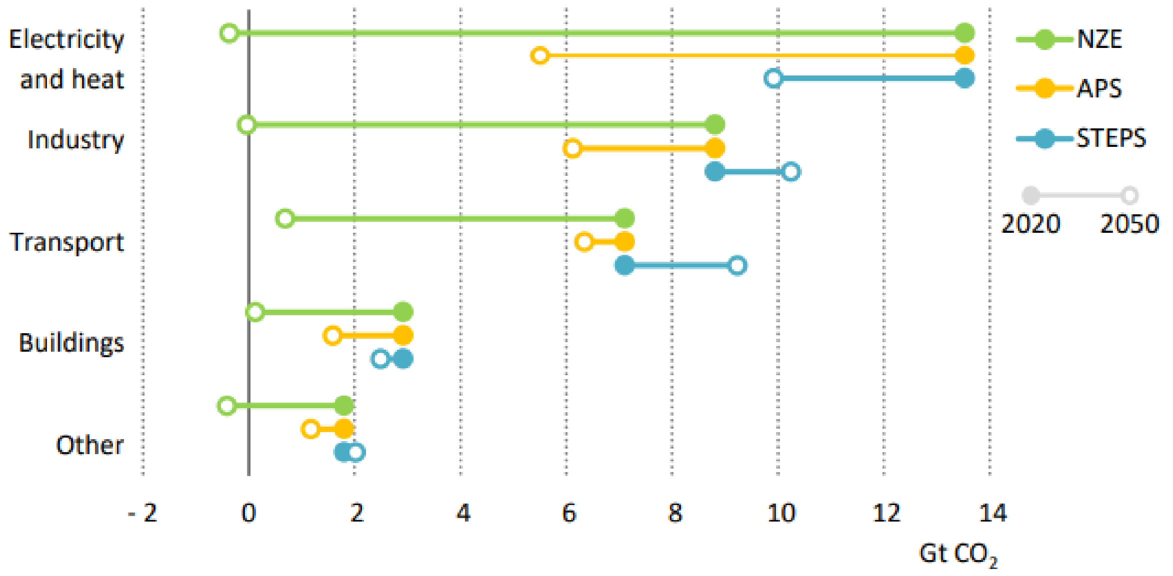
Innovation in Chemical Manufacturing: Low-Temperature Solutions for Energy Efficiency and Emissions Reduction

Kamal Hadidi
Massachusetts, USA
Kamal.hadidi@gmail.com

The need for a sustainable chemical industry: Current energy consumption and GHG emissions

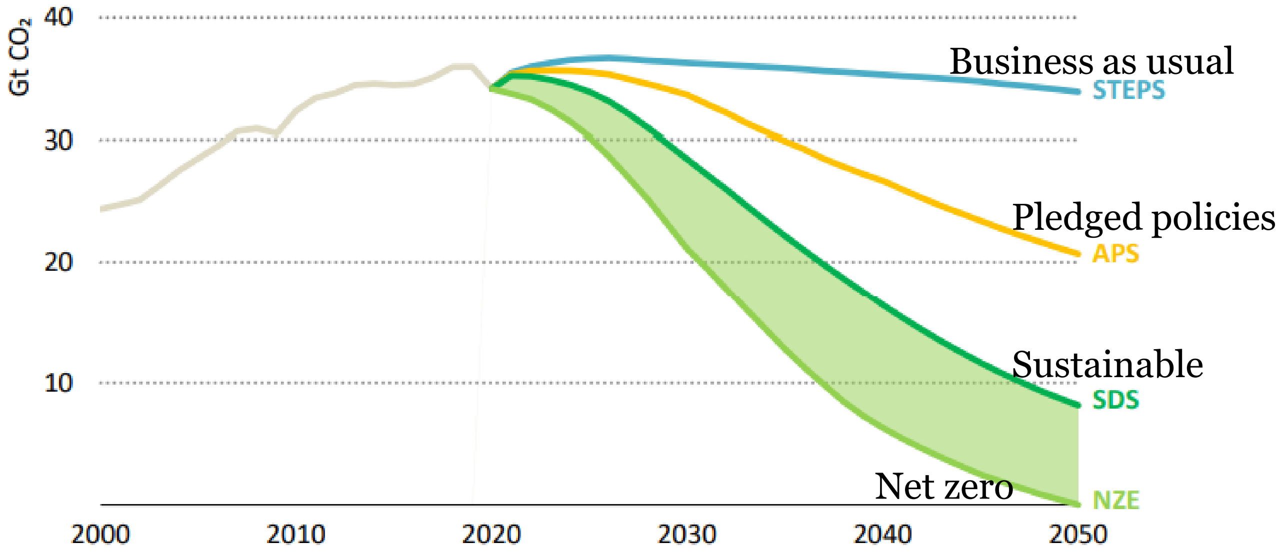
Figure 1.1 ▹ CO₂ emissions by sector and scenario



IEA. All rights reserved.

Clean electricity can do a lot of the heavy lifting, but it is harder to bend the emissions curve in industry and transport

Figure 1.4 ▹ CO₂ emissions in the *WEO-2021* scenarios over time



IEA. All rights reserved.

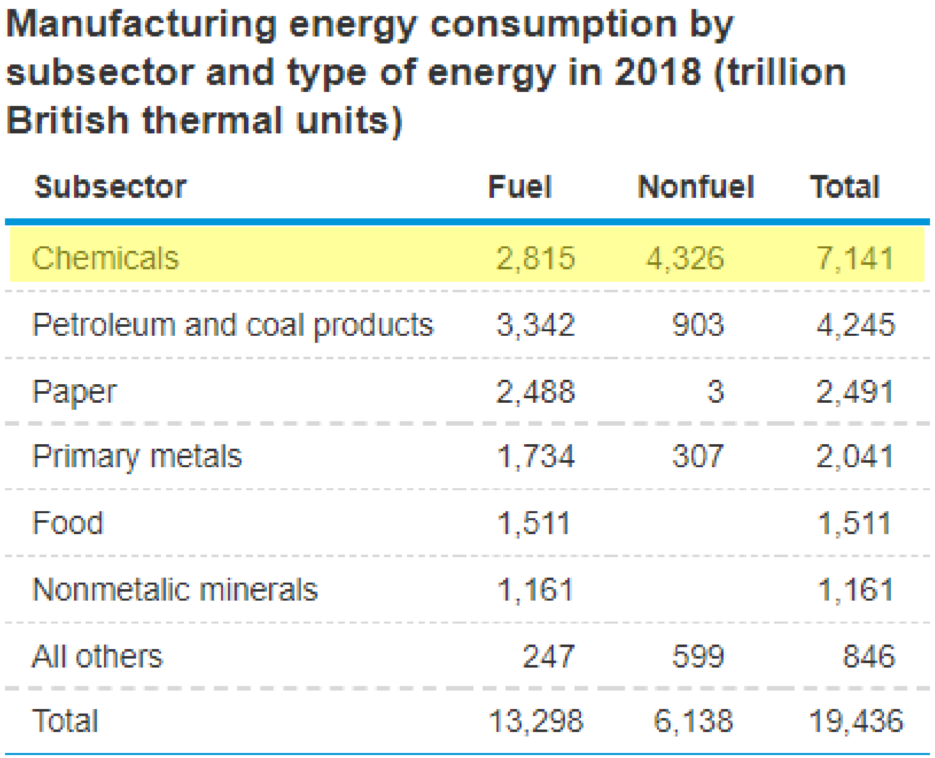
The APS pushes emissions down, but not until after 2030; the SDS goes further and faster to be aligned with the Paris Agreement; the NZE delivers net zero emissions by 2050

Note: APS = Announced Pledges Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario. STEPS: Stated Policies Scenario (today's policies)

"There is no guarantee that the emergence of this new energy economy will be smooth, and it is not coming forward quickly enough to avoid severe impacts from a changing climate."

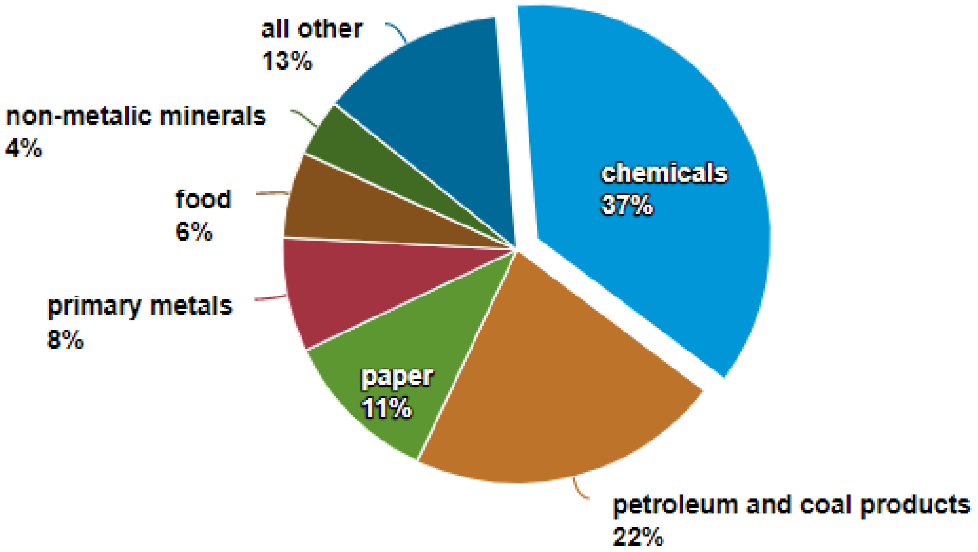
World Enery Outlook. IEA. Oct. 2021

Chemical industry has the largest energy consumption of U.S. manufacturing sector



Manufacturing energy consumption by subsector and type of energy in 2018 (trillion British thermal units)

Subsector	Fuel	Nonfuel	Total
Chemicals	2,815	4,326	7,141
Petroleum and coal products	3,342	903	4,245
Paper	2,488	3	2,491
Primary metals	1,734	307	2,041
Food	1,511		1,511
Nonmetalic minerals	1,161		1,161
All others	247	599	846
Total	13,298	6,138	19,436



U.S. Manufacturing consumption by major types of manufacturers, 2018. Total=19.44 quadrillion BTU

If we were to cut energy consumption in the chemical industry by 50%

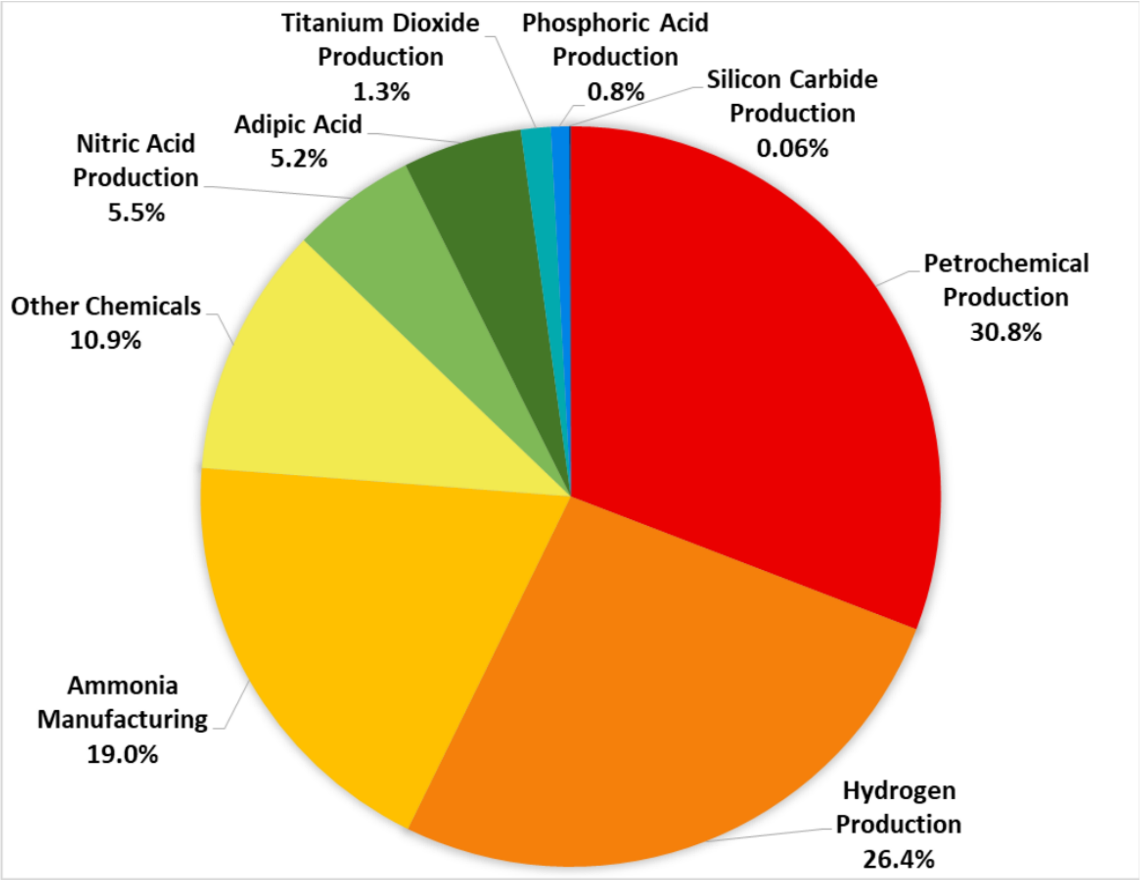
- We'll save the equivalent of 31 billion gallon of gasoline/year
- Avoid emission of 262 MT/year of CO_2
- Equivalent to taking 60 million cars off the road!

