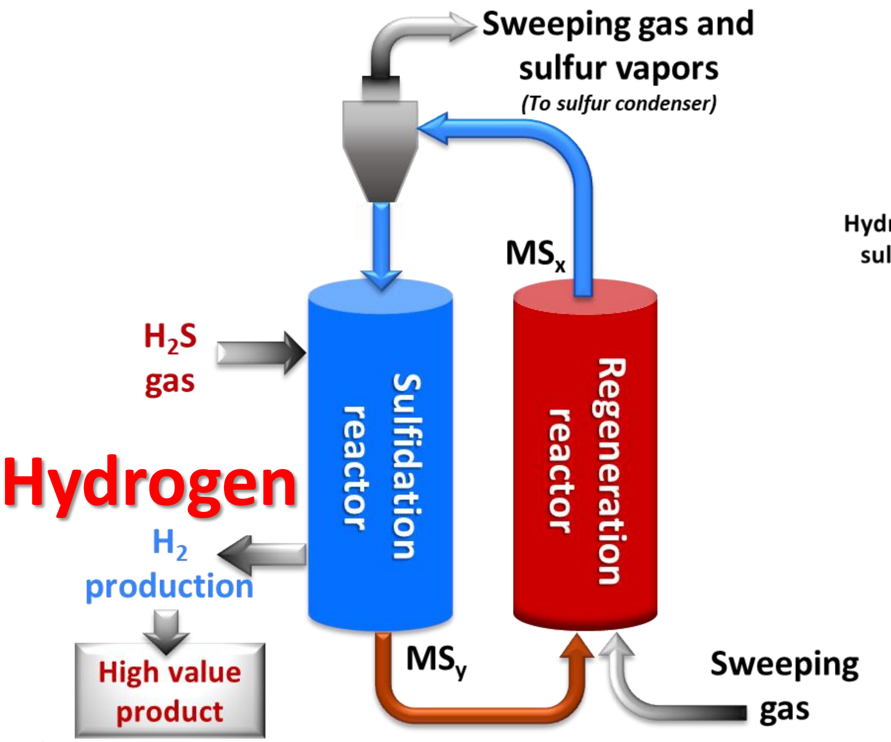
MCLC-SMR: chemical looping combustion with moving bed reducer combined with steam methane reforming

Zhang, Q., Joshi, R. and L.-S. Fan et al., International Journal of Hydrogen Energy https://doi.org/10.1016/j.ijhydene.2023.07.300, (2023).

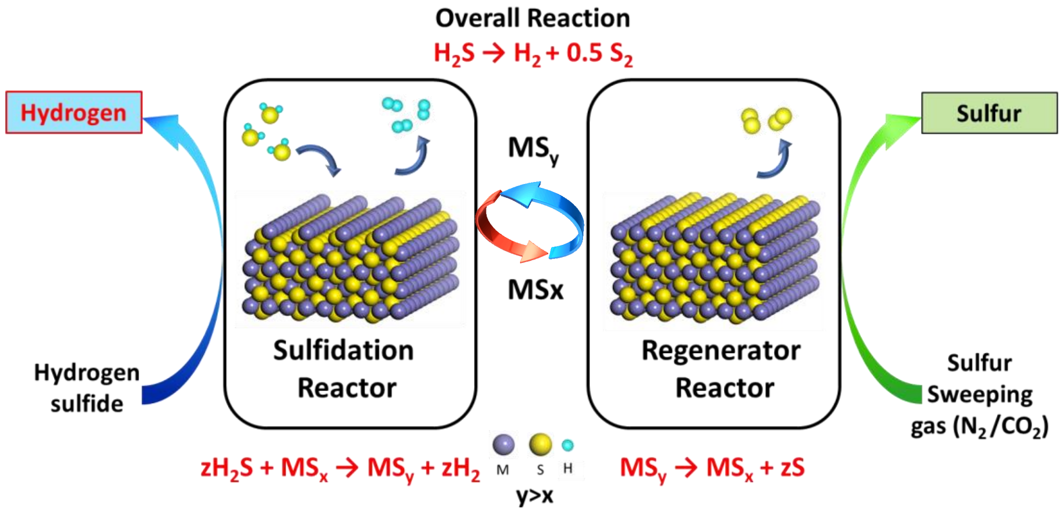
OSU Chemical Looping Sulgen Process for Hydrogen Generation from Hydrogen Sulfide



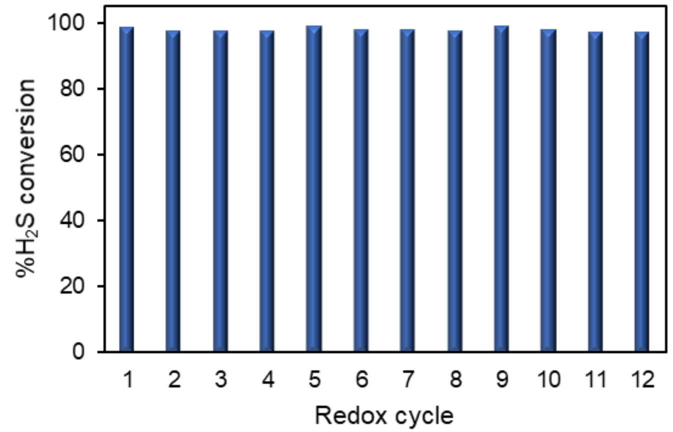
Conventional H_2S treatment using the Claus process



