joint **NGI-SUNCAT** workshop
14 September 2016

From methane to liquid fuels and beyond: **opportunities and challenges for a natural gas-powered future**

Stanford | NATURAL GAS INITIATIVE
School of Earth, Energy & Environmental Sciences
and Precourt Institute for Energy

SUNCAT
CENTER FOR INTERFACE SCIENCE AND CATALYSIS

objectives

Bring Stanford PIs and companies together

Understand the state-of-the-art

Fuel collaborations

Bridge the interests of PIs and companies

statistics

57 participants

25% from industry

60% students-postdocs

2 people from government (NSF)

structure

9.00 am – *Methane conversion: general discussion*
9.00 am – Paul Ayoub, Shell, "**The role of NG in transitioning toward tighter carbon constraints**"
9.20 am – Jim Bielenberg, ExxonMobil, "**Key issues for direct conversion routes**"
9.40 am – Ron Smith, IHS Energy, "**Markets for methane and derived products**"
10.00 am – Robert McCabe and Triantafillos John Mountziaris, NSF, "**An overview of federal funding opportunities for natural gas conversion**"
10.20 am – Discussion

10.50 am – Coffee break

11.20 am – *Biological methane conversion*
11.20 am – Craig Criddle, Stanford University, "**Challenges and opportunities for bioconversion of methane**"
11.40 am – Alfred Spormann, Stanford University, "**Microbial Life around Methane**"
12.00 pm – Discussion

12.30 pm – Lunch

2.00 pm – *Unconventional processes to convert or produce methane and related products*
2.00 pm – Ron Kent, SoCalGas, "**Conversion of renewable power to gas**"
2.20 pm – Pete Johnson, Monolith Materials, "**Natural gas conversion to carbon black**"
2.40 pm – Matt Kanan, Stanford University, "**Conversion of CO_2 to chemicals**"
3.00 pm – Discussion