- ! Assuming 22 miles/gallon and 11,500 miles/year

Source: eia website

Hydrogen and ammonia production combined have the largest GHG emissions of the chemical industry

Nitrogen fixation products manufacturing emit as much GHG as hydrogen production



Greenhouse Gas Reporting Program Industrial Profile: Chemicals Sector (Non-Fluorinated). EPA September 2019

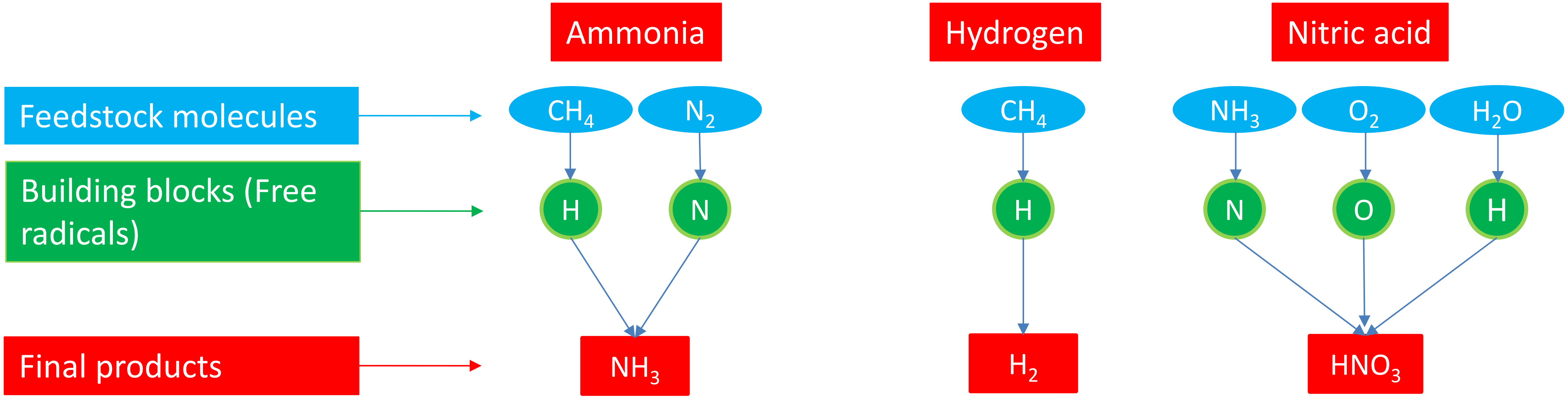
Problem: Hydrogen and other chemicals production through thermo-catalysis

- Mostly thermo catalysis:
  - Methane Steam Reforming (Hydrogen from methane)
  - Claus (Sulfur from hydrogen sulfide)
  - Haber-Bosch (ammonia from nitrogen and methane)
  - Ostwald (nitric acid from ammonia and air)
  - Many others
- Limitations:
  - Energy intensive
  - Very large scale
  - Very large GHG emissions

Thermo-catalysis uses heat to reach the dissociation energy of molecules. Most of the energy consumed is wasted in heat losses

How are these chemicals made?

- Chemical products are made from building blocks (free radicals) that derive from other molecules.



Feedstock molecules

Building blocks (Free radicals)

Final products

Ammonia

CH_4 → H

N_2 → N

H, N → NH_3

Hydrogen

CH_4 → H → H_2

Nitric acid

NH_3 → N

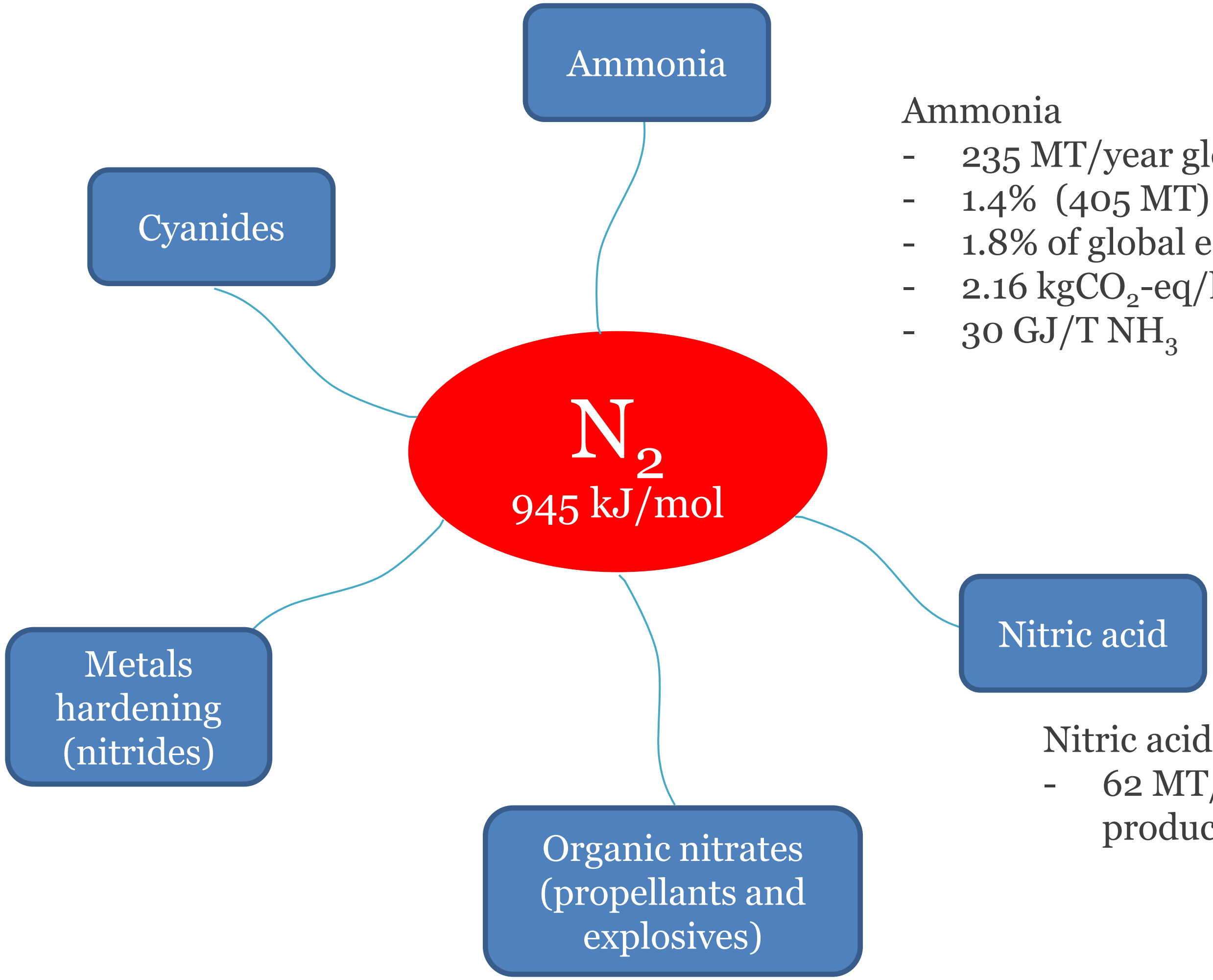
O_2 → O

H_2O → H

N, O, H → HNO_3

There is a need for producing the building blocks of chemicals at lower energy consumption and lower GHG emissions

Nitrogen



Ammonia

- 235 MT/year global production(2019)
- 1.4% (405 MT) of global CO_2 emissions
- 1.8% of global energy consumption
- 2.16 $kgCO_2$-eq/kg NH_3
- 30 GJ/T NH_3

Nitric acid

- 62 MT/year global production(2019)

That is the min energy needed when perfoming thermal dissociation.

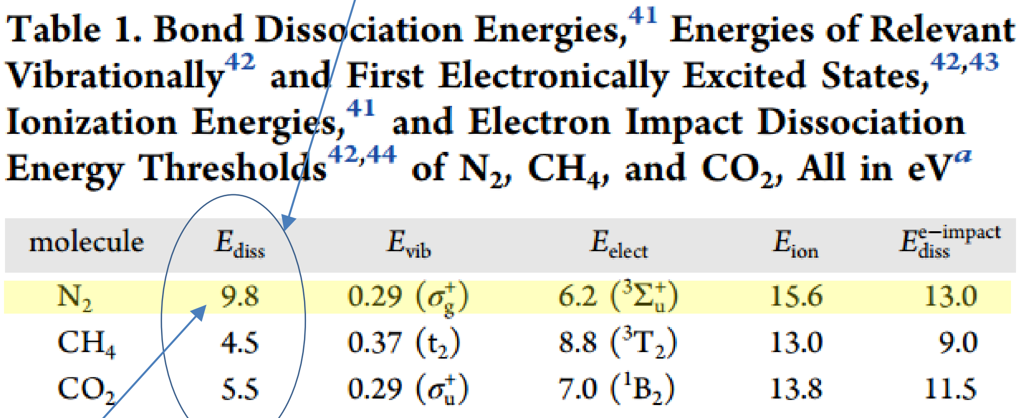


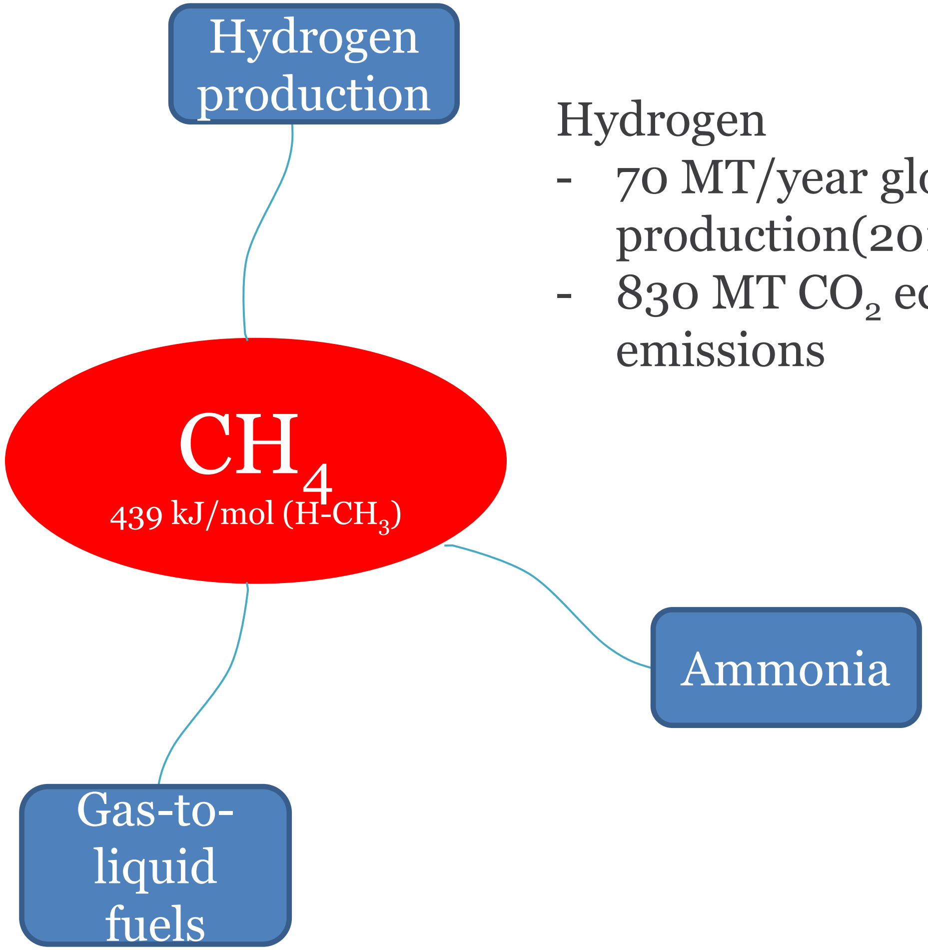
Table 1. Bond Dissociation Energies,[41] Energies of Relevant Vibrationally[42] and First Electronically Excited States,[42,43] Ionization Energies,[41] and Electron Impact Dissociation Energy Thresholds[42,44] of N_2, CH_4, and CO_2, All in eV[a]

molecule	E_{diss}	E_{vib}	E_{elect}	E_{ion}	$E_{diss}^{e-impact}$
N_2	9.8	0.29 (σ_g^+)	6.2 ($^3\Sigma_u^+$)	15.6	13.0
CH_4	4.5	0.37 (t_2)	8.8 ($^3T_2$)	13.0	9.0
CO_2	5.5	0.29 (σ_u^+)	7.0 ($^1B_2$)	13.8	11.5

Bond dissociation energy is one of the highest.

