Plasma Electrification for Power-to-X: A Promising Solution for the AD/Biogas Sector

Prof. Xin Tu (Chair in Plasma Catalysis)
Department of Electrical Engineering and Electronics
University of Liverpool, UK
E-mail: xin.tu@liv.ac.uk

Progress in Biogas VI, September 2-4, 2024, Stuttgart, Germany

Outline

I. Introduction

II. Plasma-based biogas/biomethane conversion

III. Plasma-based CO_2 conversion

IV. Plasma-based nitrogen fixation for AD

V. Summary

Global Challenges and Opportunities

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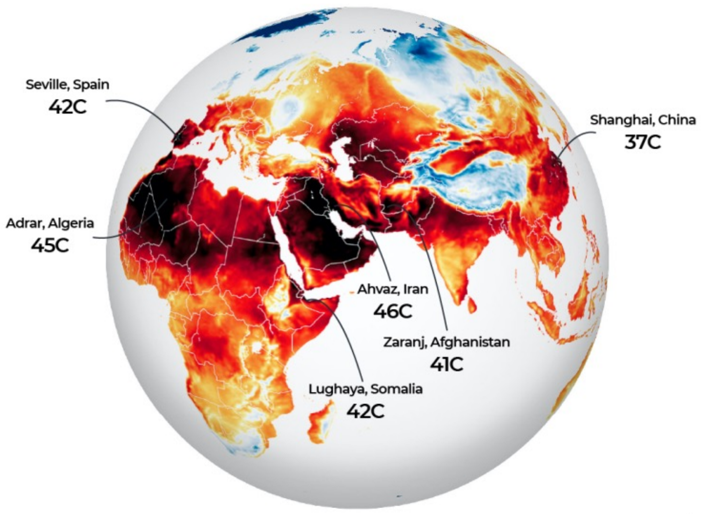
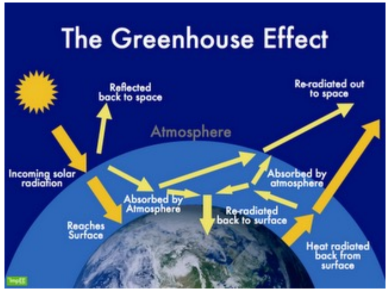
Global Warming & Climate Change