Chemical looping Sulgen process for H_2 generation from H_2S



>98% H_2S conversion in Sulfidation step



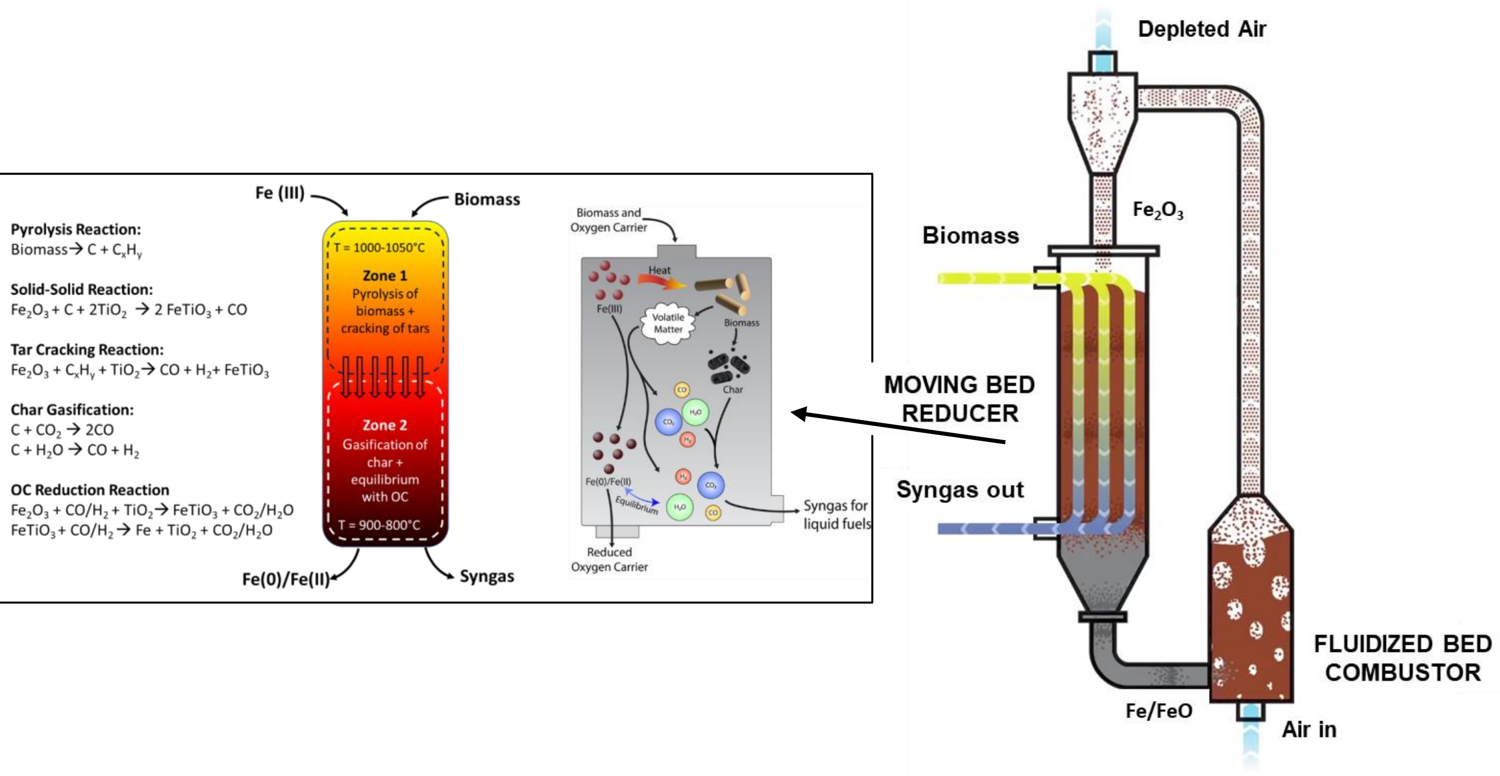
H_2S conversion into H_2 over 12 sulfidation (T: 400°C) and regeneration (T: 950°C) cycles using iron-based sulfur carrier