Prateek Mehta. ACS Energy Lett. 2019, 4, 1115−1133

Methane


Hydrogen production

CH_4

439 kJ/mol (H-CH_3)

Ammonia

Gas-to-liquid fuels

Hydrogen
- 70 MT/year global production(2018)
- 830 MT CO_2 equ. emissions

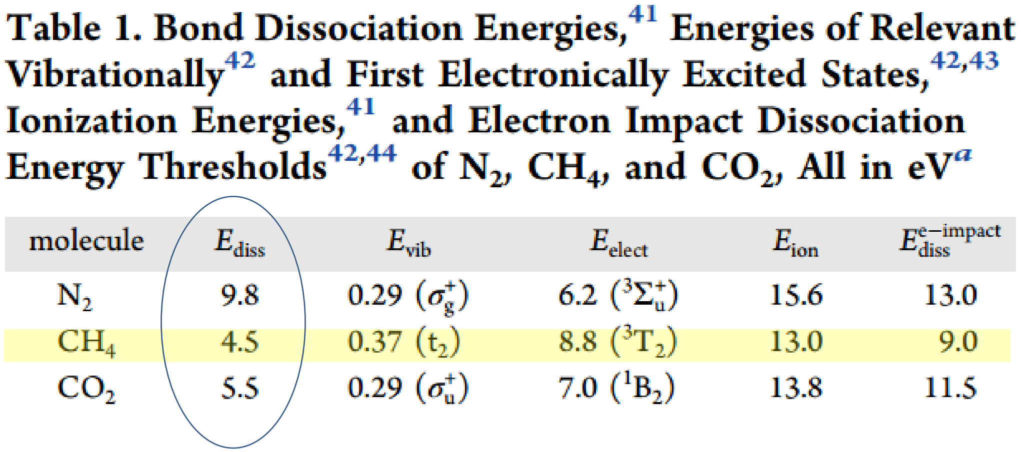


Table 1. Bond Dissociation Energies,[41] Energies of Relevant Vibrationally[42] and First Electronically Excited States,[42,43] Ionization Energies,[41] and Electron Impact Dissociation Energy Thresholds[42,44] of N_2, CH_4, and CO_2, All in eV[a]

molecule	E_{diss}	E_{vib}	E_{elect}	E_{ion}	$E_{diss}^{e-impact}$
N_2	9.8	0.29 (σ_g^+)	6.2 ($^3\Sigma_u^+$)	15.6	13.0
CH_4	4.5	0.37 (t_2)	8.8 ($^3T_2$)	13.0	9.0
CO_2	5.5	0.29 (σ_u^+)	7.0 ($^1B_2$)	13.8	11.5

Prateek Mehta. ACS Energy Lett. 2019, 4, 1115−1133

Methane-based Haber-Bosch (H-B) process is the most efficient one today for Ammonia production

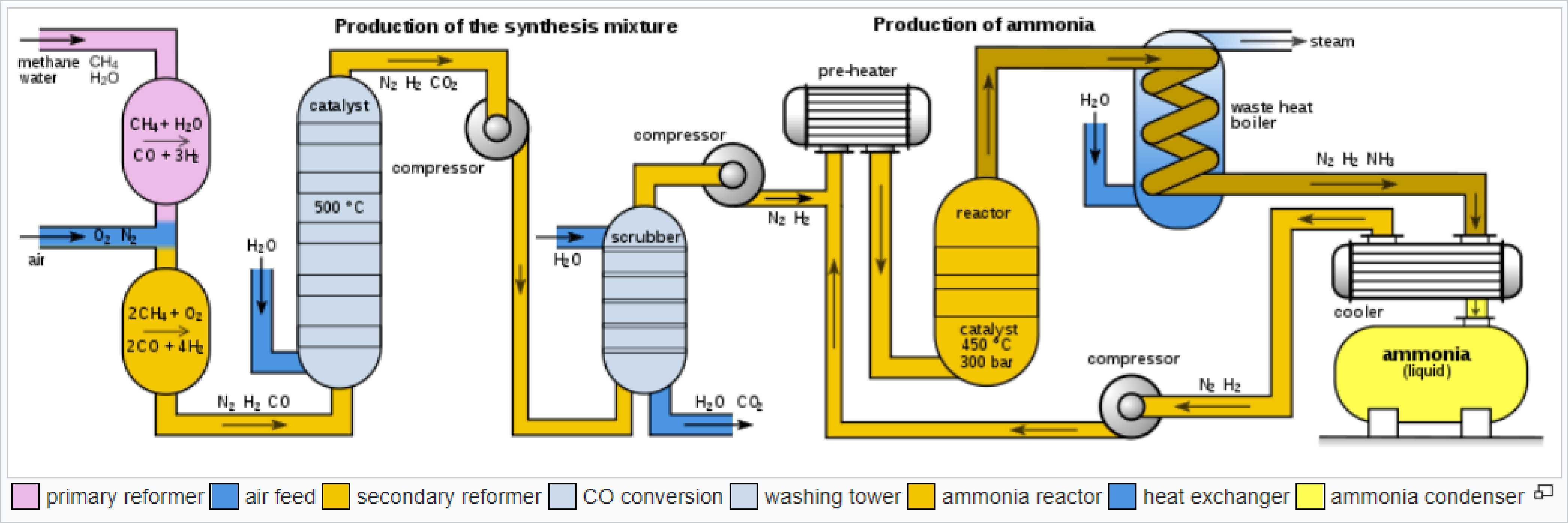
$$N_2 + 3H_2 \rightarrow 2NH_3 \; \Delta H=-92.8 \text{ kJ/mol}$$

- Catalytic reaction at 150–350 atm., and 450-600 °C
- Equilibrium favors the formation of HN_3 at low temp., but high temp is required to achieve a higher rate of NH_3 formation
- Breaking the N_2 triple bond is rate-limiting
- Iron containing iron oxide, MgO on Al_2O_3 and ruthenium on carbon have been employed as catalysts

CH_4/HB energy consump. MJ/mol	Electro/HB energy consump. MJ/mol	NH_3 energy content MJ/mol	Energy wasted in CH_4/HB MJ/mol
0.48 – 0.6	1.5	0.32	Up to 0.28

Methane-based H-B is 3x less energy intensive than electro-based H-B process

Schematic diagram for a natural gas-based H-B process



SMR $CH_{4(g)} + H_2O_{(g)} \rightarrow CO_{(g)} + 3H_{2(g)}$ DH = +206 kJ/mol
$2CH_{4(g)} + O_{2(g)} \rightarrow 2CO_{(g)} + 4H_{2(g)}$ DH = -71 kJ/mol
$CO_{(g)} + H_2O_{(g)} \rightarrow CO_{2(g)} + H_{2(g)}$ DH = -41 kJ/mol

N_2 adsorbed → 2N adsorbed
$H_{2(ads)} \rightarrow 2H_{(ads)}$
$N_{(ads)} + 3H_{(ads)} \rightarrow NH_{3(ads)}$
$NH_{3\,(ads)}) \rightarrow NH_{3(g)}$

By Francis E Williams. - This file was derived from:, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=12204693

Ostwald process is the most efficient one today for Nitric Acid production

1- Ammonia oxidation to NO:
600C–800C and 4–10 atm, Rh/Pt
$4NH_3 + 5O_2 \longrightarrow 4NO + 6H_2O$ $DH^o_r = -905$ kJ mol^{-1}

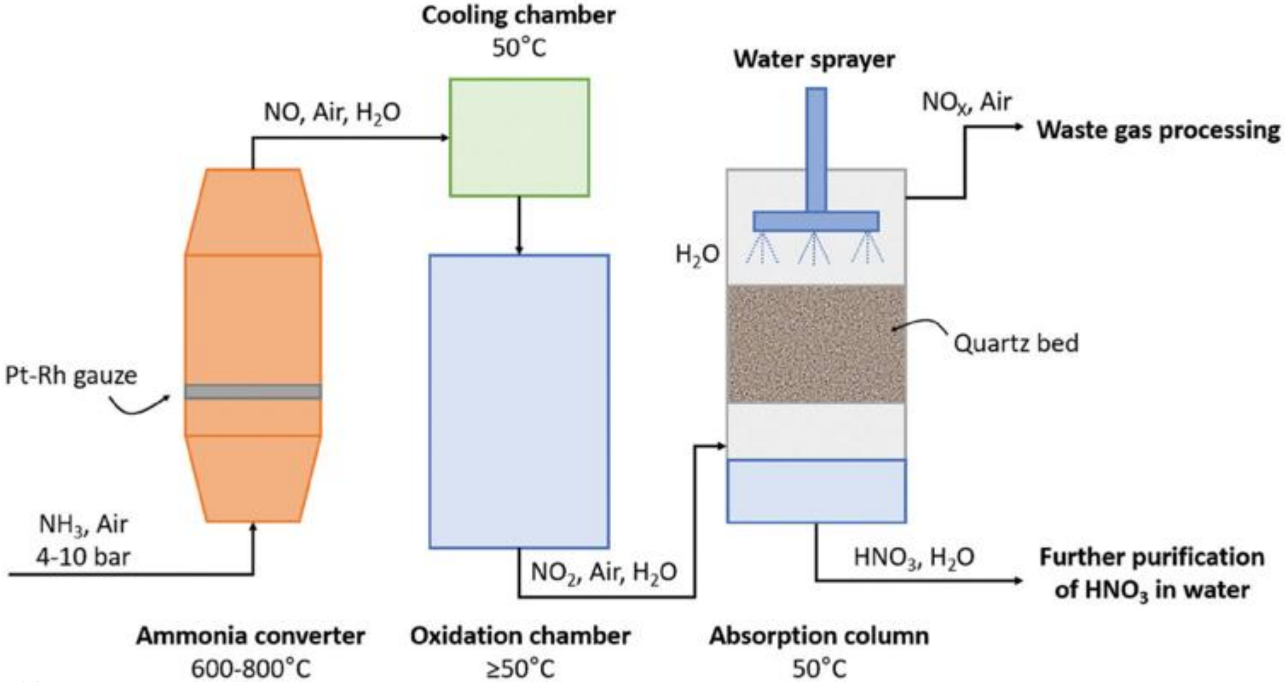
2- NO oxidation to NO_2:
50C
$2NO + O_2 \longrightarrow 2NO_2$ $DH^o_r = -114$ kJ mol^{-1}

3- NO_2 reaction with water to produce HNO_3
$3NO_2 + H_2O \longrightarrow 2HNO_3 + NO$ $DH^o_r = -117$ kJ mol^{-1}

75–80% of the HNO_3 produced is used for ammonium nitrate production

$NH_3 + HNO_3 \longrightarrow NH_4NO_3$

Ostwald process gets nitrogen radicals from ammonia instead of nitrogen molecule due to lower dissociation energy.



Kevin Hendrik Reindert Rouwenhorst et al. Energy & Environmental Science · March 2021

Thermal plasma has also been used - Birkeland–Eyde (B-E) process, but not efficient

$N_2 + O_2 \leftrightarrow 2NO; \Delta H = 90\ \text{kJ/mol}$

Zeldovich mechanism:
$O + N_2 \rightarrow NO + N$
$N + O_2 \rightarrow NO + O$

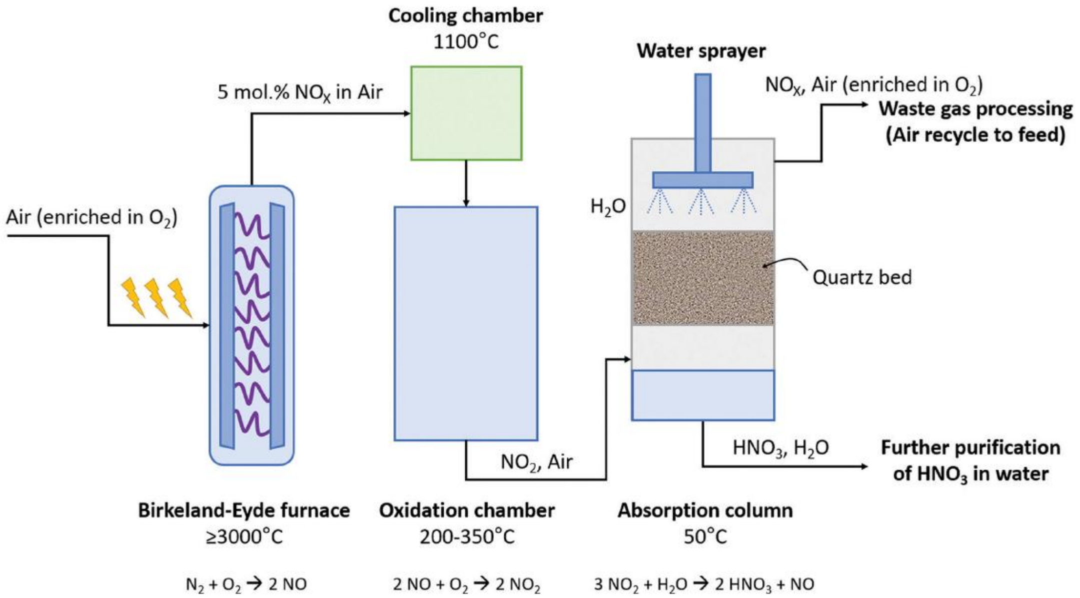


Fig. 2 Process scheme for the Birkeland–Eyde industrial nitrogen-fixation process. Inspired by Patil *et al.*[9]