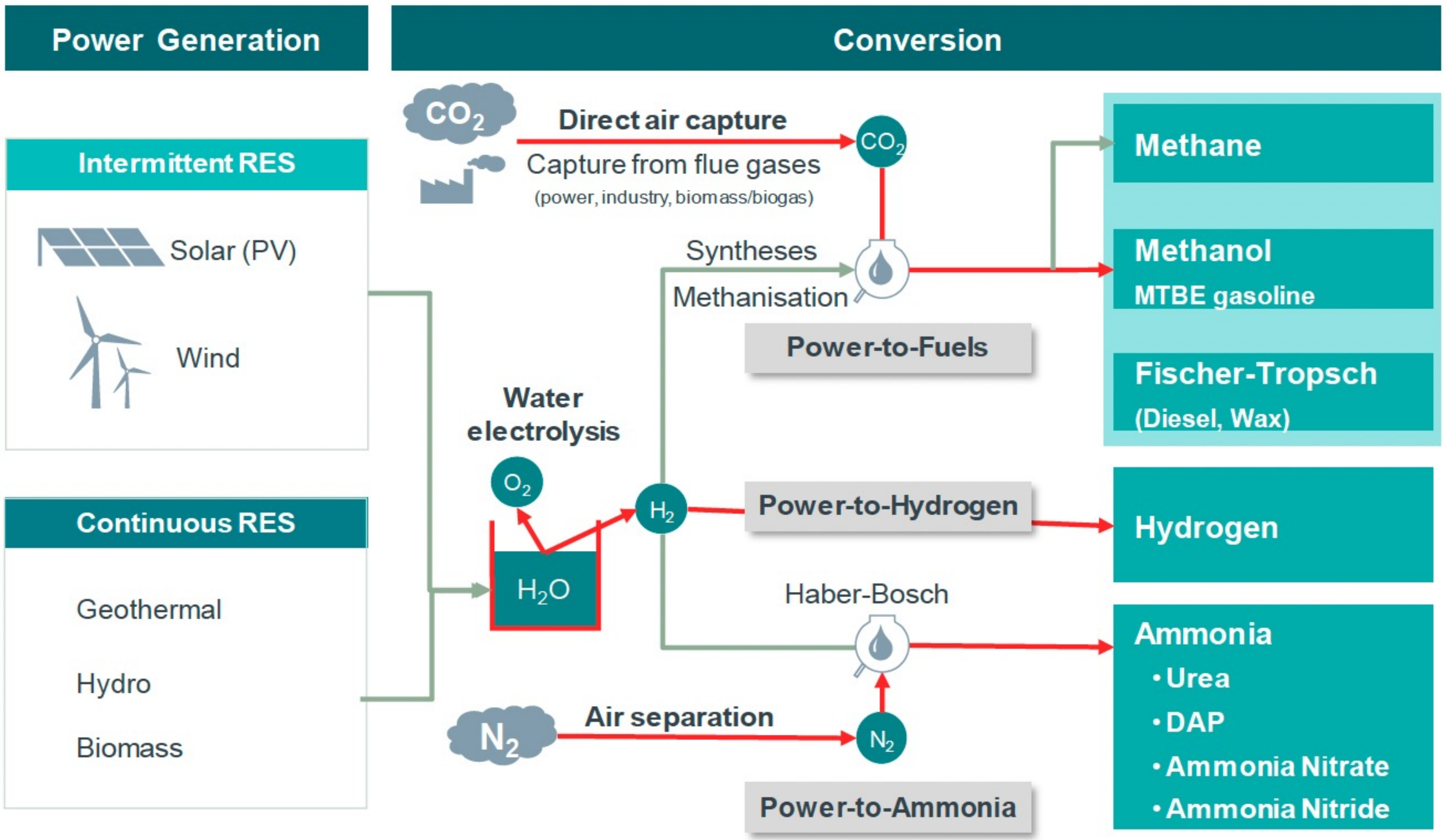




Net Zero Strategy

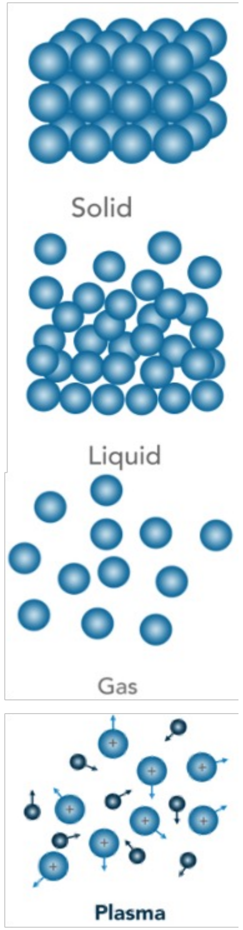
- ❑ Energy related **CO_2 emissions** continue to rise, reaching 363 Gt in 2021 (IEA).
- ❑ **Decarbonisation** of all sectors of the economy is critical to achieving net zero.
- ❑ **Electrification** can speed up the decarbonisation process.
- ❑ Current **chemical processes** largely rely on fossil fuels.
- ❑ **We need action now!**

Electrification: Power-to-X (PtX)
Carbon-neutral fuels and chemicals



Source: World Energy Council 2018

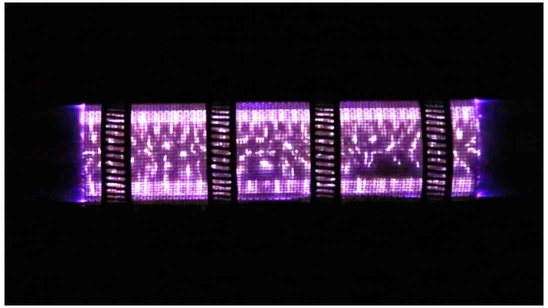
Non-thermal plasma (NTP) technology



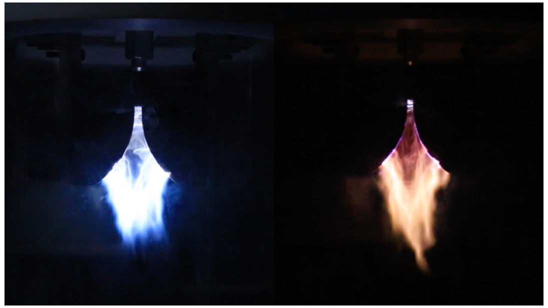
- Operation under ambient conditions
- Enhanced process intensification
- Instant switch on/off
- Modular & scalable
- Flexible electrification

Decentralised, modular and on-demand production of fuels and chemicals using intermittent RES

Dielectric barrier discharge

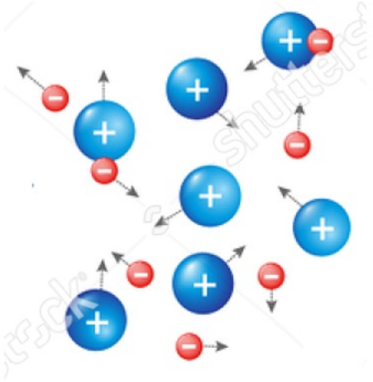


Gliding arc



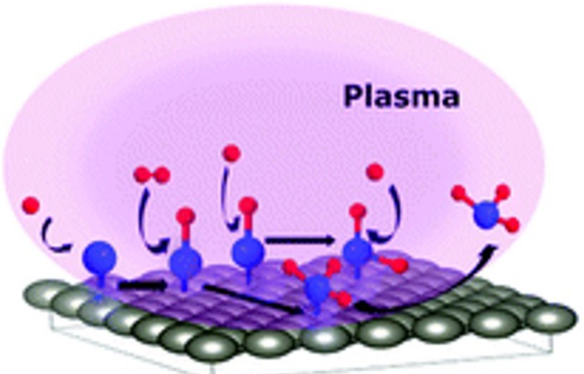
Plasma Catalysis (Multidisciplinary) Combination of NTP and catalysis