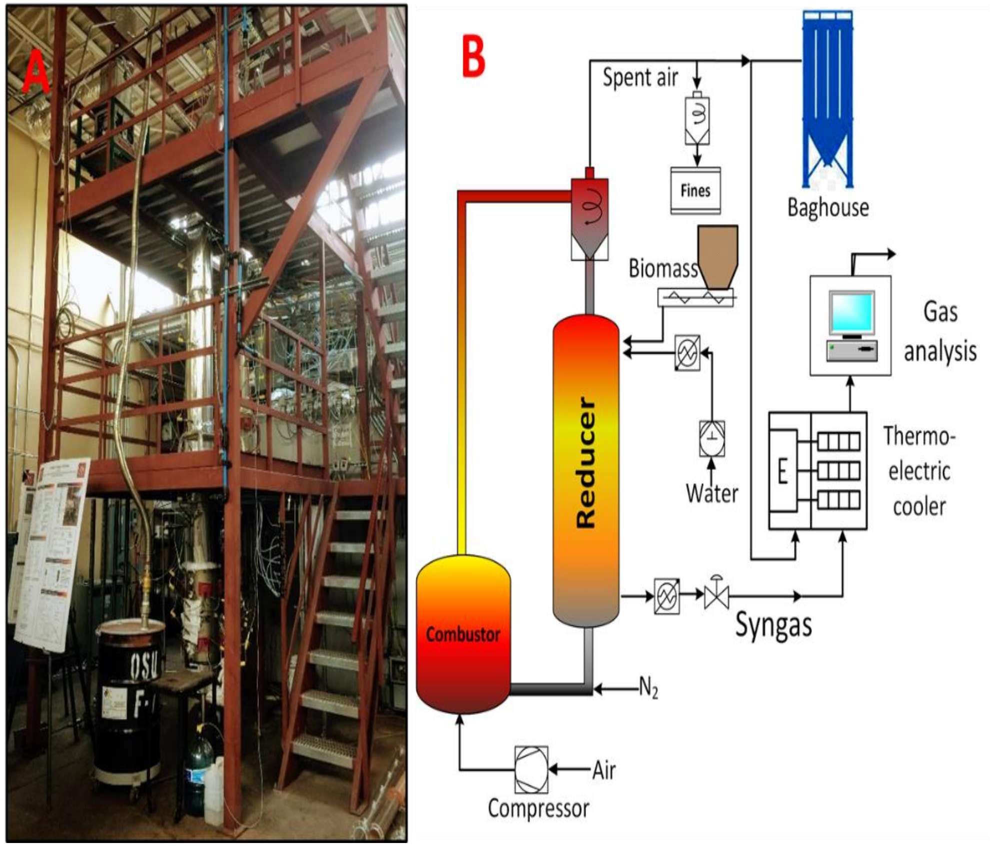
Key advantages over the Claus process:

- Production of H_2 instead of steam
- ~99% reactive separation of H_2S into H_2 from syngas, natural gas, acid gas and hydrocarbon (C_2-C_4) stream
- Significant reduction in processing units, cost and energy requirement

Nadgouda SG, Jangam KV, Fan L.-S. Systems, methods and materials for hydrogen sulfide conversion. 2018 (62/716,705 (US), patent pending).
Jangam and Fan et al., ACS Sustainable Chem. Eng. 2021
Jangam and Fan et al., Chem. Eng. J., 2021
Sassi and Gupta, Am. J. Environ. Sci.,2008

Biomass to Syngas (BTS) Technology





Picture of the actual sub-pilot unit. B) Schematic of the experimental setup with accessories

- 15 kW_{th} unit has been built at OSU with the capacity to process 3.6 kg/hr of biomass
- The unit has been successfully run for over 600 hours with 150 hours of continuous operation
- The system exhibits the ability to process various types of biomass feedstocks

Xu, D., Fan, L.-S., et al., Applied Energy, 222, 119-131 (2018).

Comparison with Conventional Process

System	Indirect Gasifier	BTS
Biomass in, as received (short TPD)	81464	70152
Gasification carbon efficiency (%)	**69.7**	**89.4**
Syngas purity	87.9	82.9
Product (bbl/day)	49958	49957
Jet fuel	36944	36943
Diesel	8614	8613
Naphtha	1178	1178
LPG	3222	3222
Net power export (MW)	545.6	410.2
Thermal efficiency (%)	48.8	54.5

System	Indirect Gasifier	BTS
Syngas compression duty	324	387.7
Combustor compression duty	96.5	87.4
ASU electricity demand	114.6	-
Dryer air blower	-	2.7
F-T synthesis net export power	966	887
Net plant export power	545.6	410.2