3.30 pm – Coffee break

4.00 pm – *Poster session & reception*

thermochemical pathways

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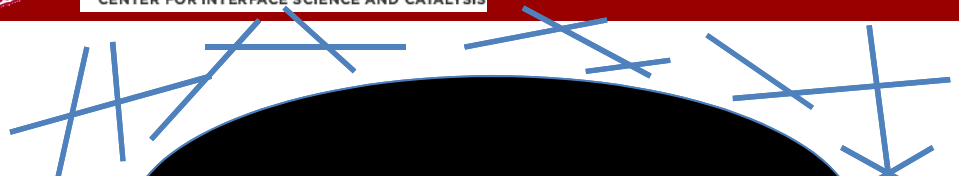
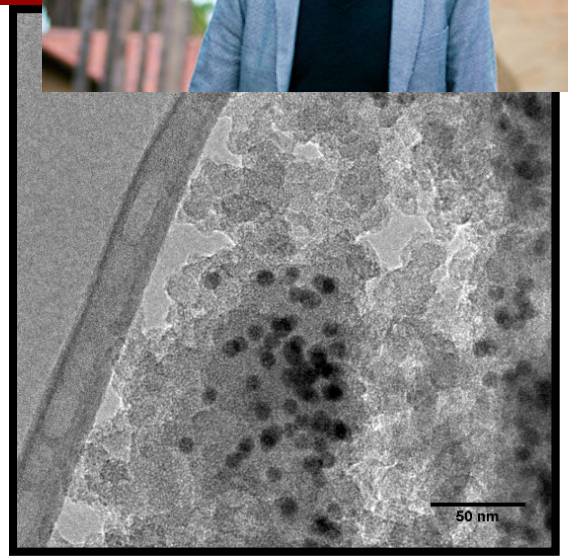
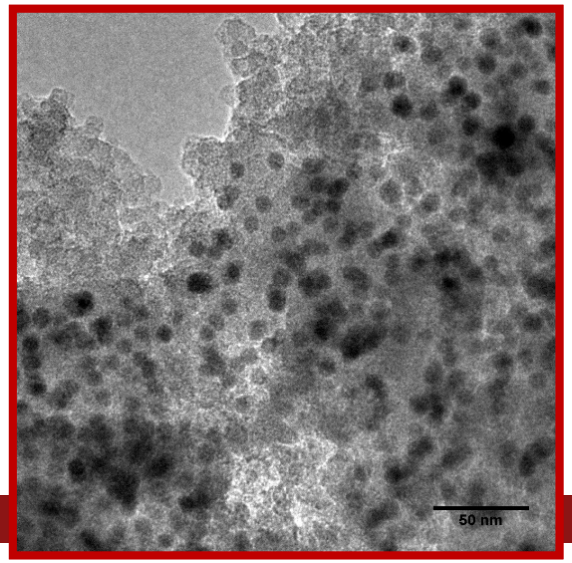
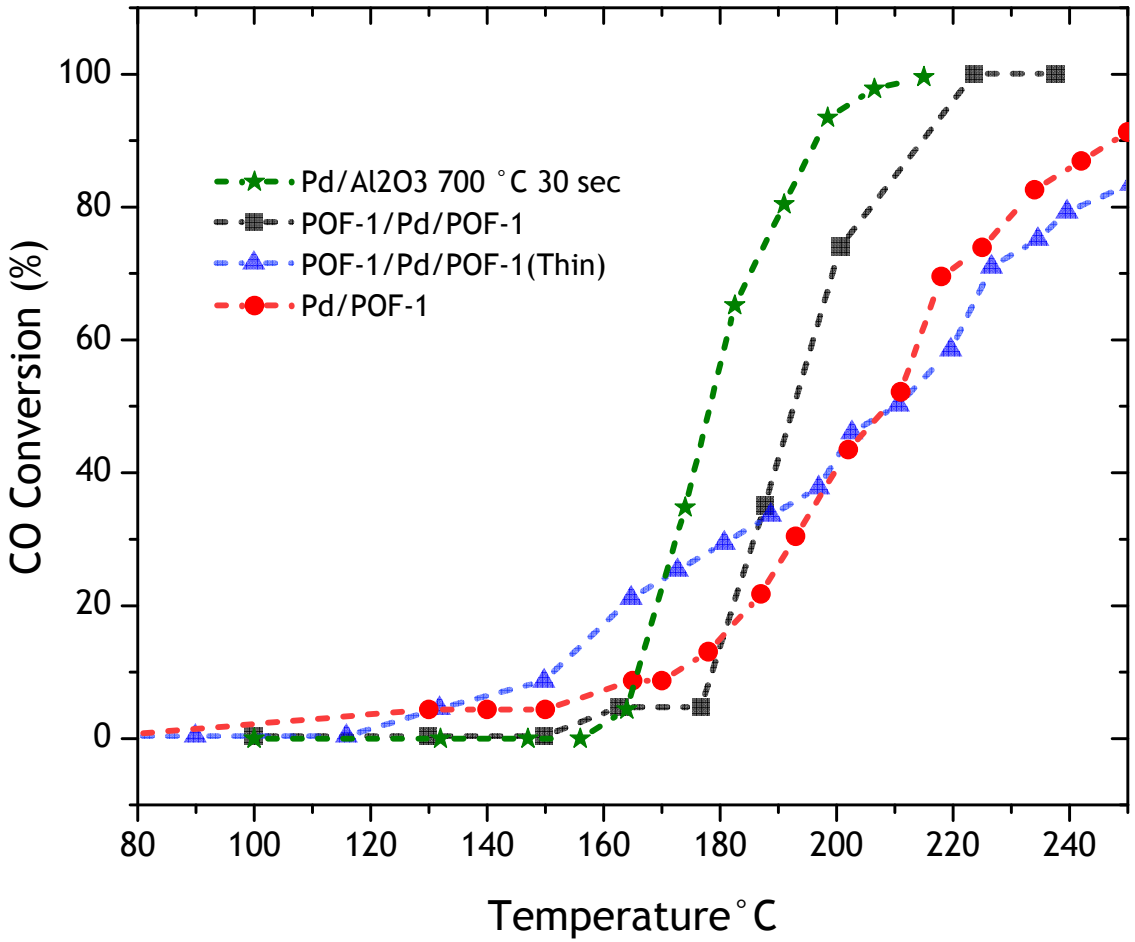








electrochemical pathways

Low temperature electrochemical methane activation

Cathode reaction:

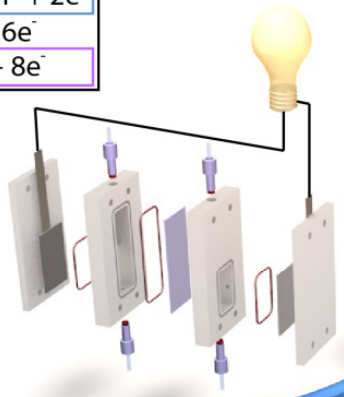
$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Possible anode reactions:

$CH_4 + H_2O \rightarrow CH_3OH + 2H^+ + 2e^-$

$CH_4 + H_2O \rightarrow CO + 6H^+ + 6e^-$

$CH_4 + 2H_2O \rightarrow CO_2 + 8H^+ + 8e^-$



Methane

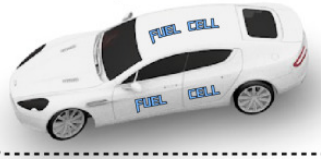
Methanol

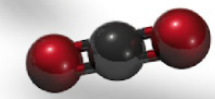
Feedstock for chemicals

Easy storage and transportation

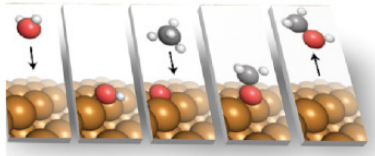
Liquid fuel for transportation

Direct fuel for CNG/LNG fuel-cell powered vehicles



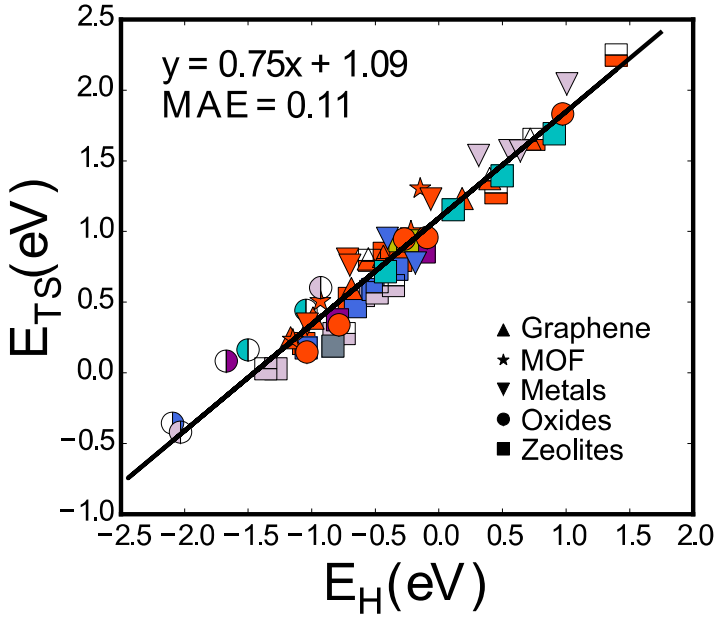


CO_2

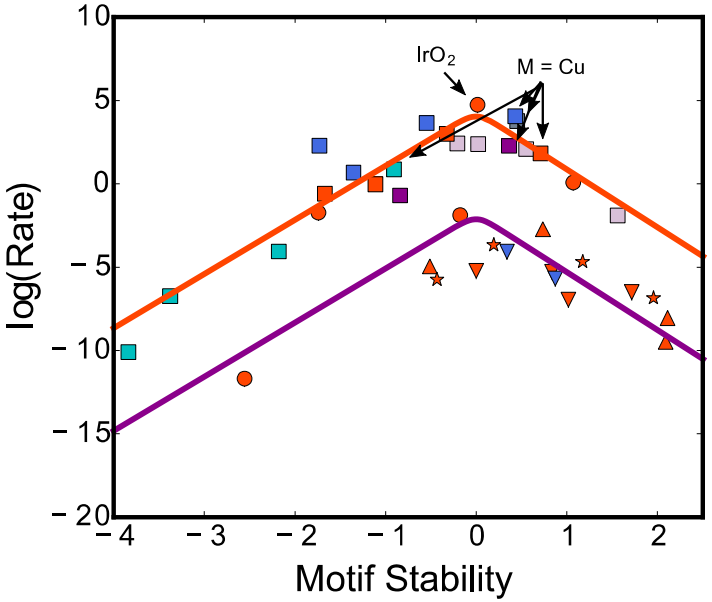


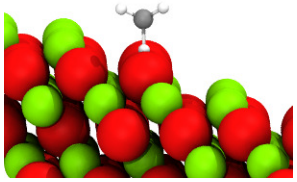
Expand knowledge on electro-chemical methane activation

universal scaling pathways

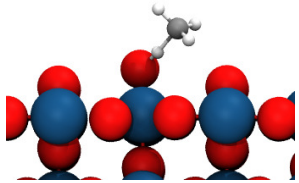


$$R_{CH4\ activation} = \vartheta_{motif}\ \frac{k_b T}{h}\ exp\left(\frac{-\Delta G_{TS}}{k_b T}\right)$$

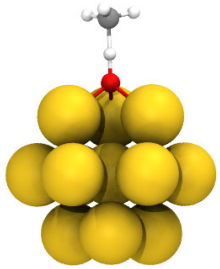




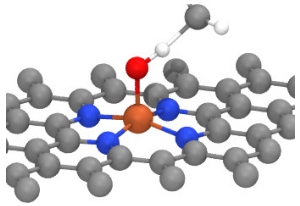
Non-reducible Oxides (MgO)



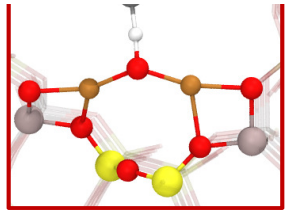
O-Promoted Reducible Oxides (IrO_2)



O-Promoted Noble Metals (Au-O)



Decorated Graphene Nanosheets (Fe-O)



Zeolites (Mordenite Cu-O-Cu)