Plasma → Plasma Catalysis ← Catalysis



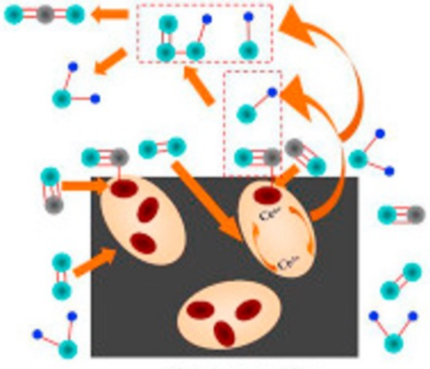
- Highly reactive
- Poor selectivity

Gas-phase reactions



- Synergistic effect

Gas-phase/Surface reactions



- Highly selective
- Activation barrier

Surface reactions

Reactor design/plasma properties

Plasma-catalyst interaction/Reactions

Catalyst design/catalyst properties

Chemical reactions using plasma catalysis

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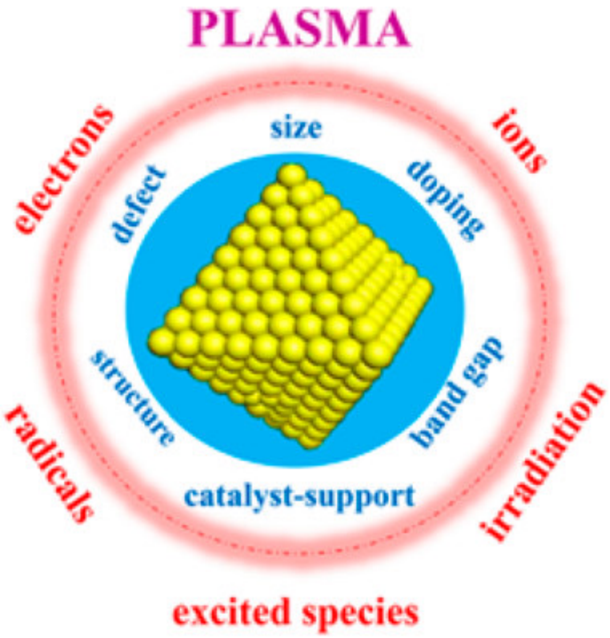
Process	Reactants	Target products
CO_2 conversion	CO_2	CO
	CO_2/H_2	CO
	CO_2/H_2	CH_4
	CO_2/H_2	Liquid fuels
	CO_2/H_2O	Syngas
	CO_2/CH_4	(see below)
	CO_2/C_2H_6	Liquid fuels
CH_4 conversion	CH_4	H_2
	CH_4	Olefins
	CH_4/CO_2	Syngas
	CH_4/CO_2	Olefins
	CH_4/CO_2	Liquid fuels
	CH_4/O_2	Syngas
	CH_4/O_2	Methanol
	CH_4/H_2O	Syngas
	$CH_4/CO_2/H_2O$	Syngas
VOC oxidation	Nonhalogenated VOCs/air	CO_2/H_2O
	Halogenated VOCs/air	CO_2/H_2O/HCl or HF
Odour control	Odour/air	Haress compounds
NH_3 synthesis	N_2/H_2	NH_3
NO_x synthesis	N_2/O_2 or air	NO/NO_2
NO_x removal	Reduction of NO_x by hydrocarbons	N_2
	Reduction of NO_x by NH_3	N_2
	NO_x oxidation	NO_2
Tar reforming	Tar	Syngas
Water gas shift reaction	CO/H_2O	CO_2/H_2
Methanol conversion	$MeOH/H_2O$	H_2
Ethanol conversion	$EtOH/H_2O$	H_2

Bogaerts et al., ***J. Phys. D: Appl. Phys.*** 2020, 53, 443001

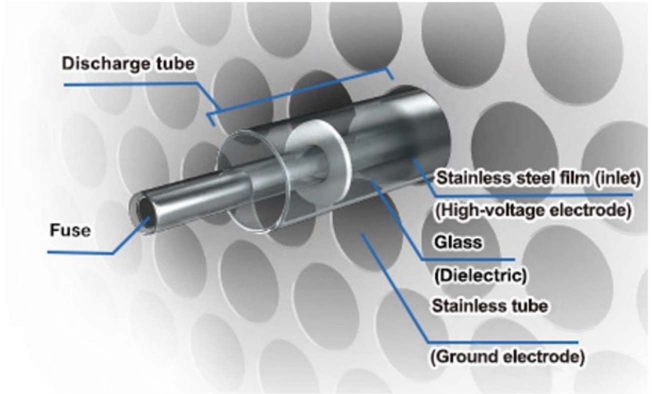
Plasma catalysis has also been extended for the synthesis and modification of catalysts.



Wang et al., ***ACS Catal.*** 2018, 8, 2093-2110

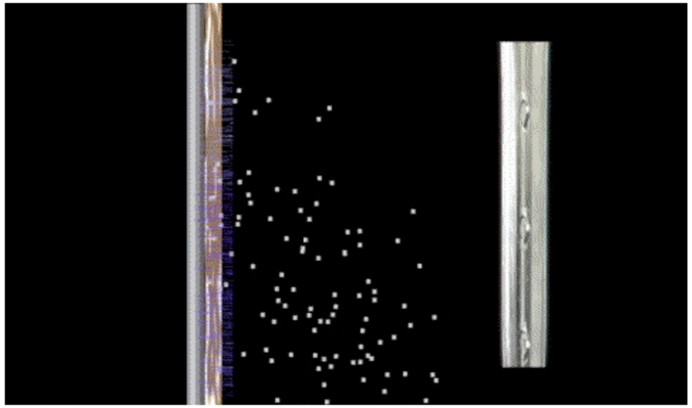
Success stories for industrial-scale development