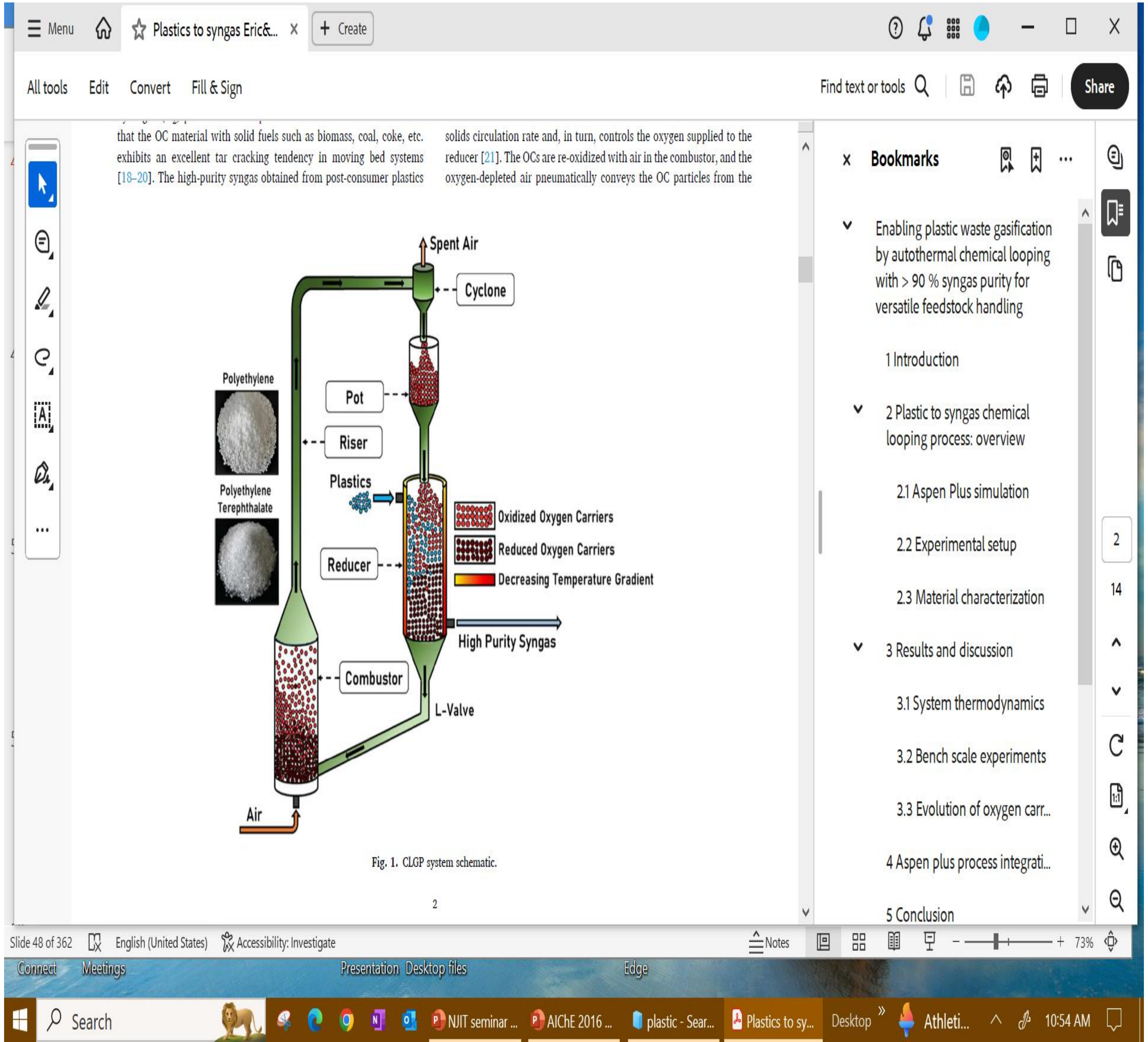
- To validate the superior performance of BTS, it was compared with Indirect gasification for liquid fuel production through FT synthesis
- The results indicate that BTS has higher thermal and carbon efficiency than indirect gasification
- Furthermore, BTS achieves process intensification by eliminating the energy-intensive Air Separation Unit

Applications in Energy and Combustion Science 19 (2024) 100270

Enabling plastic waste gasification by autothermal chemical looping with > 90 % syngas purity for versatile feedstock handling

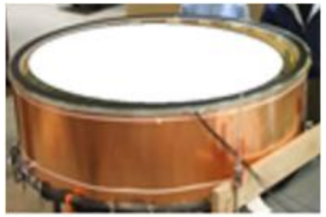
Eric Falascino [1], Rushikesh K. Joshi [1], Sonu Kumar , Tanay Jawdekar , Ishani K. Kudva , Shekhar G. Shinde , Zhuo Cheng , Andrew Tong , Liang-Shih Fan *

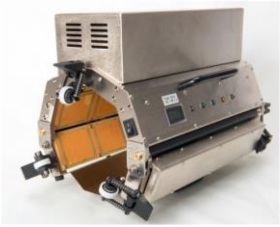
William G. Lowrie Department of Chemical Engineering, The Ohio State University, United States