Latimer, Kulkarni *et al. Nature Materials* (accepted 2016)

methane conversion: **general discussion**

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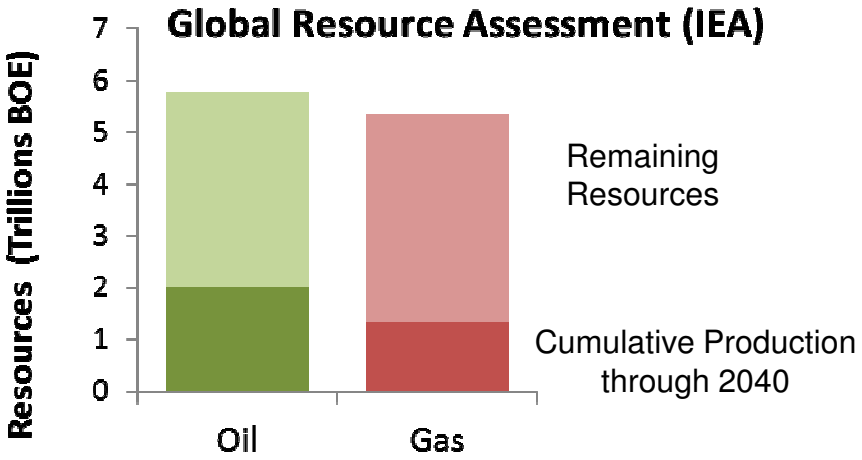
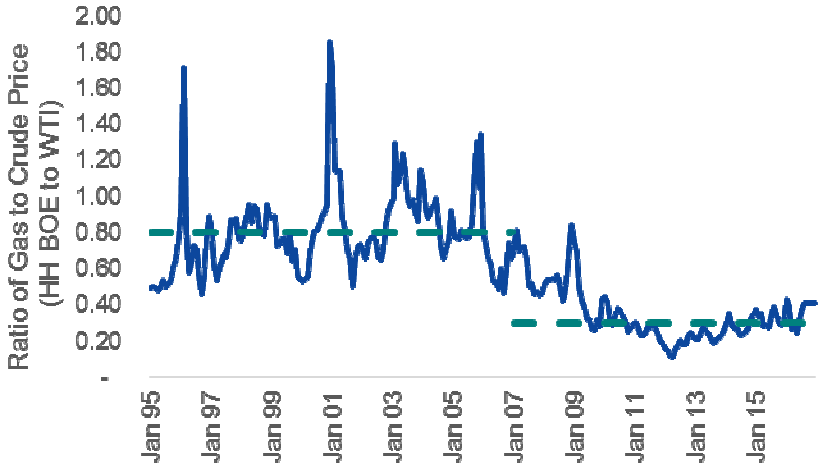
Paul Ayoub, Shell; Jim Bielenberg, ExxonMobil





methane conversion: **general discussion**

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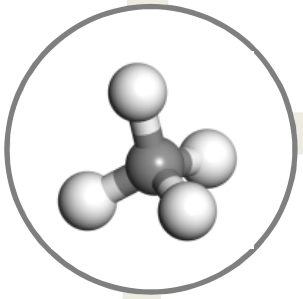
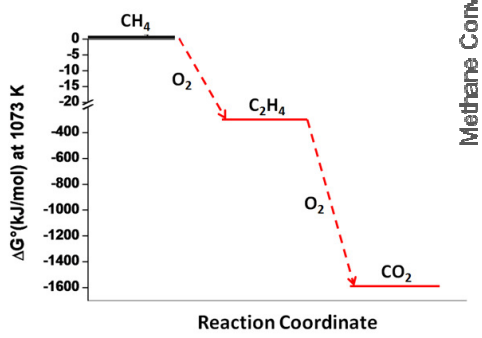
Non-Oxidative Coupling