Plasma ozone generator



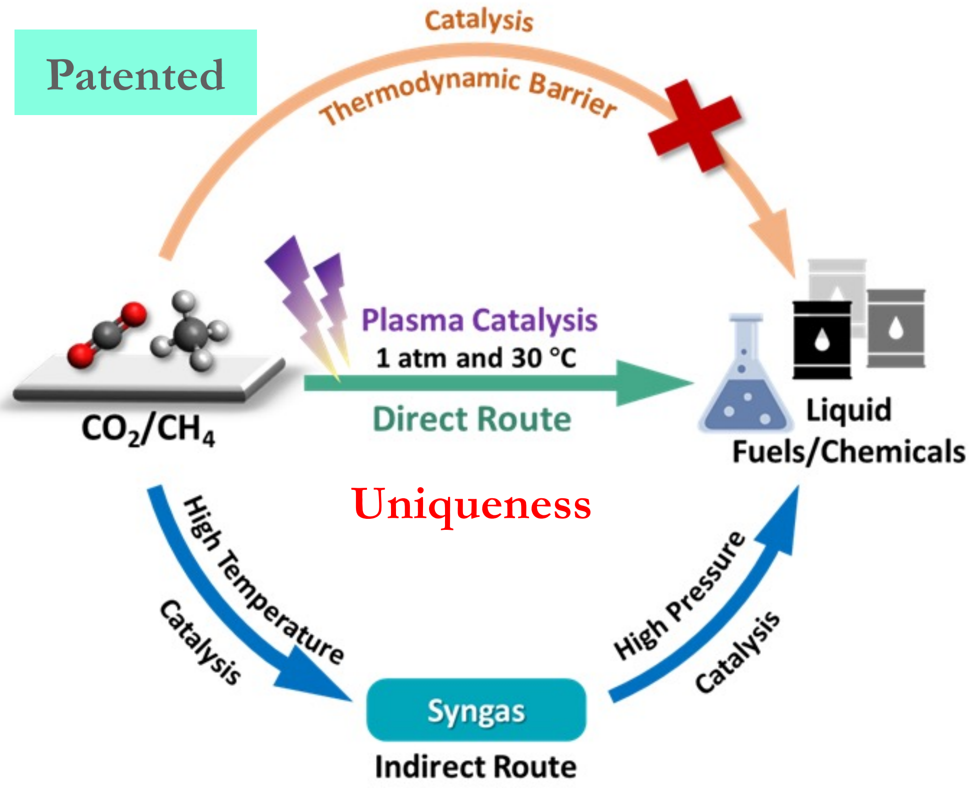
- 120 kg O_3/h (Source: Toshiba, Japan)
- Montreal, largest ozone project (45 MW)

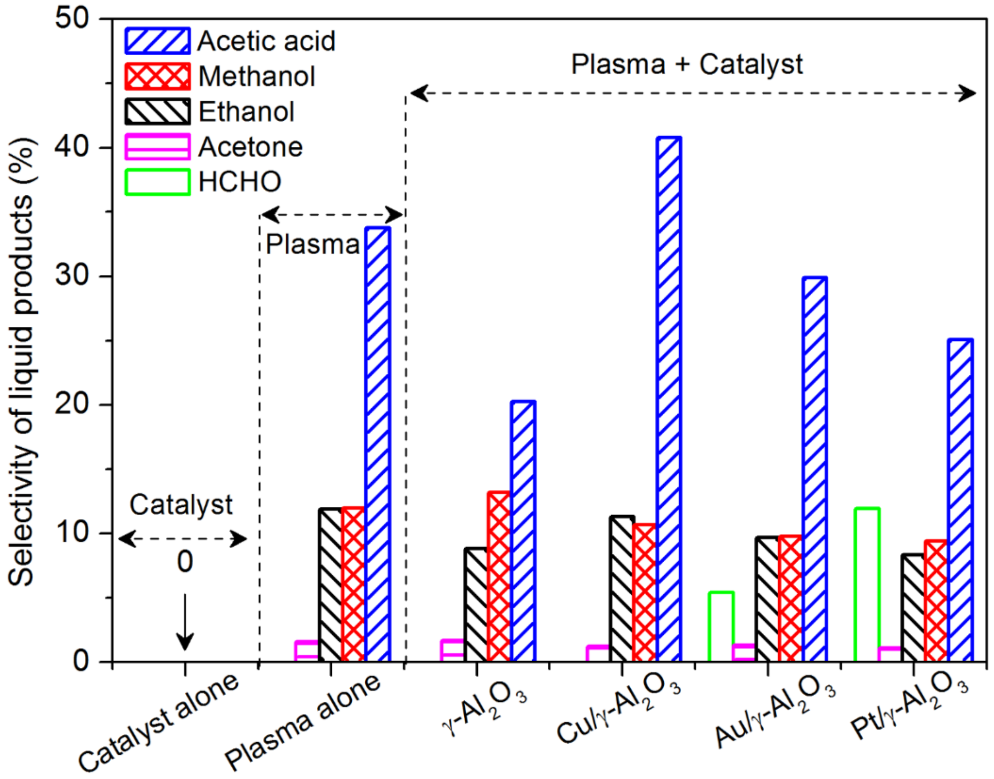
Plasma $DeNO_x/DeSO_x$



1 MW, 250,000 m^3/h flue gas (Source: TEAMS, China)

Single-step biogas conversion into liquid fuels and chemicals (30 °C/1 bar)