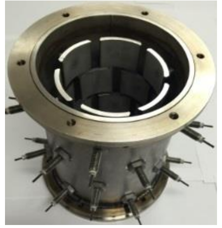


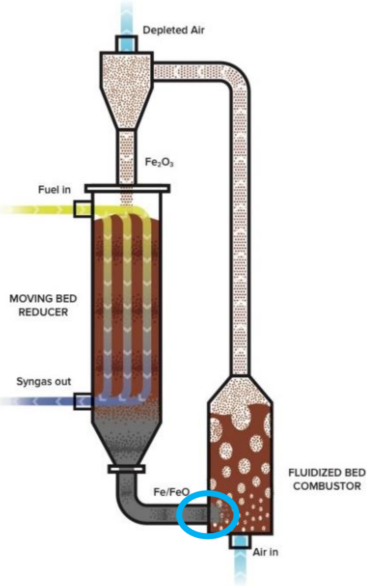
ECVT Commercial Applications

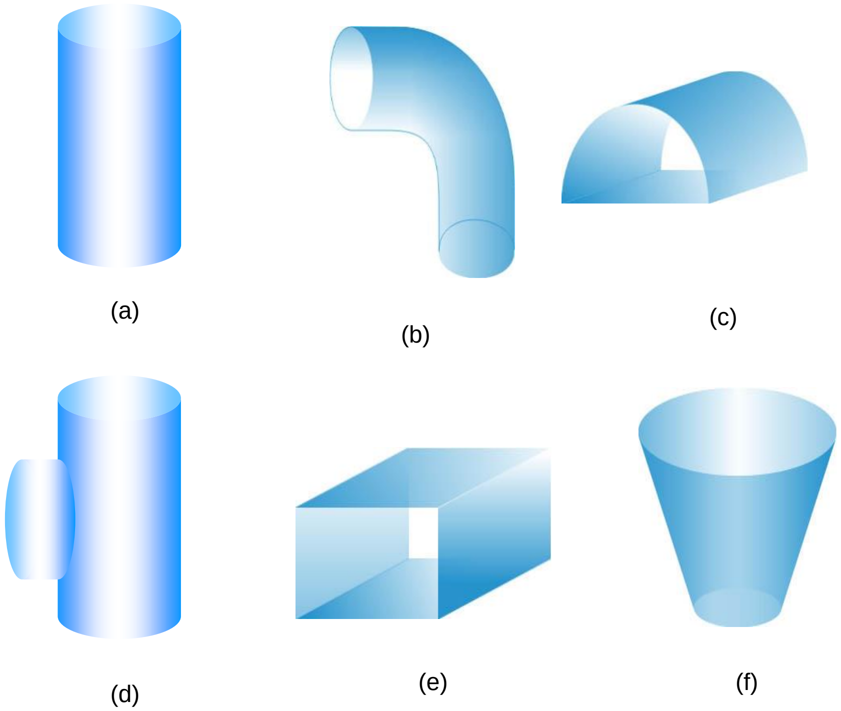
60” Sensor

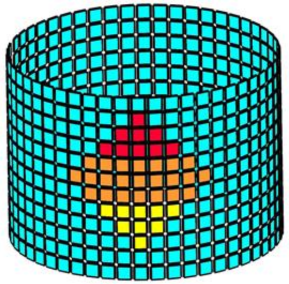


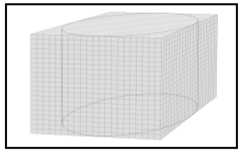










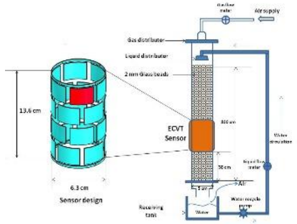


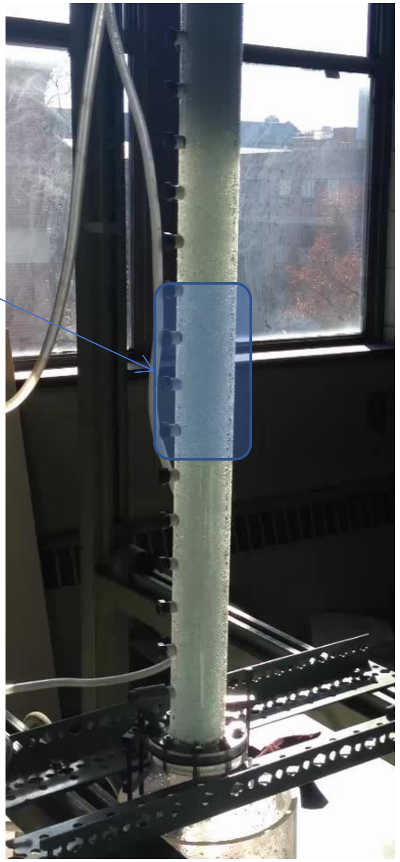
$20 \times 20 \times 20$

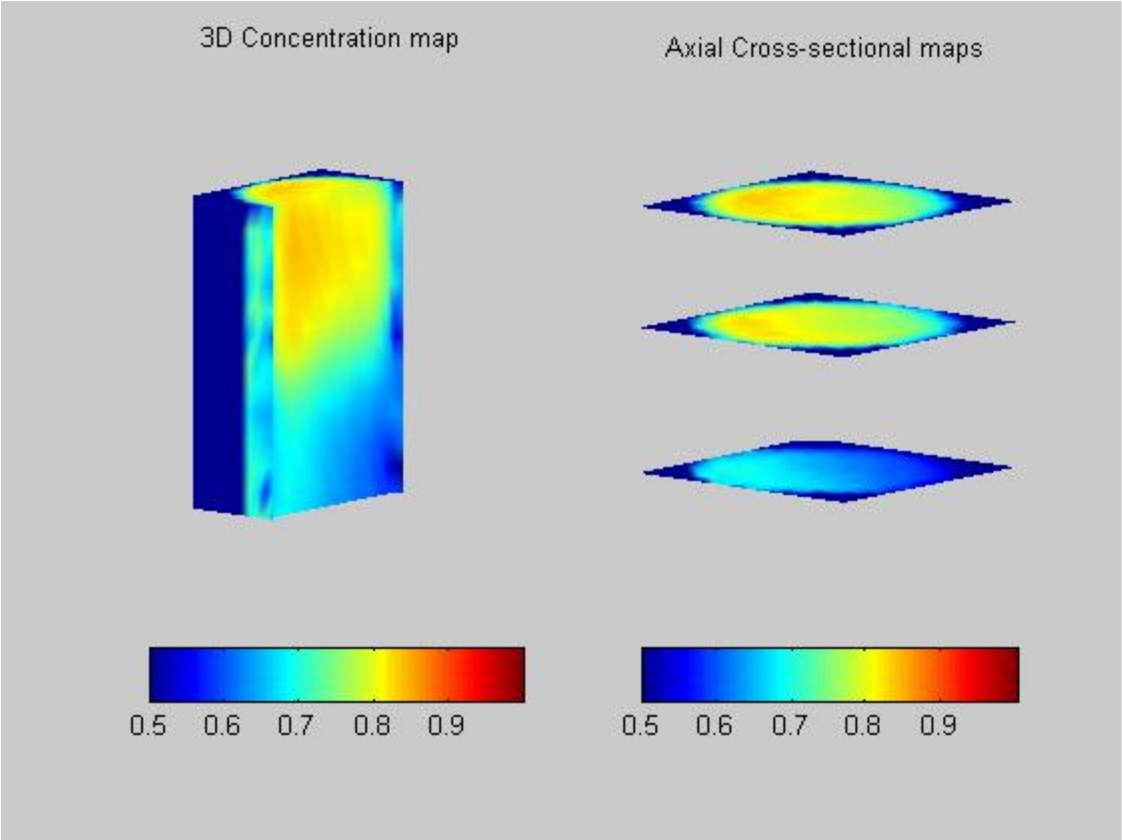
Wang, F., Yu, Z., Marashdeh, Q., Fan, L.-S. *Chemical Engineering Science*. 2010.
Warsito, W., Marashdeh, Q., Fan, L.-S. *Sensors Journal, IEEE*. 2007.
Marashdeh, Q. M., Teixeira, F. L., Fan, L.-S. *Sensors Journal, IEEE*. 2014.