B-E energy consumption MJ/mol	Min theoretical energy consumption MJ/mol	Yield %
2.4 – 3.1	0.72	1 - 2

B-E process is 5 to 8 x more energy intensive than H-B process

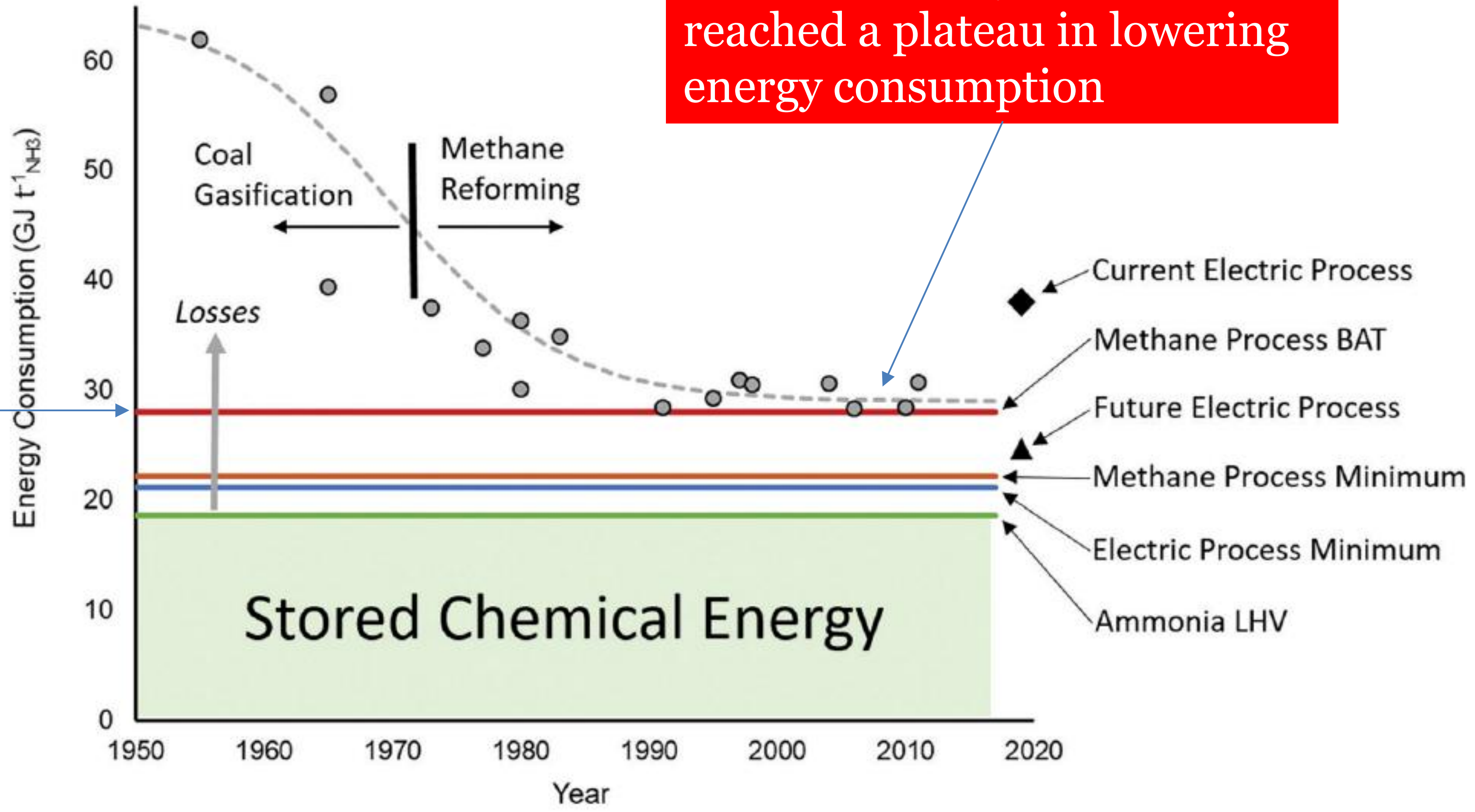
Kevin Hendrik Reindert Rouwenhorst et al. Energy & Environmental Science · March 2021

What are the limits of current practices?

For ammonia:

For the last 20 years, we have reached a plateau in lowering energy consumption

This is where we are today with H-B process



Collin Smith et al. Energy Environ. Sci., 2020, 13, 331--344

New R&D in ammonia production processes concern mainly electrolysis

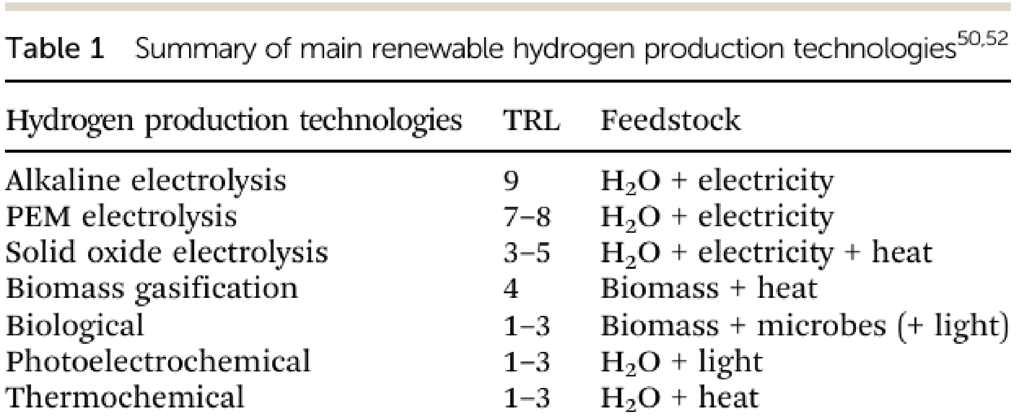
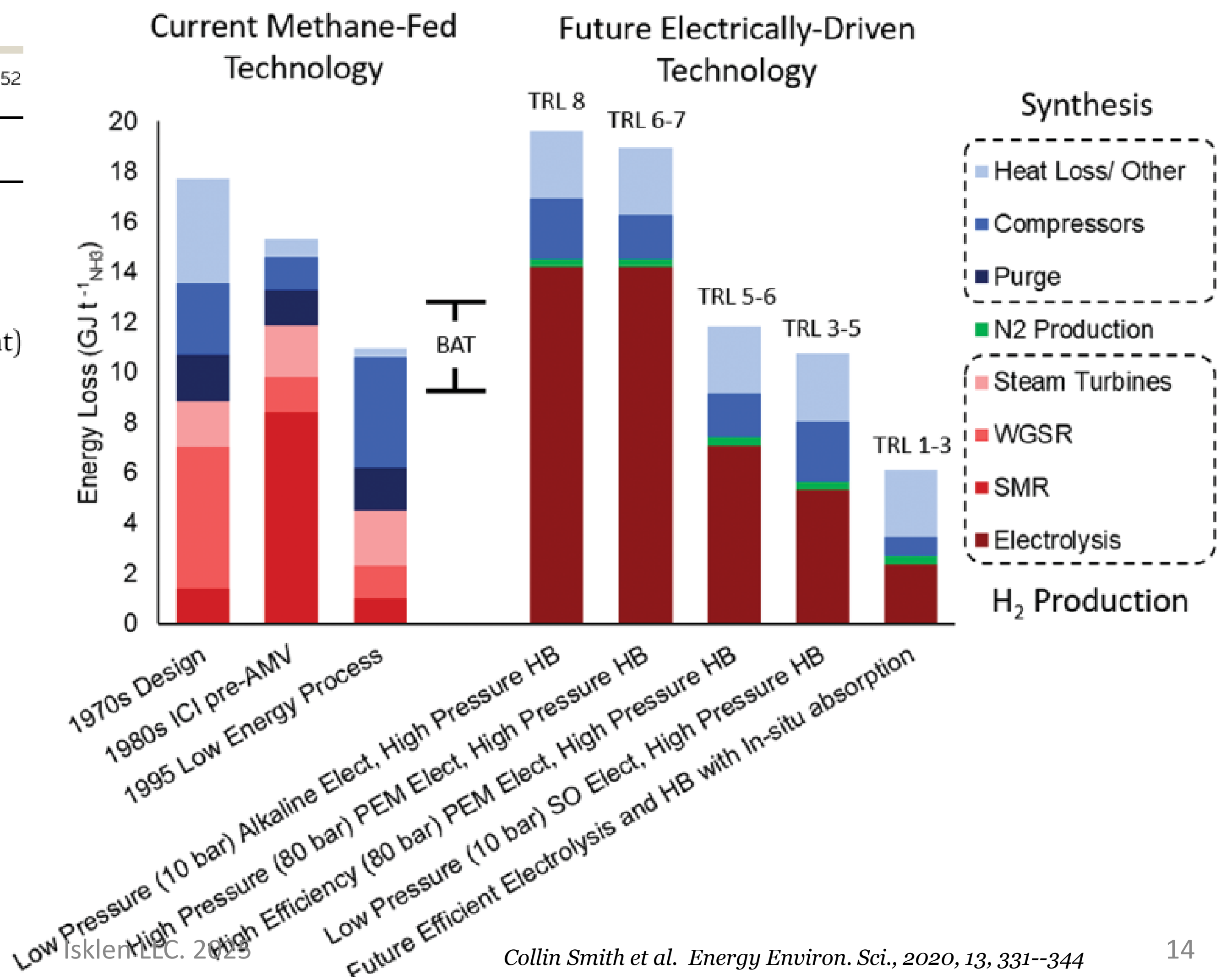


Table 1 Summary of main renewable hydrogen production technologies[50,52]

Hydrogen production technologies	TRL	Feedstock
Alkaline electrolysis	9	H_2O + electricity
PEM electrolysis	7–8	H_2O + electricity
Solid oxide electrolysis	3–5	H_2O + electricity + heat
Biomass gasification	4	Biomass + heat
Biological	1–3	Biomass + microbes (+ light)
Photoelectrochemical	1–3	H_2O + light
Thermochemical	1–3	H_2O + heat



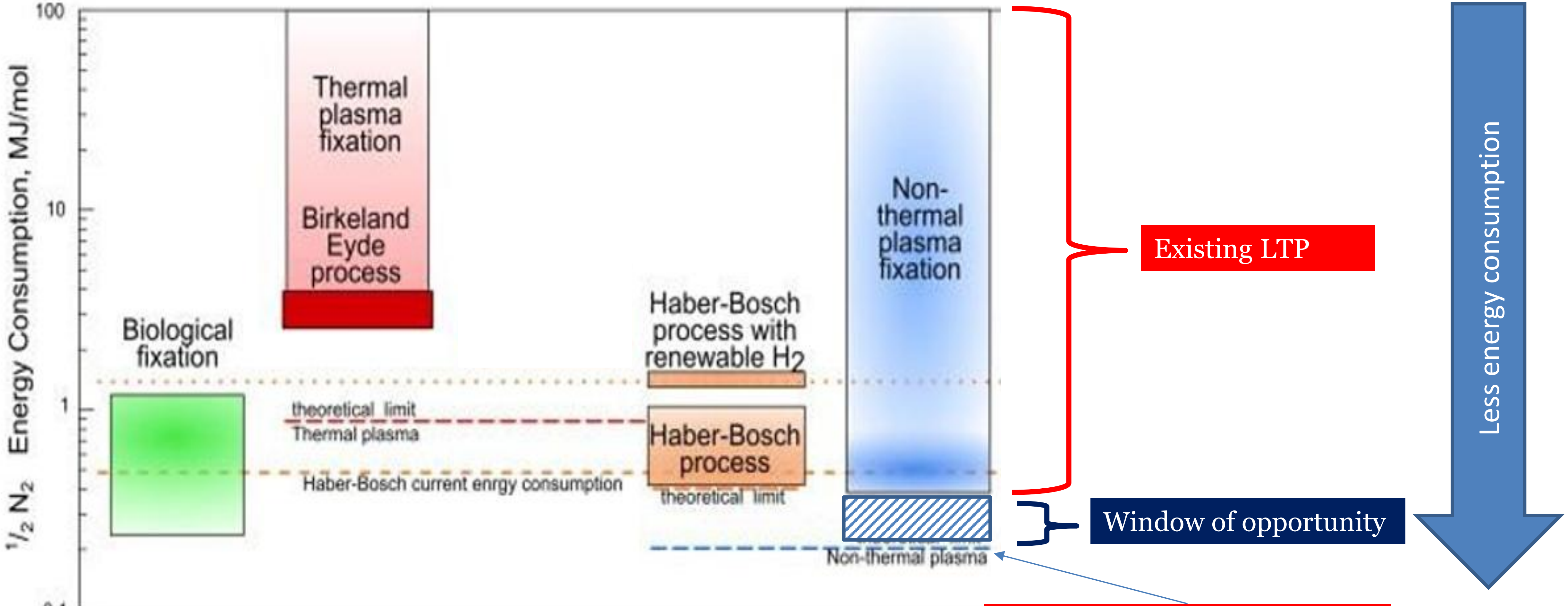
Collin Smith et al. Energy Environ. Sci., 2020, 13, 331--344

Photocatalysis chemistry

- Syzygy Plasmonics is a **light-powered (photocatalytic) chemical reactor** that uses light instead of heat from combustion to drive chemical reactions (from **Rice University)**.
  - Eliminates GHG emissions
  - Low efficiency due to limited efficiency of LEDs (30-40%) and low cross sections for electron-hole creation.