Wang et al., ***Angew. Chem. Int. Ed.*** 2017, 56, 13679-13683; Wang et al., **Chem. Eng. J.** 2022, 450, 137860

Featured in >10 media and trade magazines

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PHYS.ORG

OCTOBER 6, 2017

Breakthrough in direct activation of CO2 and CH4 into liquid fuels and chemicals

by University of Liverpool

The Chemical Engineer

Process 9th October 2017

Plasma synthesis turns CO2 and CH4 into fuels and chemicals

Article by Neil Clark

RESEARCHERS have reported a "major breakthrough" in reforming CO_2 and CH_4 into liquid fuels and chemicals, by using a highly selective one-step process at ambient conditions.

The Engineer

Low-energy carbon activation process could replace methane flaring

News

University of Liverpool develops process that converts methane and CO2 into reactive organic chemicals, holding promise for renewable energy storage in chemical form

Methane emissions from gas flaring being hidden from satellite monitors

Use of enclosed combustors leaves regulators heavily reliant on oil and gas companies' own flaring data

ColdSpark project

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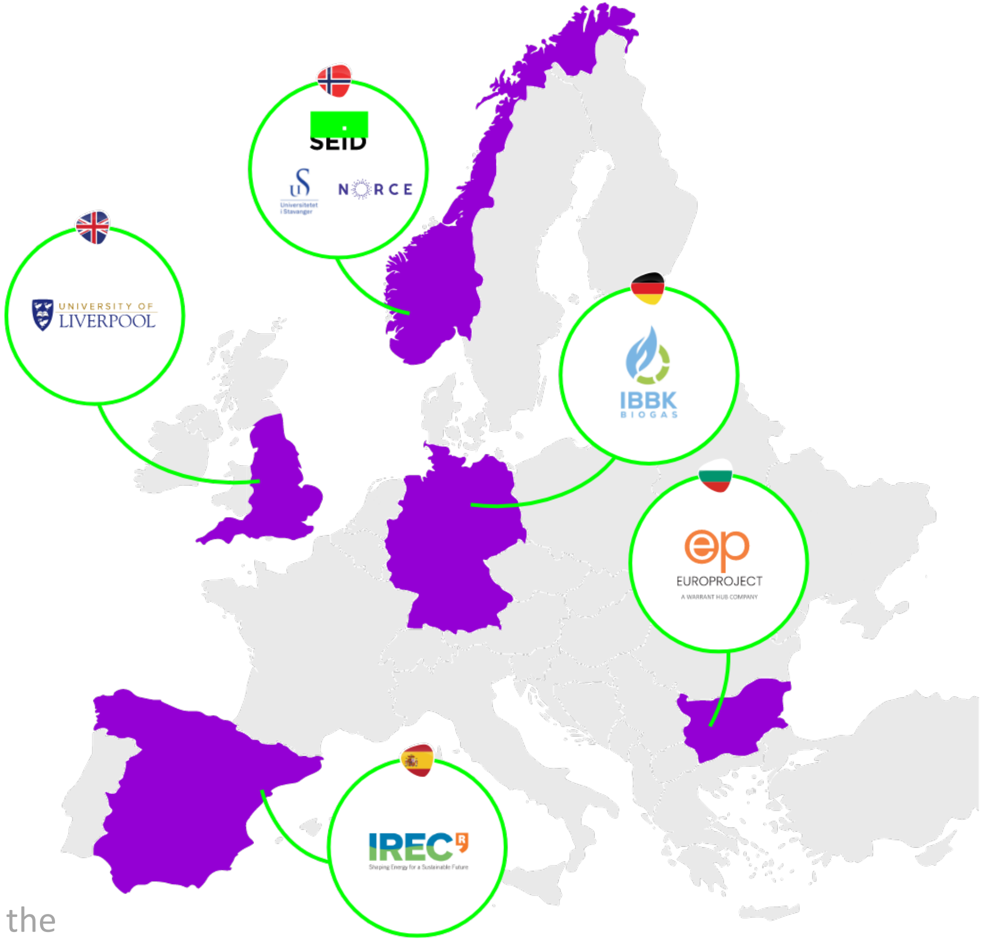
Cold Methane Pyrolysis

PROJECT COLDSPARK®

A novel approach to sustainable hydrogen production



Project ColdSpark® has received funding from the European Union's Horizon Europe Research and Innovation Programme
Grant Agreement ID: 101069931