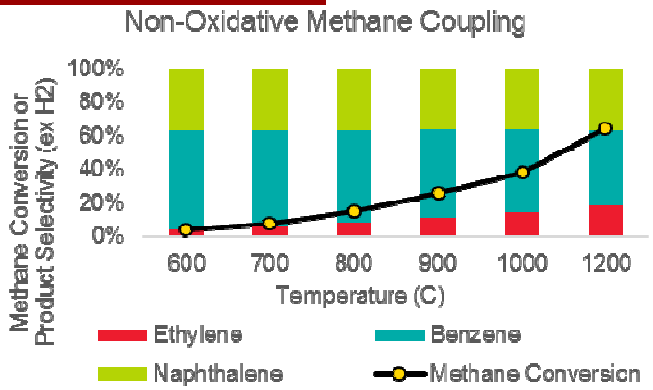
Oxidative Coupling

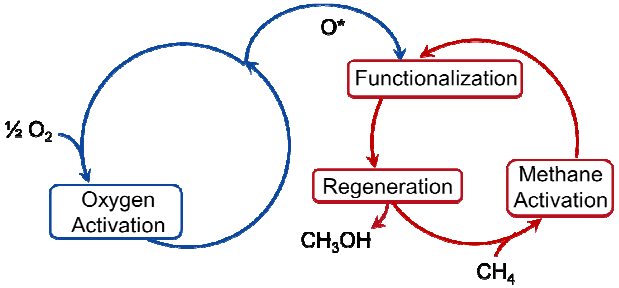
Low Temp Direct Oxidation

Conversion via Syngas







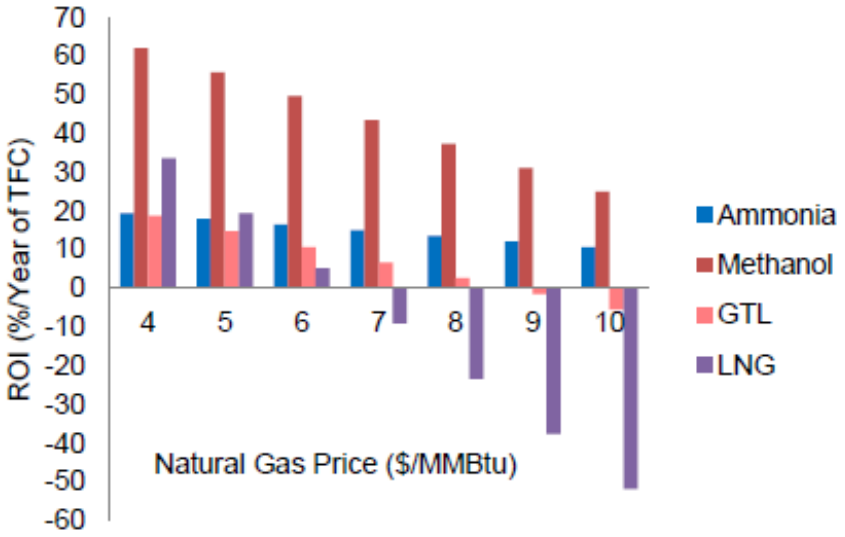


Ron Smith, IHS

Overall Economics for Natural Gas Products

Product	Plant Capacity	Total Capital Investment[a]	Capital Intensity[b]	Return-on-Investment	Annual Return[c]	Payback Period
Ammonia	3,300 MTPD[d]	1.56	427,727	9.2%	142.2	14.2 Yrs
GTL Product	35,000 BPD[e]	2.76	78,857	8.2%	227.0	16.4 Yrs
LNG	19,436 MTPD[d]	2.51	129,142	15.9%[f]	399.1[g]	8.1 Yrs
Methanol	5,000 MTPD[d]	0.94	188,000	51.2%	438.6	3.2 Yrs

a. Billion of US dollars
b. US dollars per daily installed capacity
c. Annual return ($ in millions) is based on the difference betv
product market price
d. MTPD: Metric Tons/Day
e. BPD: Barrels/Day
f. Calculated for UK at a local LNG price of $10.00/MMBtu
g. LNG profitability is increased when it is exported to Japan



methane conversion: **general discussion**

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Bob McCabe, Lakis Mountziaris, NSF

Science
AAAS

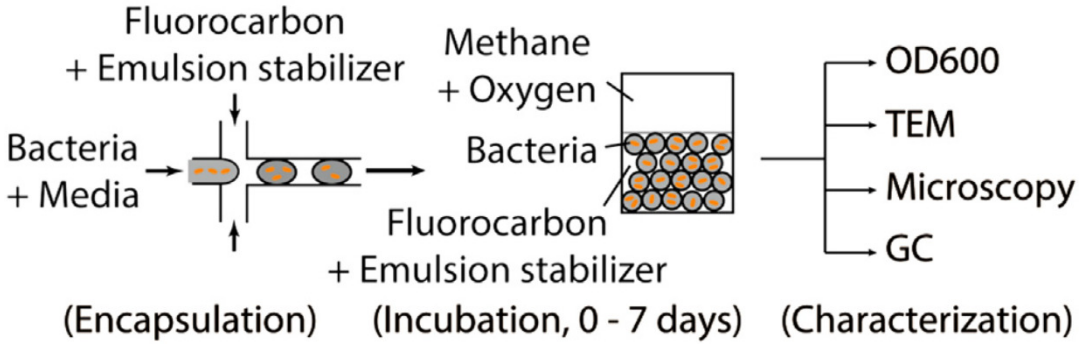
Direct, Nonoxidative Conversion of Methane to Ethylene, Aromatics, and Hydrogen
Xiaoguang Guo *et al.*
Science **344**, 616 (2014);
DOI: 10.1126/science.1253150