SYZYGY
PLASMONICS

Low-temperature plasmas have the lowest theoretical energy consumption for nitrogen fixation



Existing LTP

Window of opportunity

Less energy consumption

LTP theroretical limit:
>200% more efficient than Haber-Bosch

Energy consumption by different nitrogen fixation processes.

Modified from: Sirui Li et al. Processes 2018, 6, 248; doi:10.3390/pr6120248

Different types of LTP for N_2 fixation

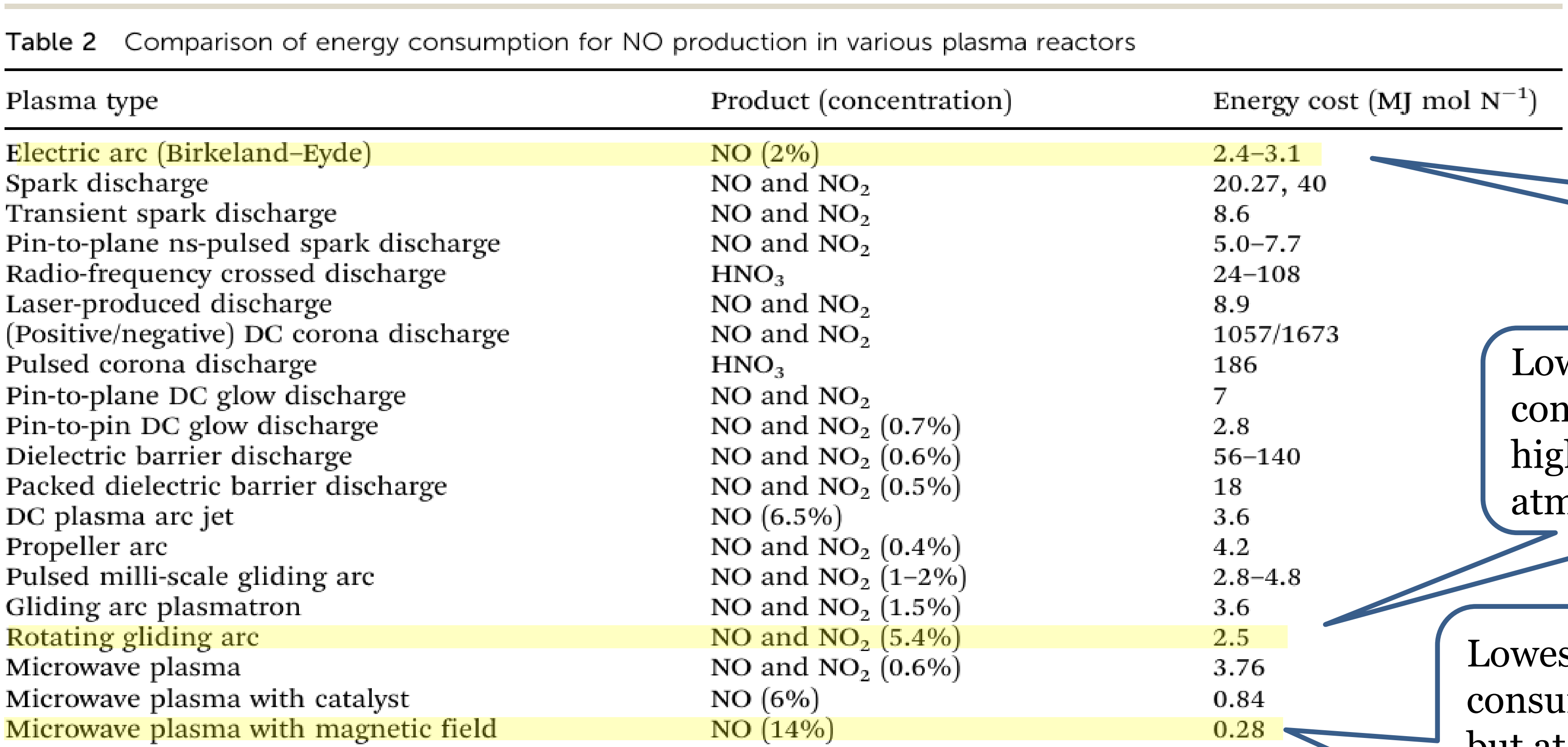


Table 2 Comparison of energy consumption for NO production in various plasma reactors

Plasma type	Product (concentration)	Energy cost (MJ mol N^{-1})
Electric arc (Birkeland–Eyde)	NO (2%)	2.4–3.1
Spark discharge	NO and NO_2	20.27, 40
Transient spark discharge	NO and NO_2	8.6
Pin-to-plane ns-pulsed spark discharge	NO and NO_2	5.0–7.7
Radio-frequency crossed discharge	HNO_3	24–108
Laser-produced discharge	NO and NO_2	8.9
(Positive/negative) DC corona discharge	NO and NO_2	1057/1673
Pulsed corona discharge	HNO_3	186
Pin-to-plane DC glow discharge	NO and NO_2	7
Pin-to-pin DC glow discharge	NO and NO_2 (0.7%)	2.8
Dielectric barrier discharge	NO and NO_2 (0.6%)	56–140
Packed dielectric barrier discharge	NO and NO_2 (0.5%)	18
DC plasma arc jet	NO (6.5%)	3.6
Propeller arc	NO and NO_2 (0.4%)	4.2
Pulsed milli-scale gliding arc	NO and NO_2 (1–2%)	2.8–4.8
Gliding arc plasmatron	NO and NO_2 (1.5%)	3.6
Rotating gliding arc	NO and NO_2 (5.4%)	2.5
Microwave plasma	NO and NO_2 (0.6%)	3.76
Microwave plasma with catalyst	NO (6%)	0.84
Microwave plasma with magnetic field	NO (14%)	0.28

Kevin H. R. Rouwenhorst et al., Energy & Environmental Science · March 2021.

Thermal plasma

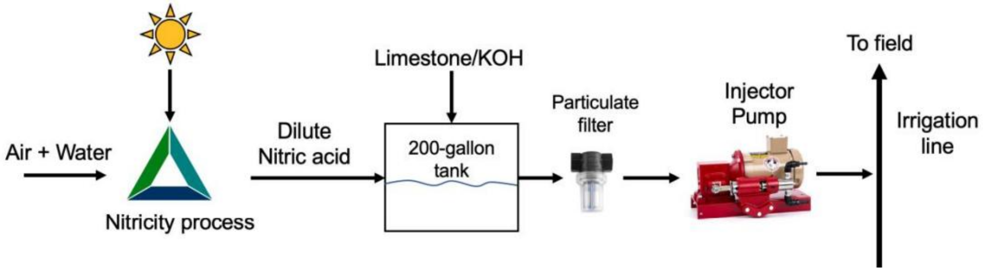
Lowest energy consumption & highest NO_x yield at atmospheric pressure

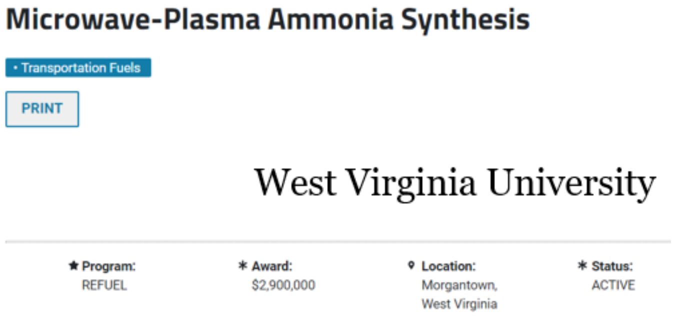
Lowest energy consumption, but <u>at low-pressure</u>

So far, rotating gliding arc has shown the lowest energy consumption and highest yield for N_2 fixation

ARPA-E is funding a small LTP N_2 fixation effort

"Nitricity Inc. is developing an atmospheric **microwave plasma reactor** that uses air, water, and renewable electricity to produce nitrogen fertilizer.





Microwave-Plasma Ammonia Synthesis

West Virginia University

Program:	Award:	Location:	Status:
REFUEL	$2,900,000	Morgantown, West Virginia	ACTIVE

"West Virginia University Research Corporation (WVURC) will develop a process to convert renewable electricity, water, and air into ammonia using plasma excitation **at low temperatures and pressures**.

LTP-assisted catalysis has shown yield enhancement in HN_3 synthesis from N_2/H_2 plasma

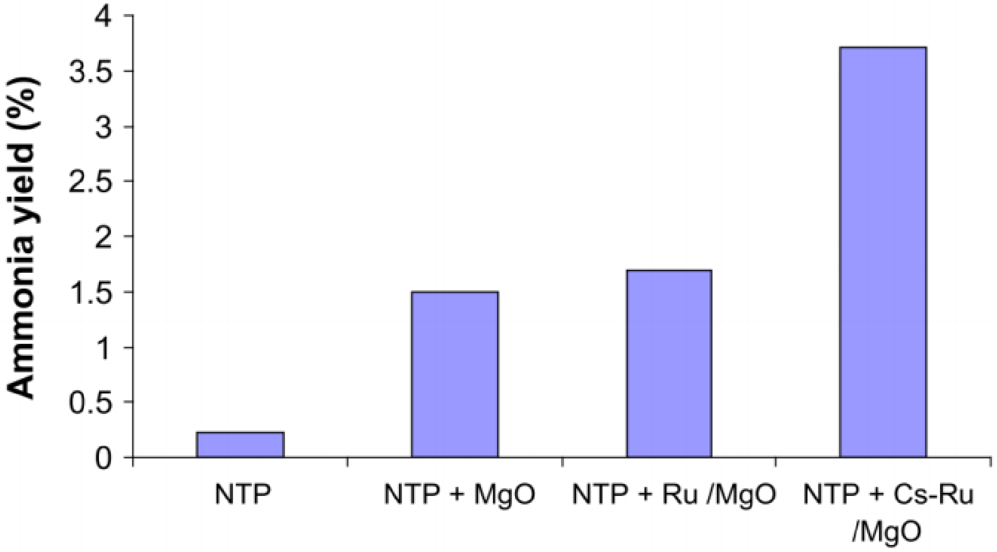
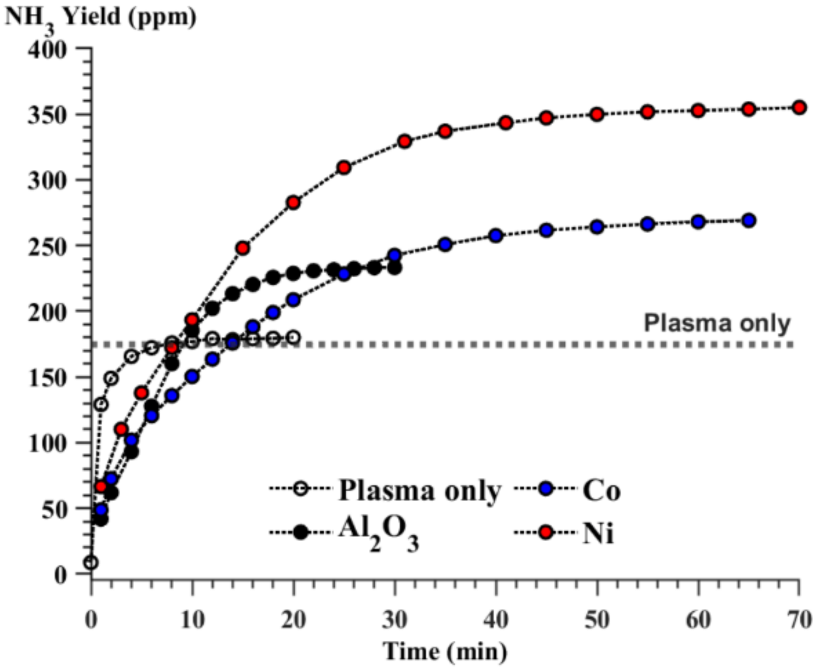


Figure 8. Ammonia synthesis by non-thermal plasma alone, and with different packings ($V_{N_2}:V_{H_2}$ = 3:1, N_2 and H_2 total flow rate 60 mL/min, voltage 5000 V, frequency 8000 Hz). Reprinted by permission from Springer Nature, Plasma Chemistry and Plasma Processing, "Atmospheric Pressure Ammonia Synthesis Using Non-Thermal Plasma Assisted Catalysis", Peng et al. [107], [**COPYRIGHT**] (2018).