https://coldspark.eu/

Plasma (bio)methane pyrolysis to hydrogen and value-added carbon materials

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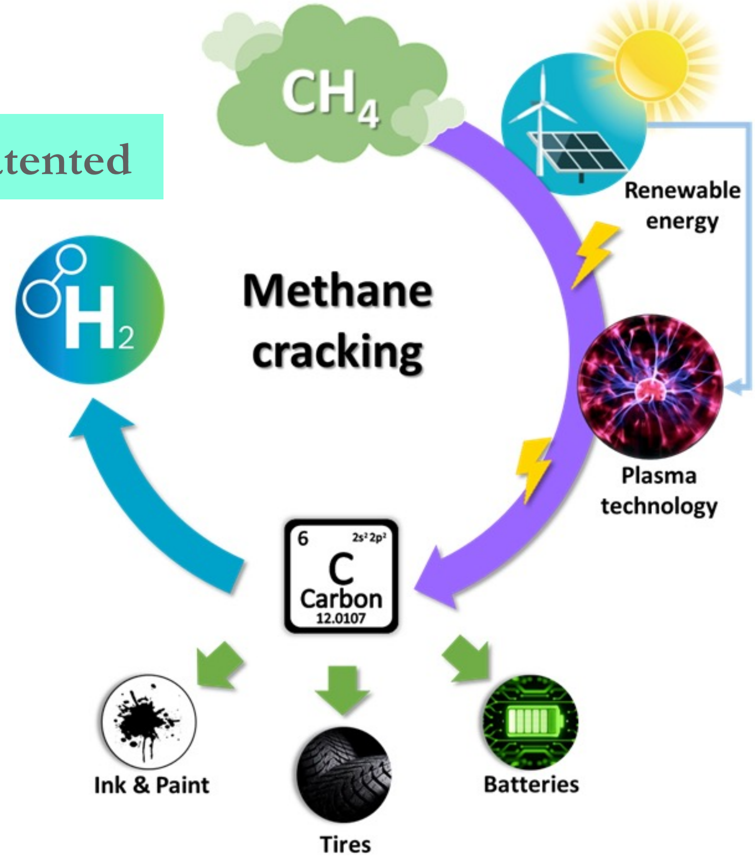
Patented

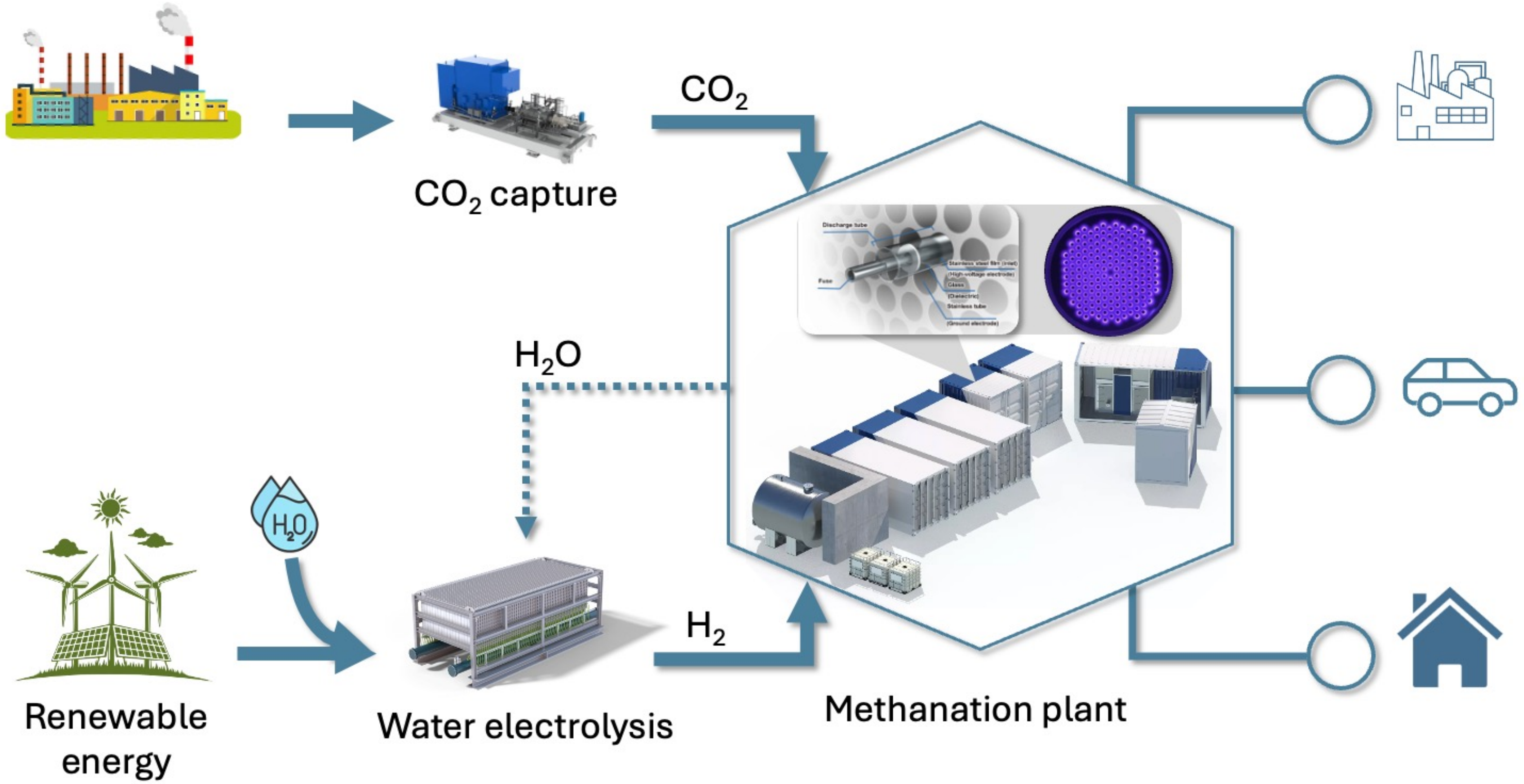


			Direct CO_2 emissions in kg CO_2/kg hydrogen	Minimum energy demand in kJ/mol hydrogen*
State-of-the-art	Steam reforming of natural gas	$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	8.85	27
Option 1	Water electrolysis	$2H_2O \rightarrow 2H_2 + O_2$	0	286
Option 2	Methane pyrolysis	$CH_4 \rightarrow 2H_2 + C$	0	37