Electrical Capacitance Volume Tomography Videos for pulsation flow
(G: 0.454 kg/m^2s, L:21.7 kg/m^2s)

ECVT Sensor location







Original video in normal speed

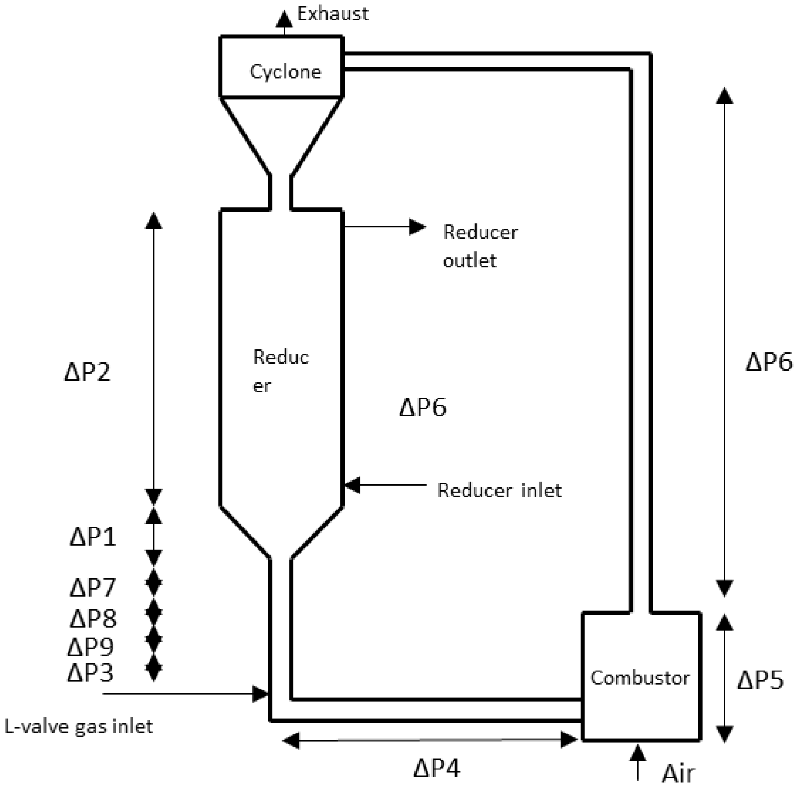
ECVT reconstructed video in normal speed (50fps)

Recurrent Neural Network (AI) Based Metal Oxide *Attrition* Risk Assessment on Arching in Chemical Looping Systems

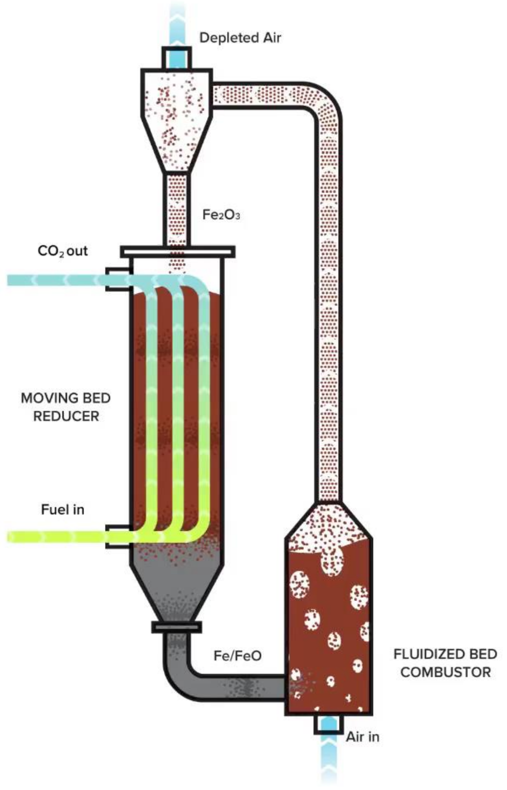
- 9 different pressure transducers (ΔP1 – 9) were installed across the cold flow model
- Three different gas inputs: L-valve, Combustor and Reducer
- ITCMO particles with particle density of 2500 kg/m3 and particle diameter of 1.5 mm

Experimental conditions:

Reducer	2 SCFM
L-valve	2 SCFM
Combustor	1000 SLPM

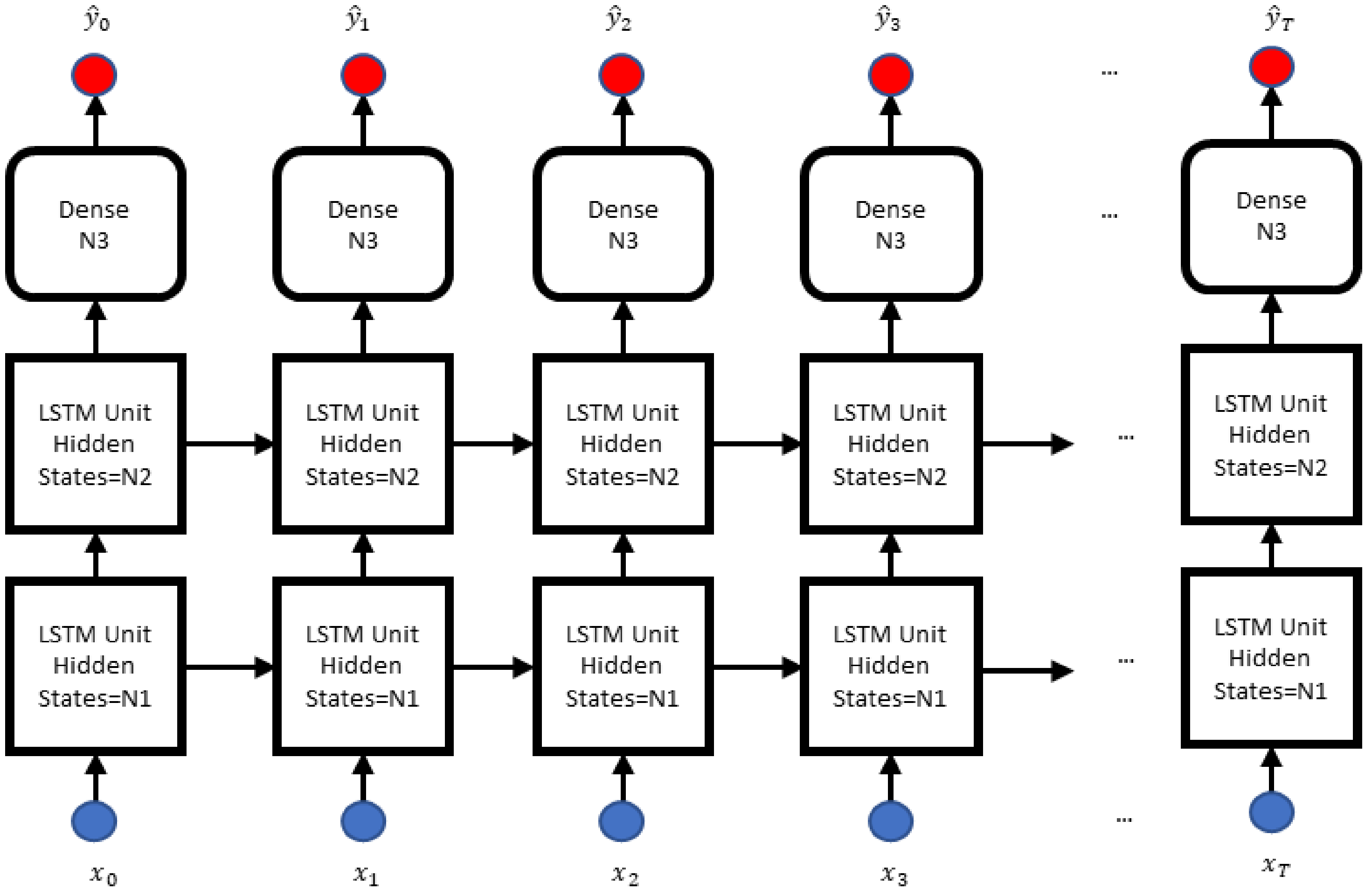


Experimental Setup



Pan J. and L.-S. Fan *et al.*, Powder Technology, 367, 266-276 (2020).

Recurrent NN model Setup



- Layers in different time steps share the same weights
- Activation function in the dense layer is the rectifier function:

  $f(x) = \max(0,x)$

- Activation function in the output layer is the sigmoid function:

  $f(x) = \frac{1}{1+e^{-x}}$

- **Loss function is binary cross entropy**

$$\frac{-1}{T+1}\sum_{t=0}^{T}(1-y_t)\log(1-\hat{y}_t)+y_t\log(\hat{y}_t)$$

LSTM Scheme

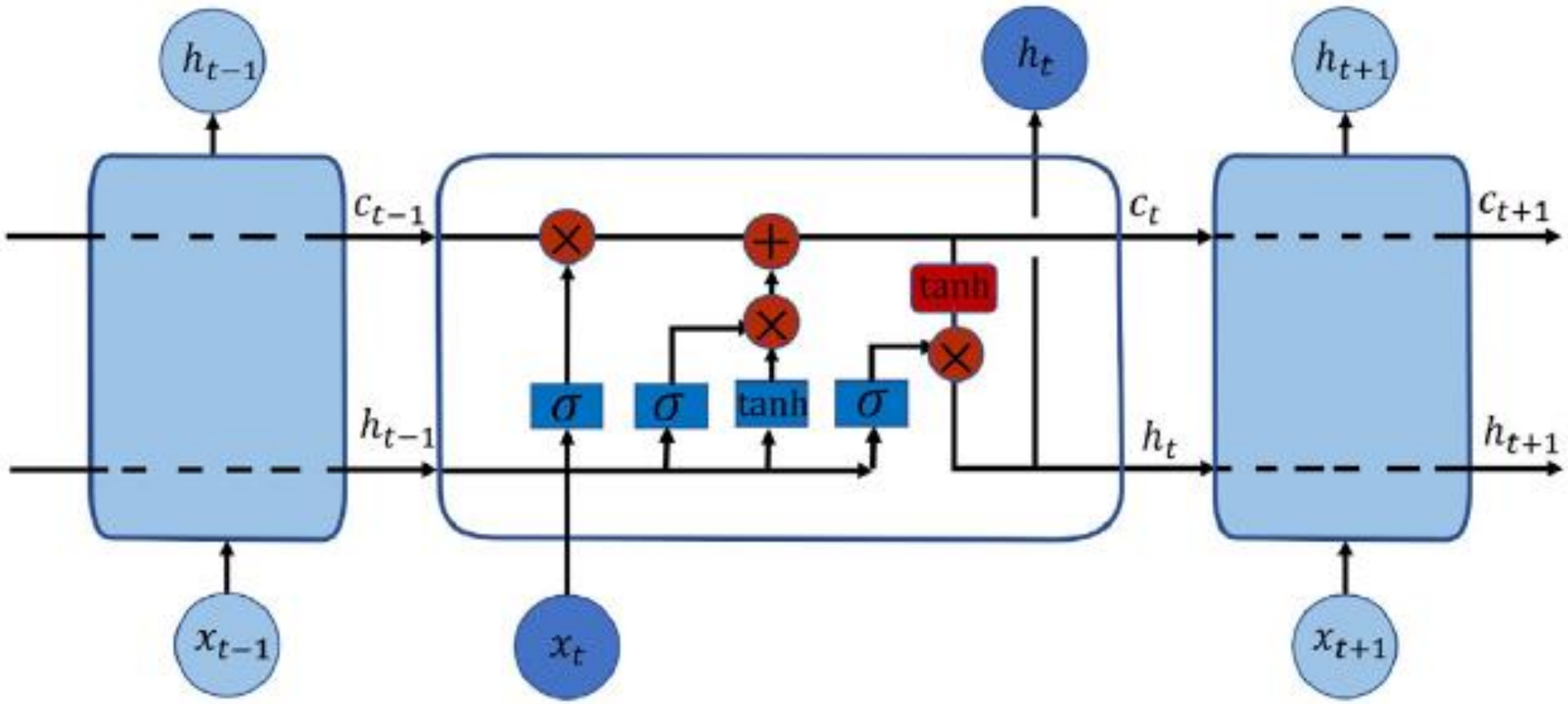


Fig. 5. Flow chart of the LSTM unit, referenced from Olah [33].

Training, Validation and Testing Results

[N1,N2; N3]	Training	Validation	Testing Dataset				
	Loss	Loss	Loss	Accuracy	Precision	Recall	F1 Score
[128,64;32]	0.0361	0.0932	0.108	0.960	0.689	0.838	0.757
[128,32;32]	0.0380	0.0961	0.152	0.9399	0.559	0.896	0.688
[64,32;32]	0.0374	0.0962	0.122	0.959	0.680	0.841	0.752
[64,32;16]	0.0370	0.0931	0.141	0.948	0.607	0.861	0.712
[64,16;16]	0.0364	0.0947	0.125	0.952	0.624	0.876	0.729
[128;32]	0.0358	0.0907	0.119	0.951	0.621	0.882	0.729
[128;16]	0.0342	0.0905	0.154	0.942	0.569	0.873	0.688

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad Precision = \frac{TP}{TP + FP} \quad \mathbf{Recall} = \frac{TP}{TP + FN} \quad F1 = \frac{2}{1/Precision + 1/Recall}$$

TP: True Positive (correctly predict it happens); TN: True Negative; FP: False Positive (incorrectly predict it happens); ***FN: False Negative (incorrectly predict it did not happen);*** *True Positive – correct prediction of bubbles (1); true negative – correct prediction of no bubbles (0)*

Early stopping was used to choose weights corresponding to the lowest validation loss

Concluding Remarks

- Chemical Looping concept and practice started 125 years with the Bergmann Process, followed by some pilot plant demonstrations along with hundreds of labs worldwide working on metal oxide redox materials and bench-scale processes for generation of various products. Despite its long history of development efforts, no commercial plant is yet in operation.
- Chemical Looping is an enabling platform technology with high Exergy efficiency for generation of a variety of products such as hydrogen, syngas, fuels and chemicals. It is particularly attractive for a process operation with decarbonization requirement.
- Chemical Looping multi-scale approaches encompassing four essential scale levels - molecular, particle, reactor, and system - in synergism interaction propel successful chemical looping and other new energy and fuel technology development. Interfacing between the levels is of the area where exciting research continues to evolve.
- The first Chemical Looping commercial plant is expected to be in operation within one years by Babcock and Wilcox Company, a licensee of the technology from the Ohio State University based on unique moving-bed reducer configuration and iron-based metal oxide oxygen carrier for hydrogen production.