LTP enhances ammonia yield by 15x when used with Cs-Ru/MgO catalyst

Peng, P et al. Plasma Chem. Plasma Process. 2016, 36, 1201–1210

Nano-pulsed discharge
10%H_2 in N_2, 190 Torr, 300C

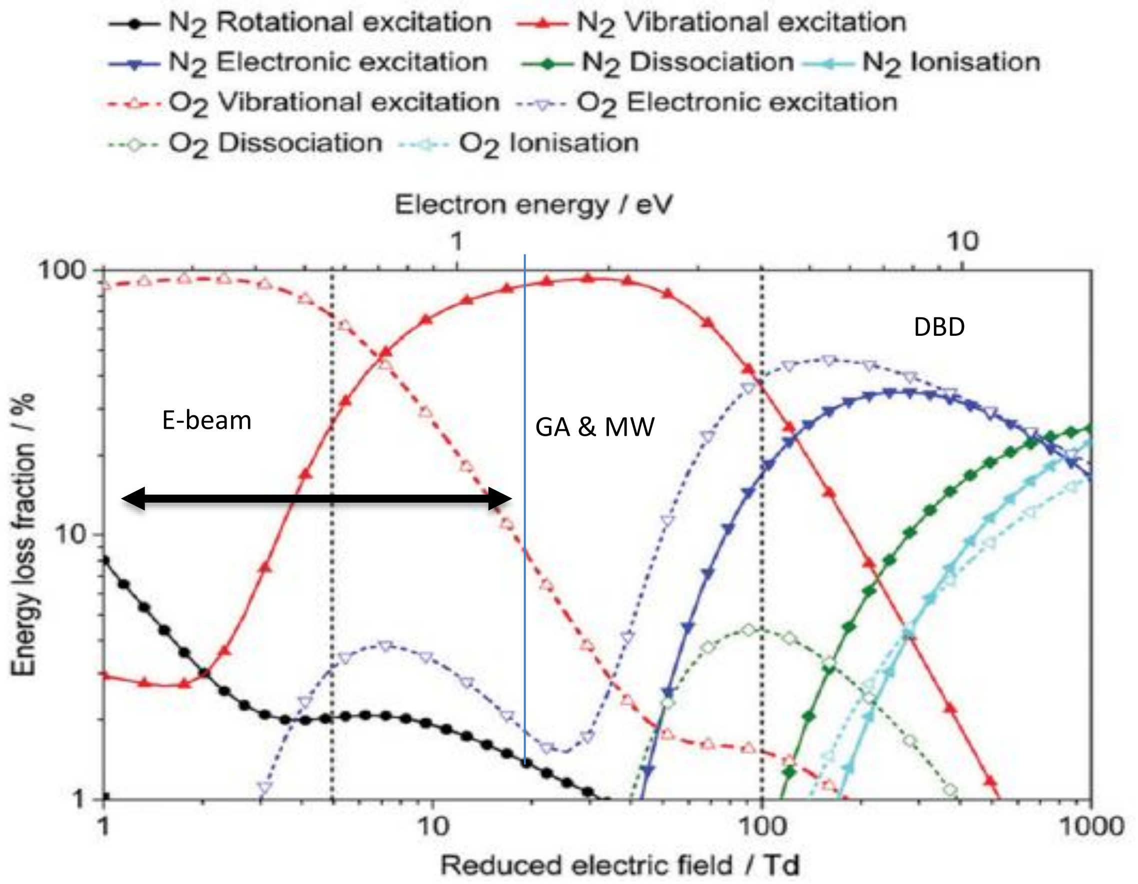


Xin Yang, Caleb Richards, and Igor V. Adamovich. LTP Centers and User Facilties Annual Meeting. Sept. 23-24 2021

Energy dissipating channels in a LTP

- Many energy dissipating channels during a LTP discharge
- What are the channels that lead to dissociation and at what energy expense?

Understanding fundamental physics of LTP is key to improving their efficiency



Fine-tune LTPs to optimize for dissociative vibrational ladder-climbing process

molecule	E_{diss}	E_{vib}	E_{elect}	E_{ion}	$E_{diss}^{e-impact}$
CO_2	5.5	0.29 (σ_u^+)	7.0 ($^1B_2$)	13.8	11.5

Bond energy

V-V collisions
(Ladder climbing)

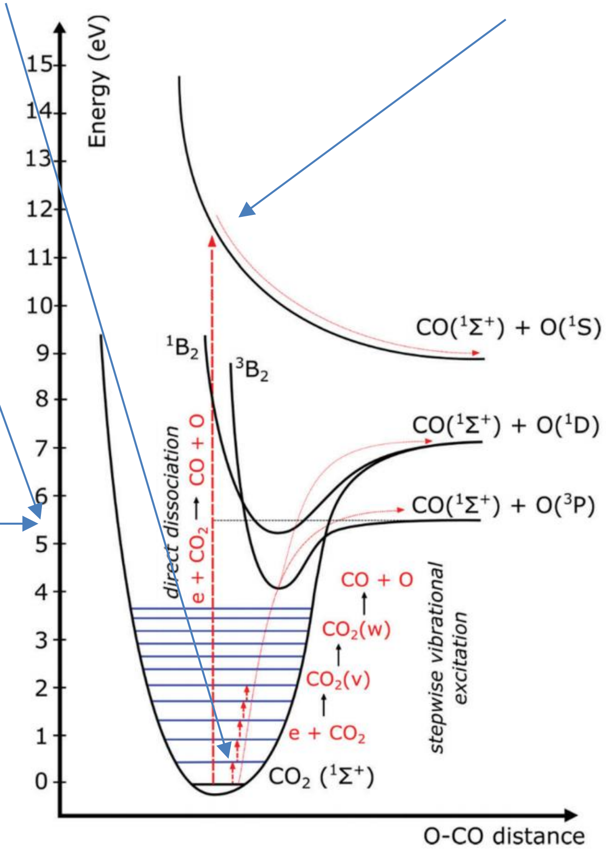


Fig. 12 Schematic of some CO_2 electronic and vibrational levels, illustrating that much more energy is needed for direct electronic excitation–dissociation than for step-wise vibrational excitation, *i.e.* the so-called ladder-climbing process (reproduced from ref. 91 with permission from the Royal Society of Chemistry).

Current LTPs
(Black box)

Proposed LTPs
(Fine-tuning)
Energy where it is needed
and only min amount needed

Tune plasma to maximize energy transfer to vibrational excitation and minimize other losses

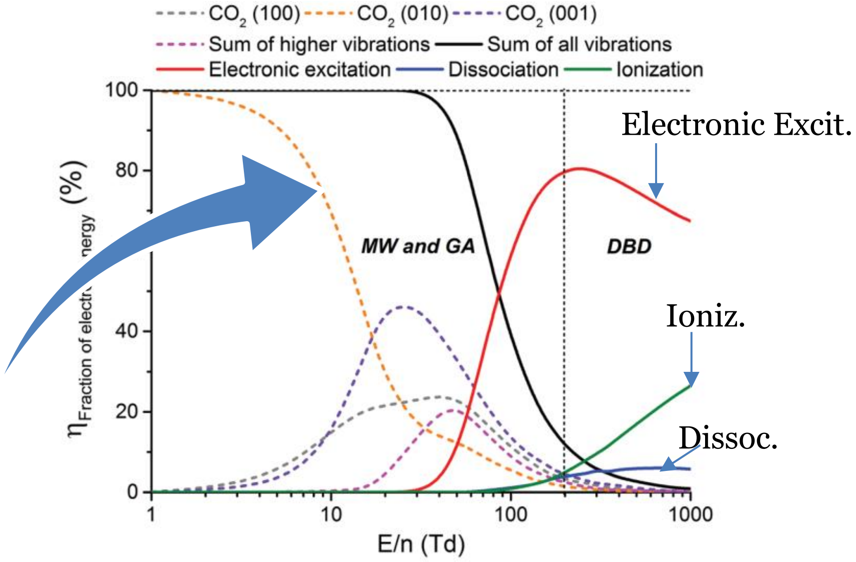


Fig. 11 Fraction of electron energy transferred to different channels of excitation, as well as to the ionization and dissociation of CO_2, as a function of the reduced electric field (*E*/*n*), as calculated from the corresponding cross-sections of the electron-impact reactions. The *E*/*n* regions characteristic for MW and GA plasma and for DBD plasma are indicated.

Enhanced vibrational ladder-climbing dissociation in a LTP

We maximize the vibrationally-enhanced ladder-climbing dissociation (VELC) process by using a nanopulsed e-field.

Min theoretical energy used by existing thermal technologies

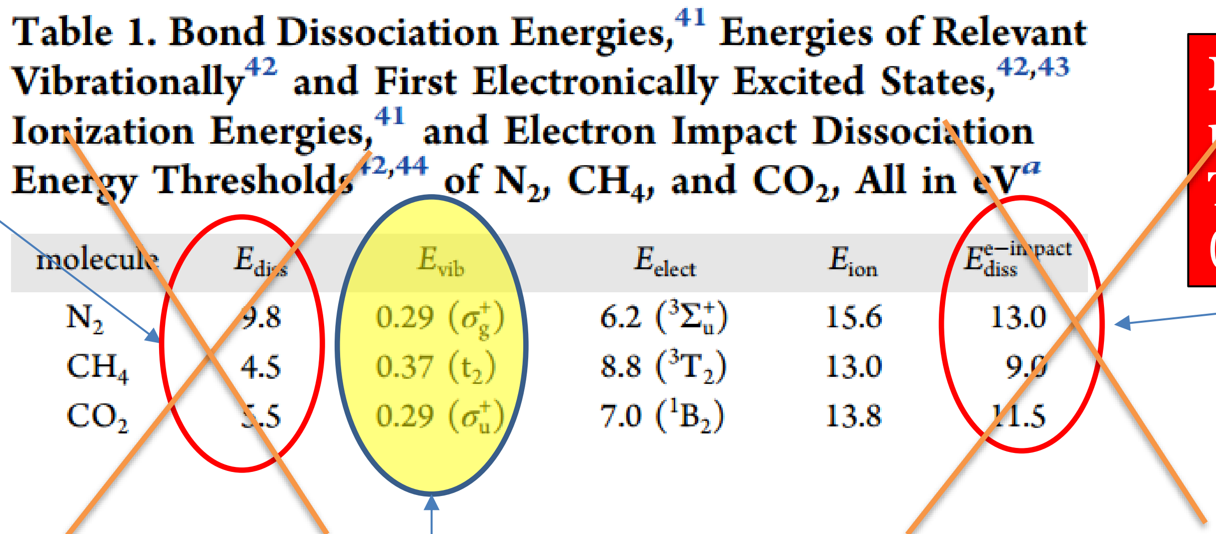


Table 1. Bond Dissociation Energies,[41] Energies of Relevant Vibrationally[42] and First Electronically Excited States,[42,43] Ionization Energies,[41] and Electron Impact Dissociation Energy Thresholds[42,44] of N_2, CH_4, and CO_2, All in eV[a]

molecule	E_{dis}	E_{vib}	E_{elect}	E_{ion}	$E_{diss}^{e-impact}$
N_2	9.8	0.29 (σ_g^+)	6.2 ($^3\Sigma_u^+$)	15.6	13.0
CH_4	4.5	0.37 (t_2)	8.8 ($^3T_2$)	13.0	9.0
CO_2	5.5	0.29 (σ_u^+)	7.0 ($^1B_2$)	13.8	11.5

Min theroretical energy used by existing Non-Thermal Plasmas (NTPs)

Vibrationally-enhanced dissociation: Energy directed only at target molecular bonds to reach min bond energy

Prateek Mehta. ACS Energy Lett. 2019, 4, 1115−1133

Vibrationally-enhanced dissociation has the theoretical potential for min energy consumption

Vibrationally-enhanced Zeldovich mechanism

$$e^- + N_2 \longrightarrow e^- + N_2(\nu) \qquad (1)$$

$$O + N_2(\nu) \longrightarrow NO + N \qquad (2)$$

$$N + O_2 \longrightarrow NO + O \qquad (3)$$

Energy consumption KJ/mol NO Eq (2&3)			**NO energy of formation**	**Energy losses for vibrational dissociation**	**Energy losses for vibrational + electronic excitation dissociation**	**Energy losses for thermal dissociation**
Only vibrational	Vibrational +electronic excitation	Thermal dissociation	kJ/mol	kJ/mol	kJ/mol	kJ/mol
200	500	722	90	110	610	632
Theoretical LTPs	Current LTPs	Current practice		55%	82%	88%

Can we minimize electronic excitations and maximize vibrational excitations in LTPs?