Advantages

- ❑ Low carbon hydrogen production
- ❑ Catalyst free & Low temperature process
- ❑ Does not use any precious materials
- ❑ Additional revenue for valuable carbon
- ❑ Very competitive energy cost
- ❑ High energy efficiency
- ❑ Modular design & decentralised production

Plasma catalysis for CO_2 methanation



Low temperature and ambient pressure

Patented

Plasma catalysis for CO_2-to-methanol

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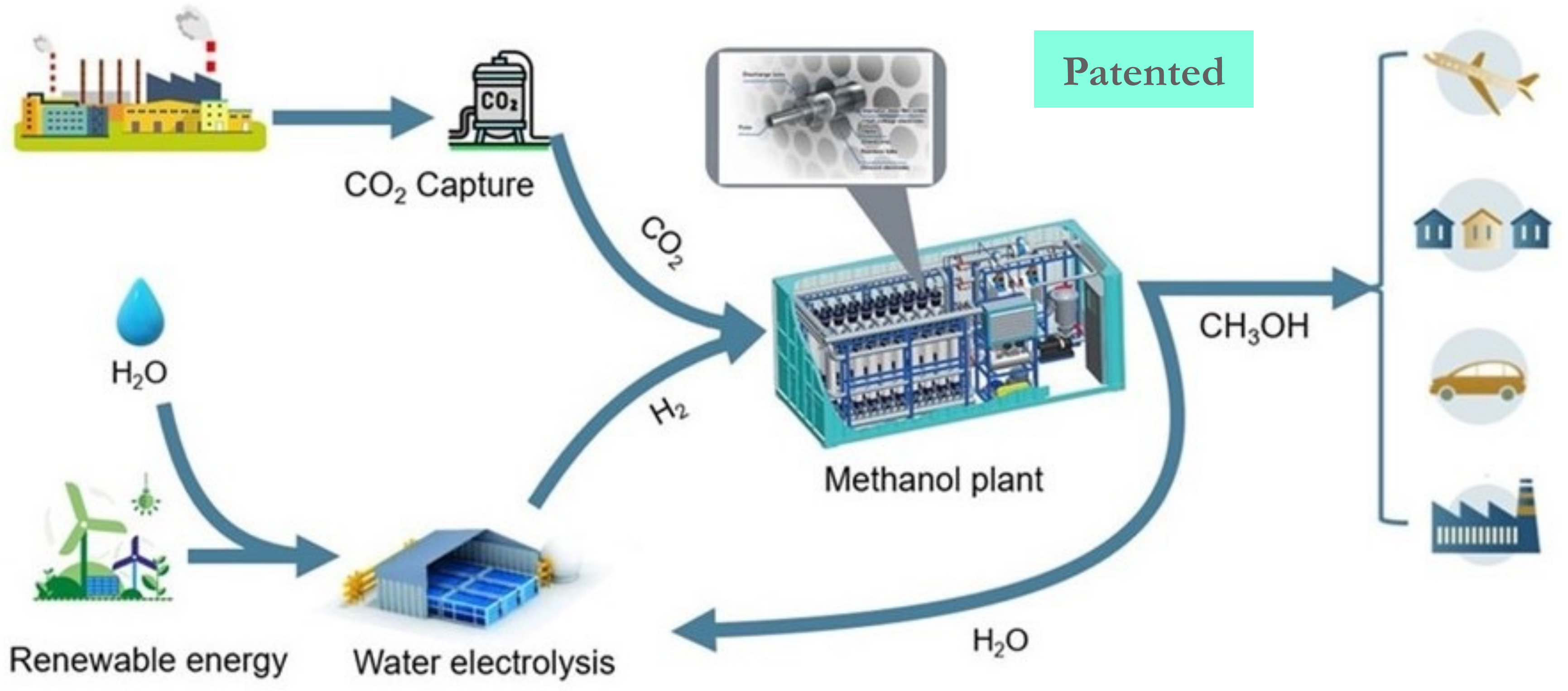