Direct, Nonoxidative Conversion of Methane to Ethylene, Aromatics, and Hydrogen

Xiaoguang Guo,[1] Guangzong Fang,[1] Gang Li,[2,3] Hao Ma,[1] Hongjun Fan,[2] Liang Yu,[1] Chao Ma,[4] Xing Wu,[5] Dehui Deng,[1] Mingming Wei,[1] Dali Tan,[1] Rui Si,[6] Shuo Zhang,[6] Jianqi Li,[4] Litao Sun,[5] Zichao Tang,[2] Xiulian Pan,[1] Xinhe Bao[1]*

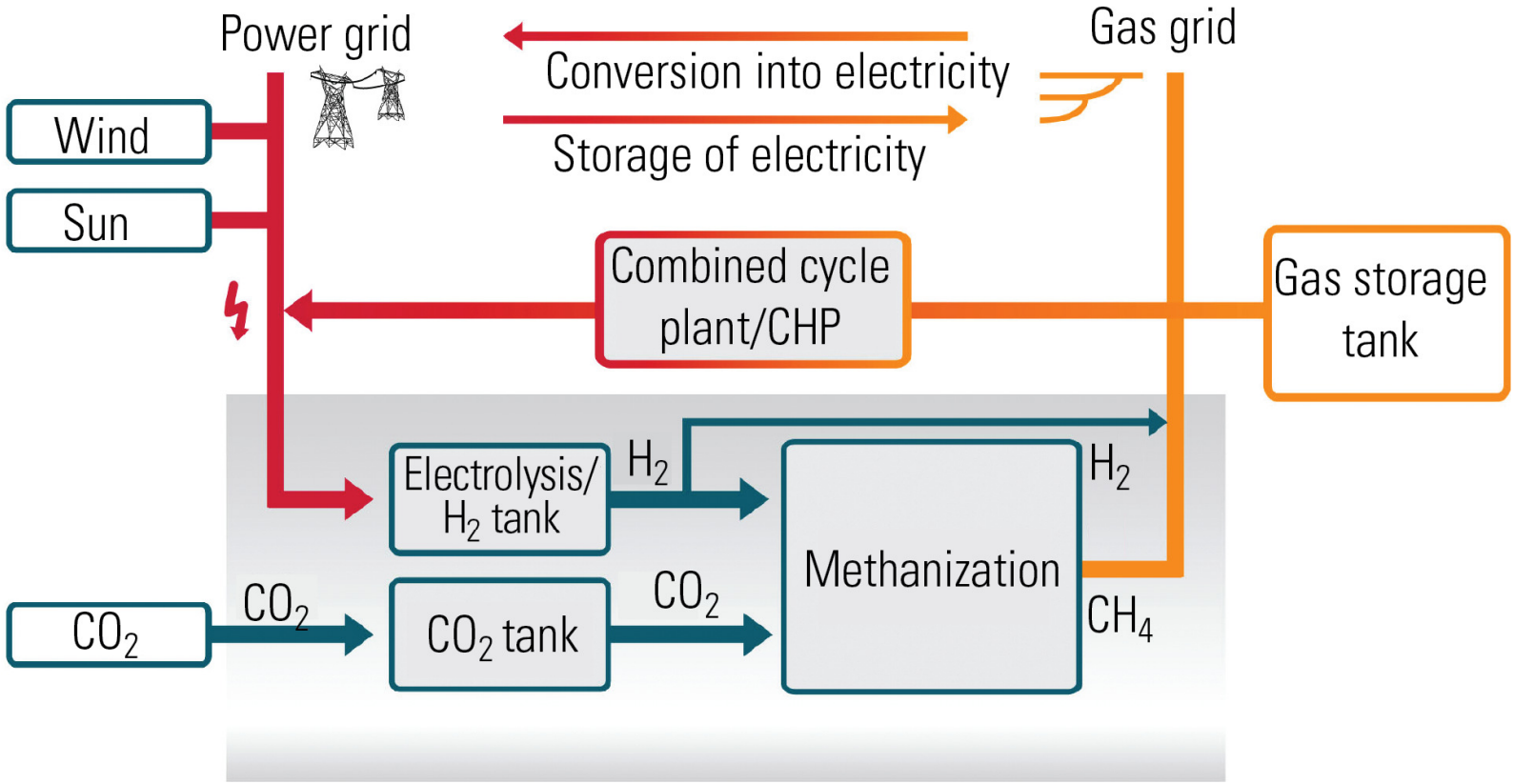
biological methane conversion

Craig Criddle, Alfred Spormann, Stanford



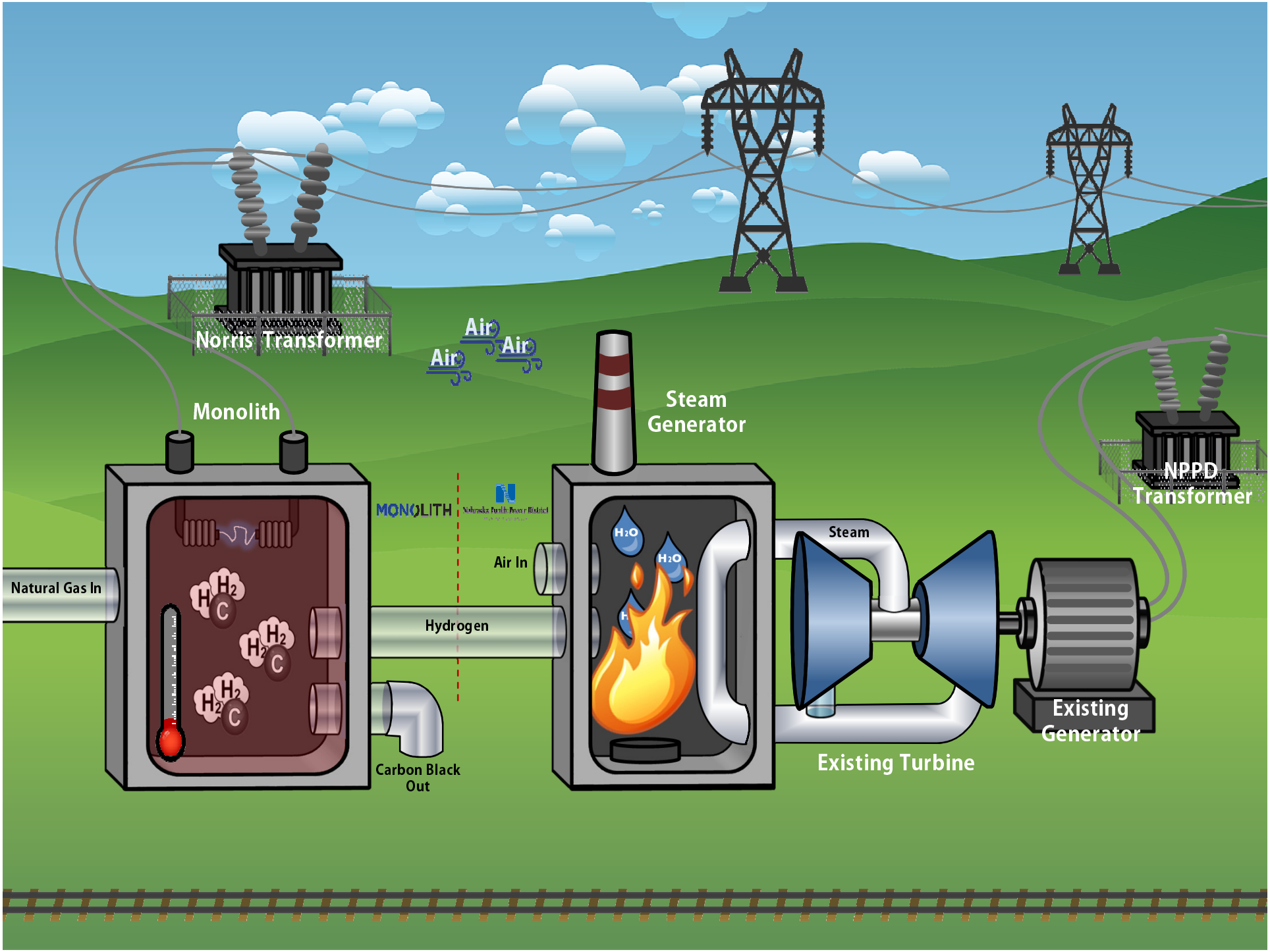
unconventional processes

Ron Kent, SoCalGas



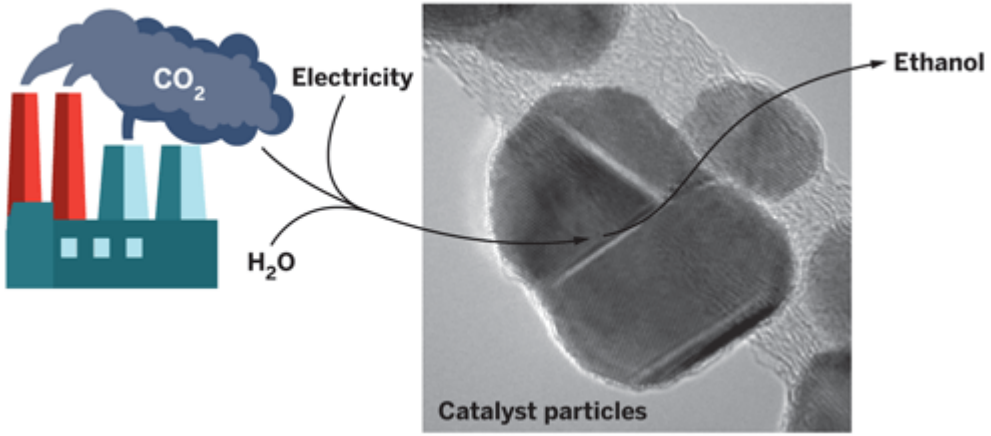
unconventional processes

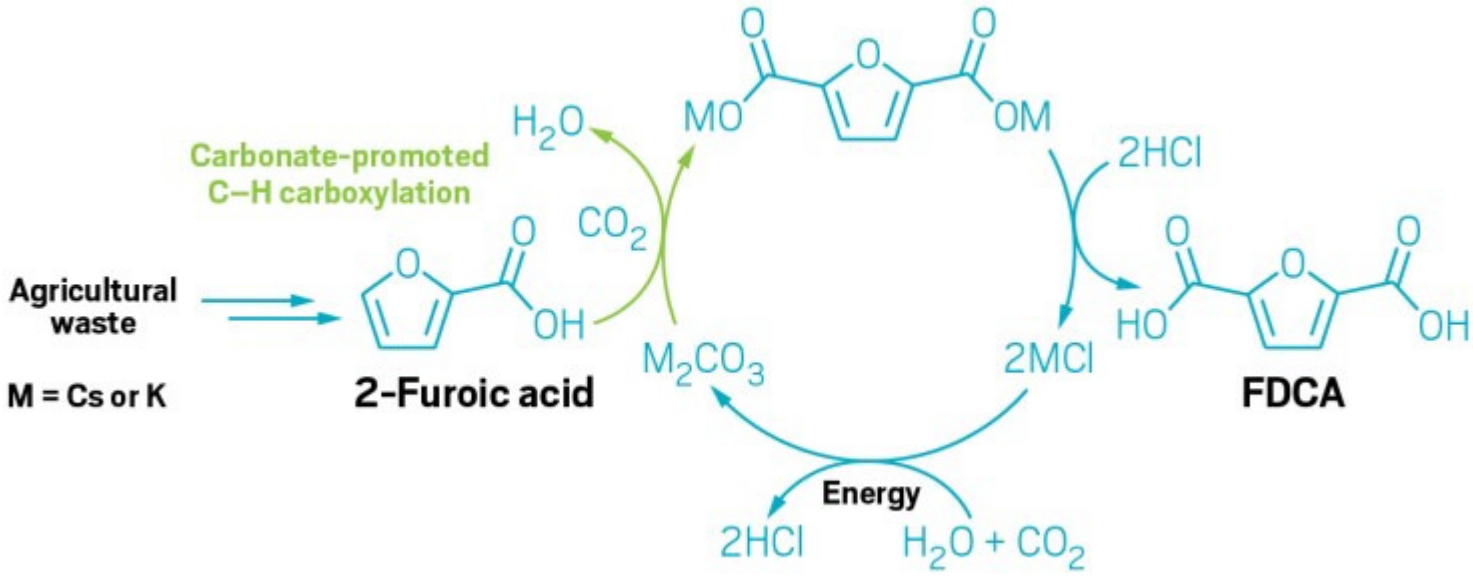