E-beam LTP G-value for different gases

For equation (1):

- Total of 3.74 N radicals
- < $2N_2$ molecules dissociated
- 26.73 eV/N radical
- ~ 3 low-energy electrons lost

When an energetic beam of electrons collides with the following gases, for 100eV of energy spent, we get:

$$4.43N_2 \xrightarrow{100\ \text{eV}} 0.29N_2^{*} + 0.885N(^2D) + 0.295N(^2P) + 1.87N(^4S) + 2.27N_2^{+} + 0.69N^{+} + 2.96e^{-} \quad (1)$$

$$5.377O_2 \xrightarrow{100\ \text{eV}} 0.077O_2^{*} + 2.25O(^1D) + 2.8O(^3P) + 0.18O^{*} + 2.07O_2^{+} + 1.23O^{+} + 3.3e^{-} \quad (2)$$

$$7.54\ CO_2 \xrightarrow{100\ \text{eV}} 4.72CO + 5.16O + 2.24CO_2^{+} + 0.51CO^{+} + 0.07O^{+} + 2.82e^{-} \quad (3)$$

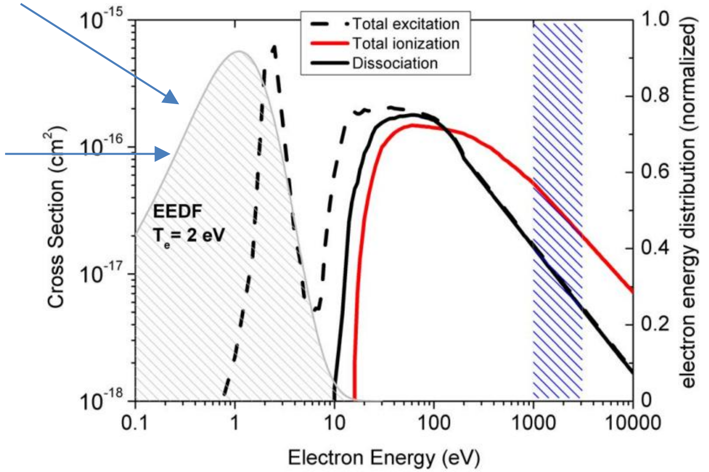
$$7.34CH_4 \xrightarrow{100\ \text{eV}} 3.94H + 2.34H_2 + 2.05CH_3 + 1.63CH_4^{+} + 1.43CH_3^{+} + 1.27CH_2 + 0.48CH + 0.32CH_2^{+} + 0.16C + 0.11H^{+} + 3.49e^{-} \quad (4)$$

Low-energy secondary electrons

The goal is to precisely control the energy of the secondary electrons to match optimum vibrational excitation energy. Or, give them a second life by accelerating them to produce more dissociation

E-beam enhanced LTP: Act fundamentally to control the chemical reaction pathways

These graphs represent:
- Energy dist. of the electrons in an ebeam plasma
- Different plasma processes for nitrogen

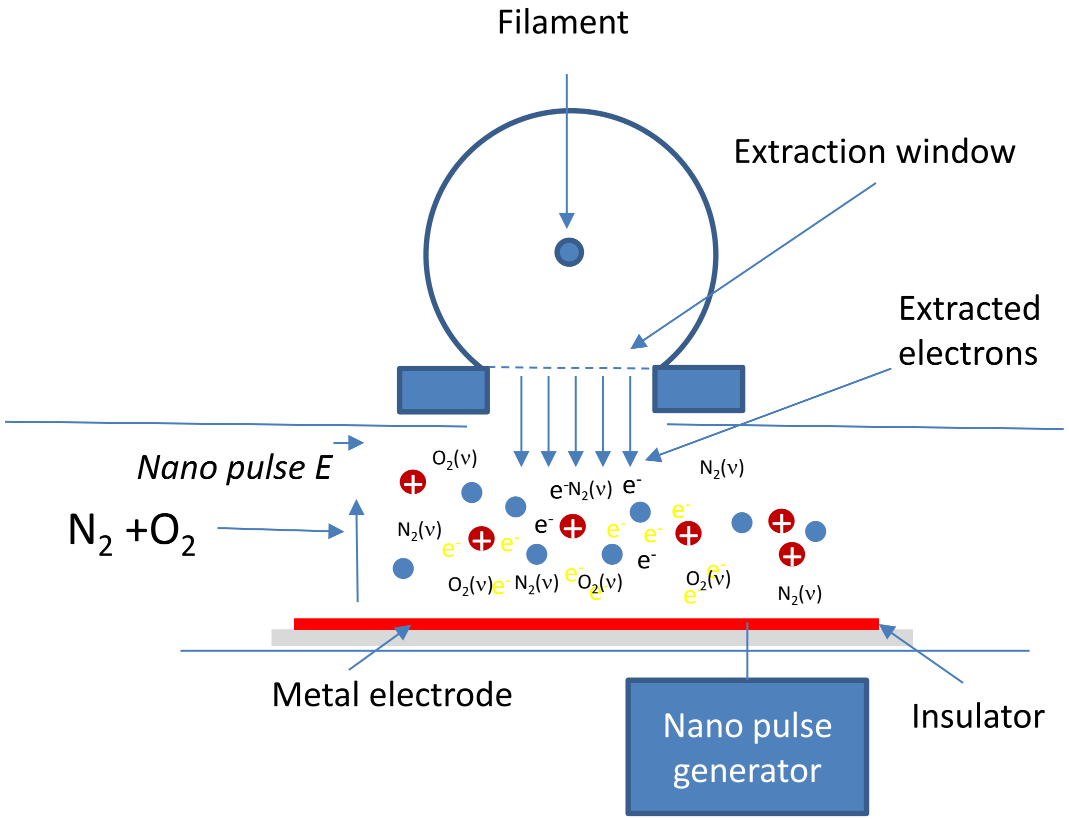


Secondary electrons from the plasma

We want to move this curve to the right, so it overlaps with the excitation curve

Figure 4. Electron impact cross sections in nitrogen for electron energies up to 10 keV. Also shown is a Maxwellian electron energy distribution function representative of a generic discharge with an electron temperature of 2 eV. Note the drastic difference in cross sections for low-energy plasma electrons and 1–3 keV beam electrons (shaded).

Walton et al. ECS Journal of Solid State Science and Technology, **4** (6) N5033-N5040 (2015)



K. Hadidi. US 12,273,987. Apr. 2025

Economics of CH_4 decompostion by current ebeam technology

Kerscher et al. international journal of hydrogen energy 46 (2021) 19897e19912

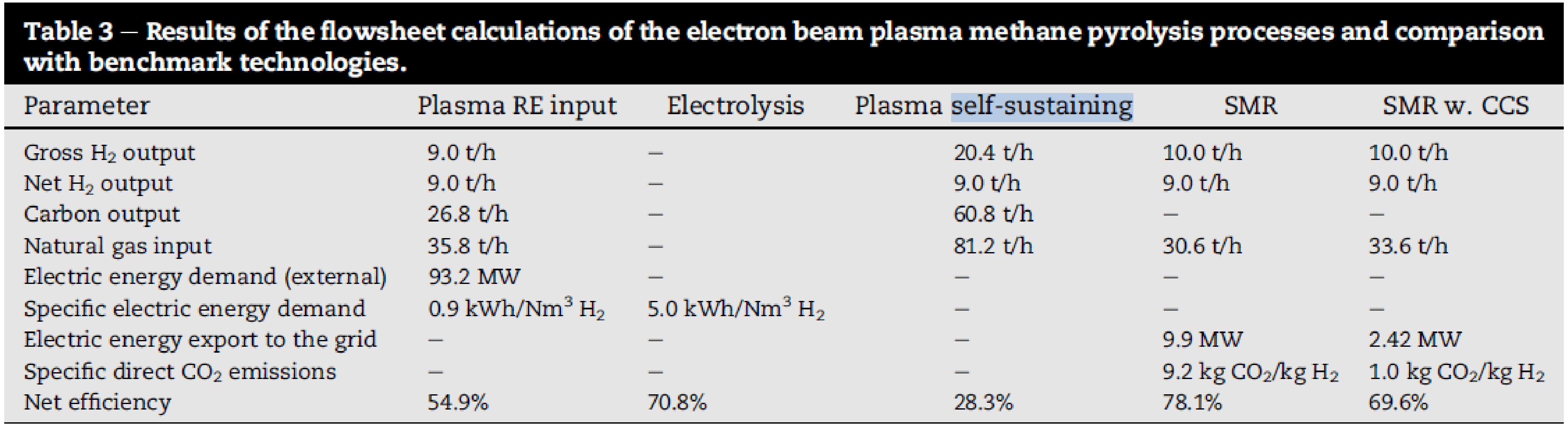


Table 3 — Results of the flowsheet calculations of the electron beam plasma methane pyrolysis processes and comparison with benchmark technologies.

Parameter	Plasma RE input	Electrolysis	Plasma self-sustaining	SMR	SMR w. CCS
Gross H_2 output	9.0 t/h	–	20.4 t/h	10.0 t/h	10.0 t/h
Net H_2 output	9.0 t/h	–	9.0 t/h	9.0 t/h	9.0 t/h
Carbon output	26.8 t/h	–	60.8 t/h	–	–
Natural gas input	35.8 t/h	–	81.2 t/h	30.6 t/h	33.6 t/h
Electric energy demand (external)	93.2 MW	–	–	–	–
Specific electric energy demand	0.9 kWh/Nm^3 H_2	5.0 kWh/Nm^3 H_2	–	–	–
Electric energy export to the grid	–	–	–	9.9 MW	2.42 MW
Specific direct CO_2 emissions	–	–	–	9.2 kg CO_2/kg H_2	1.0 kg CO_2/kg H_2
Net efficiency	54.9%	70.8%	28.3%	78.1%	69.6%

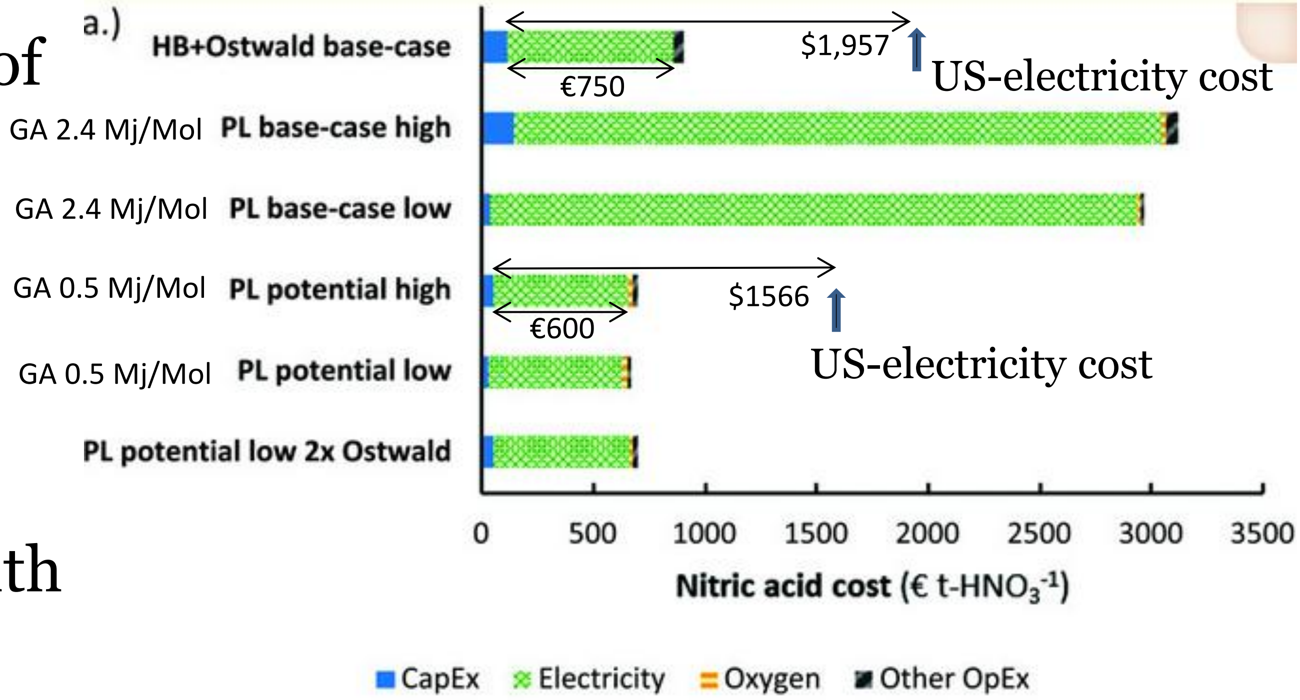
Electricity for the process comes from renewables such as solar

Some of the produced H_2 is used to generate electricity for the process

- **Net efficiency** for producing H_2 from CH_4 using existing e-beam plasma technology combined with renewable electricity input is **54.9%** and **produces no direct CO_2 emissions**
- **Cost** of hydrogen **between 2.55 Euro/kg H_2 and 5.00 Euro/kg H_2**
- Low-carbon hydrogen production with life cycle emissions between 1.9 kg CO_2 eq./kg H_2 and 6.4 kg CO_2 eq./kg H_2

Reducing energy consumption for LTPs is key to nitrogen fixation

- Assumption (paper): electricity cost of 0.020 €/kWh
- U.S. Electricity cost: \$0.052/kWh*
- CapEx is negligible compared to operational costs for LTP-based process
- Plasma process would be at parity with O/E-HB process at 0.625 MJ/mol N



*Kevin H. R. Rouwenhorst, Energy & Environmental Science · March 2021. * US Energy Information Administration (EIA)*

- Electricity consumption for an LTP-based HNO_3 plant would be the main cost driver
- LTP could be at parity in USA with combined O/E-HB at an energy consumption of 0.625 MJ/mol N

Possible Markets and Applications

Application	Product	Global Production (MT/Y)	Global GHG Emissions (MT/Y)	Total Energy Consumption	Energy Expense (kWh/kg)	Possible Precursors	Previous NTP Works
Nitrogen fixation	Ammonia	235	611	2608 TWh/Y (2% of total energy)	11.1	$H_2 + N_2$	Yes
	Nitric acid	62	192 (CO_{2equ} from N_2O)	1.24 GWh/Y	0.4	$N_2 + O_2$	Yes
Hydrogen production	**From methane**	**94**	**900**	**4175 TWh/Y (2.5% of total energy)**	**70**	**CH_4**	**Yes**
	From H_2S	**0**				**H_2S**	**Yes (H_2S decomp)**
CO_2 as feedstock	Adepic acid (C_6H_{10})$_4$)	3	6	60 MWh/Y	38.5	$CH_4 + H_2$	
	Urea (CO(NH_2)$_2$	180	450	4.5 TWh/Y	20	$CO_2 + NH_3$	
	Acetic acid (CH_3COOH)	16.7		417 MWh/Y	10.7	$CO_2 + CH_3OH$ $CO_2 + CH_4$	Yes
	Others						

Summary

- Thermo-catalytic processes have reached their efficiency limits through decades of optimization
- LTP can play a critical role in lowering/eliminating GHG emissions in chemicals manufacturing as they offer different chemical pathways
- Increasing LTP energy efficiency key to making them competitive with existing thermo-catalytic processes
- Controlling LTP at the fundamental level is key to reaching these goals.