Patented

Room temperature and ambient pressure

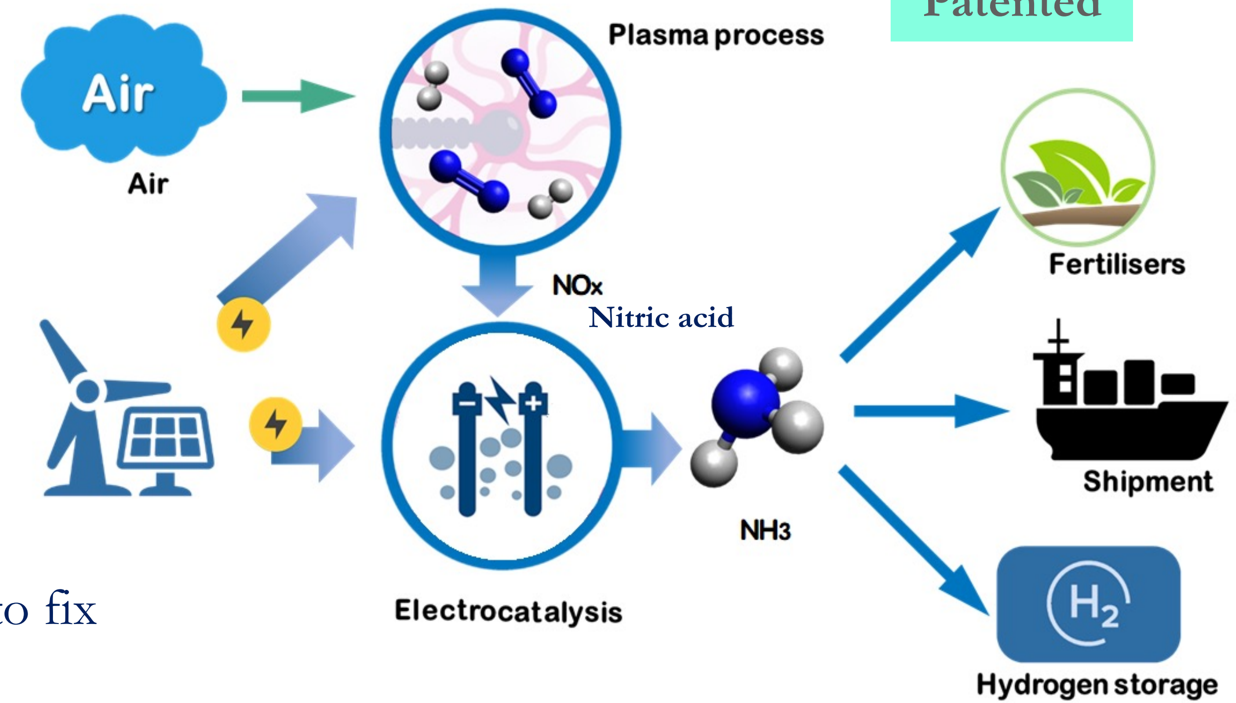
Wang et al., ***ACS Catal.*** 2018, 8, 90-100; Wang et al., ***Chem*** 2024, 10, 2590-2606.

Plasma-based nitrogen fixation

- **Nitric acid synthesis:** Plasma NO_x production from air
- **NH_3 synthesis:** Plasma nitric acid production + electrocatalytic HNO_3 reduction
- **Ammonium nitrate synthesis:** $HNO_3 + NH_3 \longrightarrow NH_4NO_3$

- Cheap feedstock
- Limited CO_2
- Mild conditions
- Flexible
- Economic benefit
- Low CAPEX

Patented



Air-rich NO_x can be used to fix ammonia in digestate

Plasma electrification - a promising route for decentralised production of fuels and chemicals

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IOP Publishing
Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. **53** (2020) 443001 (51pp)
https://doi.org/10.1088/1361-6463/ab9048

Roadmap

The 2020 plasma catalysis roadmap

Annemie Bogaerts[1], Xin Tu[2], J Christopher Whitehead[3], Gabriele Centi[4,5], Leon Lefferts[6], Olivier Guaitella[7], Federico Azzolina-Jury[8], Hyun-Ha Kim[9], Anthony B Murphy[10], William F Schneider[11], Tomohiro Nozaki[12], Jason C Hicks[11], Antoine Rousseau[7], Frederic Thevenet[13], Ahmed Khacef[14] and Maria Carreon[15]

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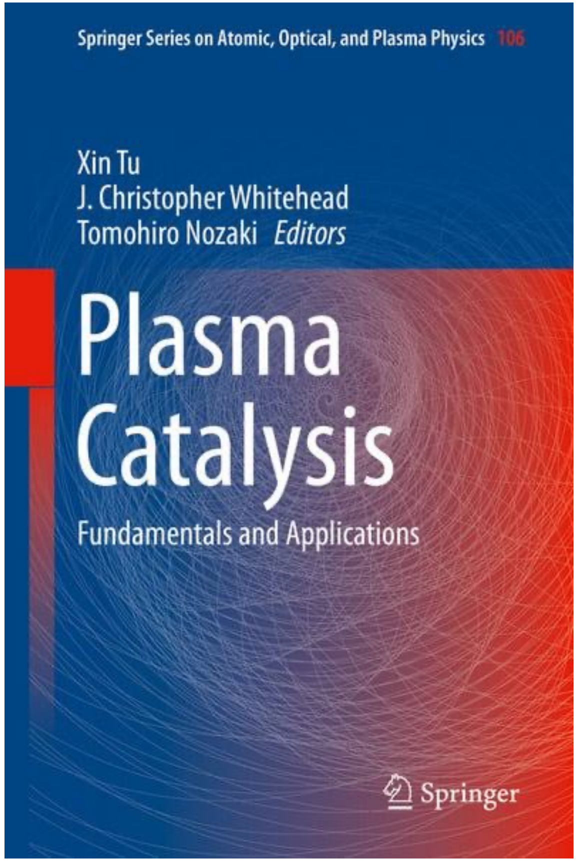

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THANK YOU