Pete Johnson, Monolith Materials


Norris Transformer
Air
Air
Air
Monolith
Steam Generator
NPPD Transformer
MONOLITH
Air In
Steam
Natural Gas In
Hydrogen
Carbon Black Out
Existing Turbine
Existing Generator

unconventional processes

Matt Kanan,
Stanford University






Shell
ExxonMobil
Each Approach to Methane Conversion Has Its Own Key Challenge To Be Addressed
Non-Oxidative Coupling
Oxidative Coupling
Low Temp Direct Oxidation
Conversion via Syngas
ExxonMobil
IHS
Technology options for monetization of natural gas - USGC evaluation results (2014)
NSF
Division of Chemical, Bioengineering, Environmental, & Transport Systems
Energy and GHG reduction
Energy Consumption 2010 [PJ]
Production 2010 [MM t]
Ammonia
Ethylene
Propylene
Methanol
BTX
National Science Foundation
Stanford
Thank you
Stanford
"From methane to liquid fuels and beyond: opportunities and challenges for a natural gas-powered future"
Microbial Life around Methane
- Microbial Metabolism of Methane -
1) Microbial Processes using Methane
- An Alternative Use
2) Microbial Processes producing Methane:
Conversion of Electricity plus CO_2 to CH_4 via Microbial Electrosynthesis ('Green Methane')
SoCal Gas
SoCalGas P2G RD&D
NREL
UCI
Monolith Materials
Process Comparison
MONOLITH NATURAL GAS ARC PROCESS
Stanford
$CO_2^{\bullet-}$-promoted C–H carboxylation