Thank you for your attention

Backup Slides

Energy consumption and yield required for an economical plasma ammonia production

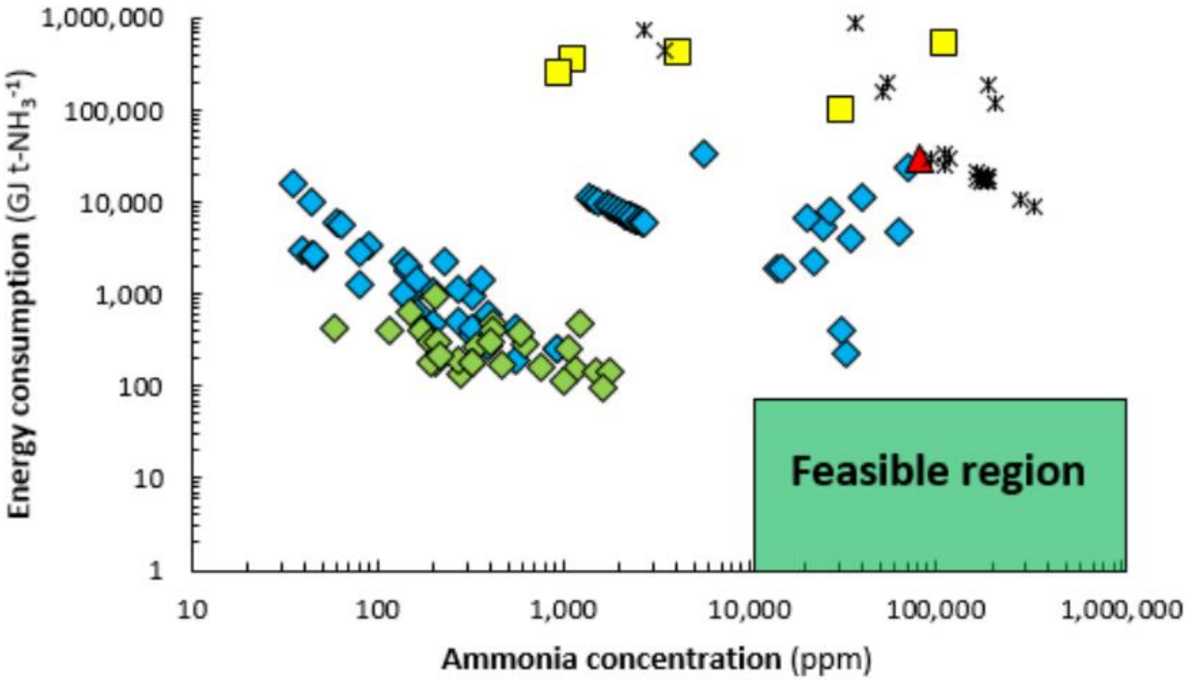


Figure 2. Reported energy yield vs. ammonia concentration at various process conditions. Constructed and extended from [38]. Original references: dielectric barrier discharge (DBD) (alternating current, AC) ◆ [39–52], DBD (pulse) ◆ [43,53], glow discharge ▲ [54], MW ☐ [55–59] and radiofrequency (RF) ⁎ [60–65]. Note that the feed composition varies among the references, and therefore the ammonia yield. In case of a stoichiometric feed ratio, the ammonia outlet concentration is equal to the yield (at 0.0 mol. % NH_3 inlet). The feasible region is discussed in Section 1.2.1.

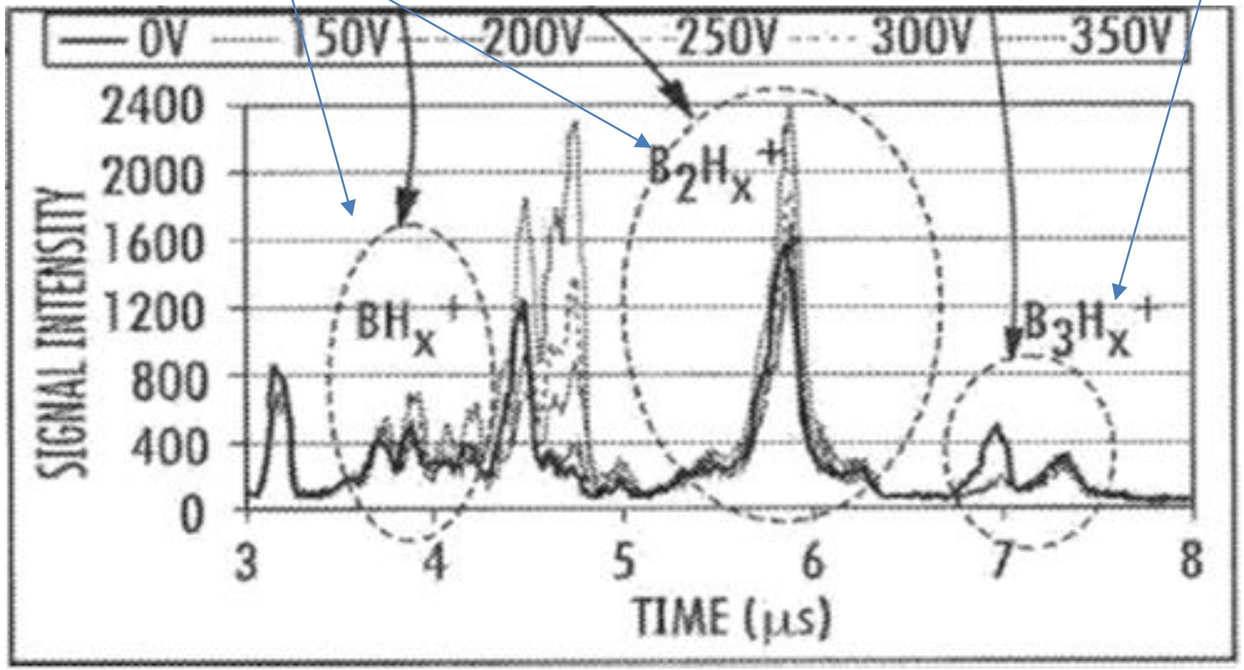
*Kevin H. R. Rouwenhorst * Catalysts 2020, 10, 999; doi:10.3390/catal10090999*

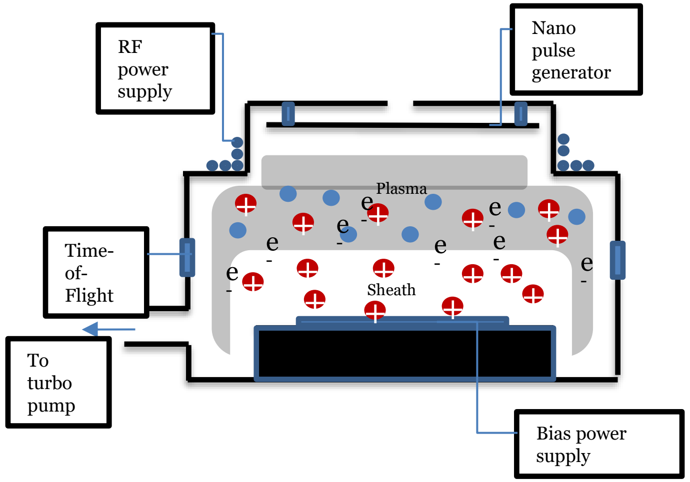
Change in plasma chemistry vs nano pulse E-field for semiconductor application

- RF power: 500W
- Pressure 6mT
- 0.1% B_2H_6
- n-Pulse duration: 1ns

Increase in $B_2H_x^+$ and BH_x^+ with pulse voltage

Decrease in $B_3H_x^+$ with pulse voltage ($B_3H_x^+$ come from recombination)

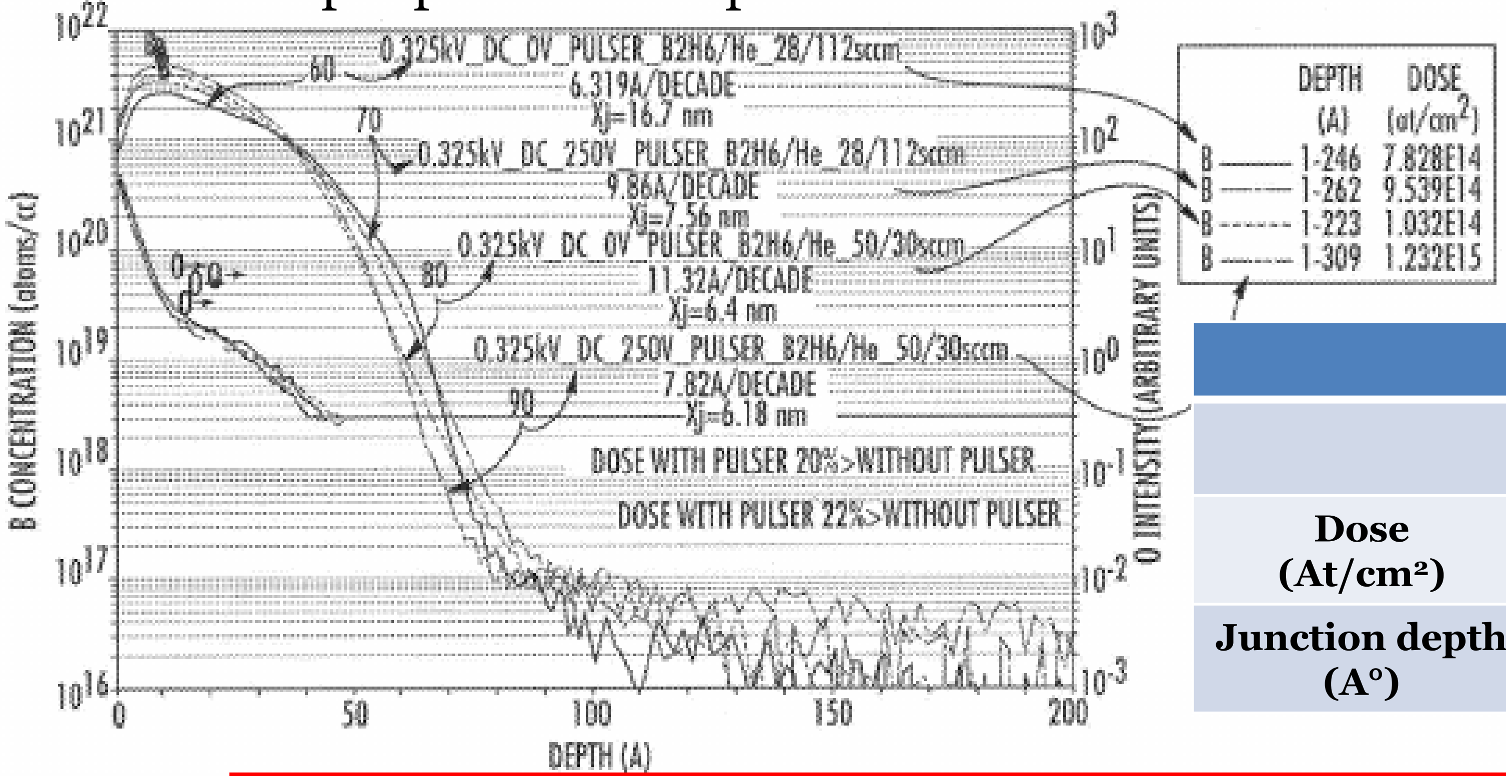




- Increase in RF power would have affected all species the same way
- Increase in nano pulse voltage has different effect on different ion species

Significant change in implanted dose and depth

SIMS depth profile for implanted B atom



Implant voltage: 325 V DC
B_2H_6/He: 0.1% and 0.5%
Nano pulse voltage: 0V and 250V
Nano pulse duration: 1ns

	0.1% B_2H_6			0.5% B_2H_6		
	No Pulse	**With Pulse**	**Change %**	**No Pulse**	**With Pulse**	**Change %**
Dose (At/cm²)	7.828 10^{14}	9.539 10^{14}	20	1.03 10^{14}	1.23 10^{15}	22
Junction depth (A°)	1.24	1.26	1.6	1.22	1.30	7

- Increase in implanted dose due to higher ion density because of the nano pulse effect on B_2H_6 and other species ionization
- Deeper implant shows a change in the plasma composition with more lighter ions produced because of the nano pulse

Isklen LLC. 2025