THE PERVASIVE PLASMA

Plasma Processes for Carbon-free Energy

P. I. John

Vikram Sarabhai Oration
Shri Vaishnav Vidyapeeth Vishwavidyalaya, Indore
18 December 2018

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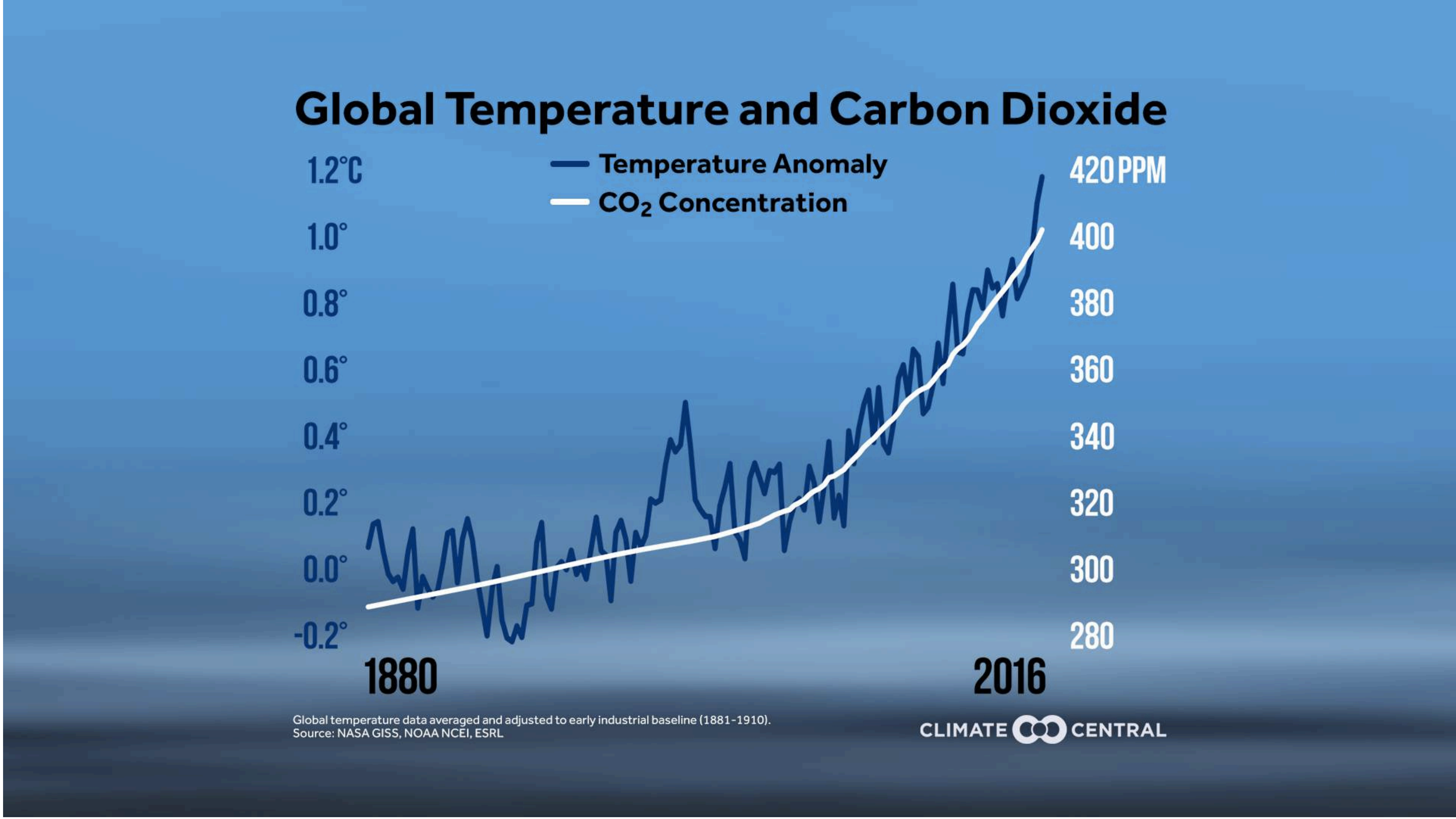
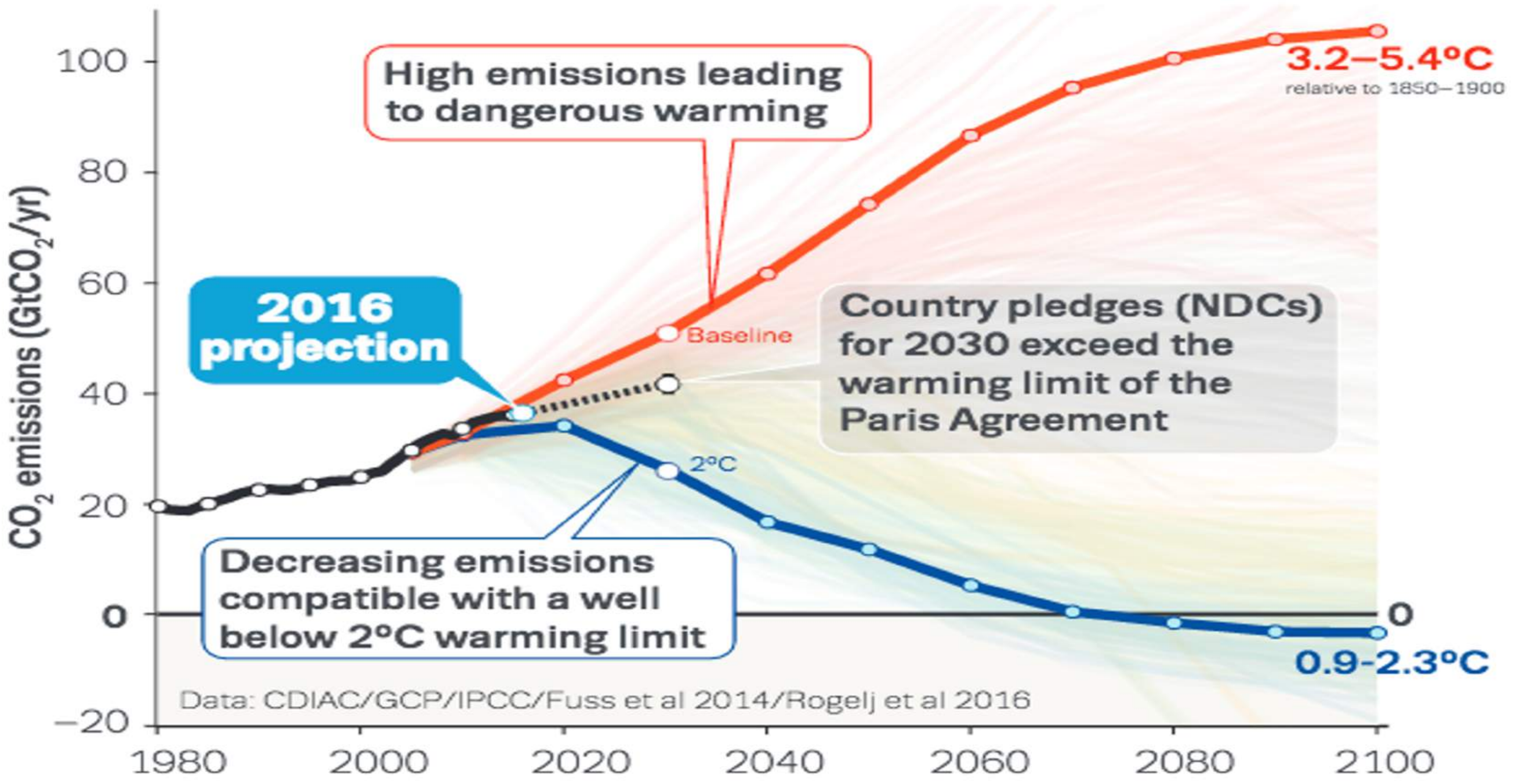
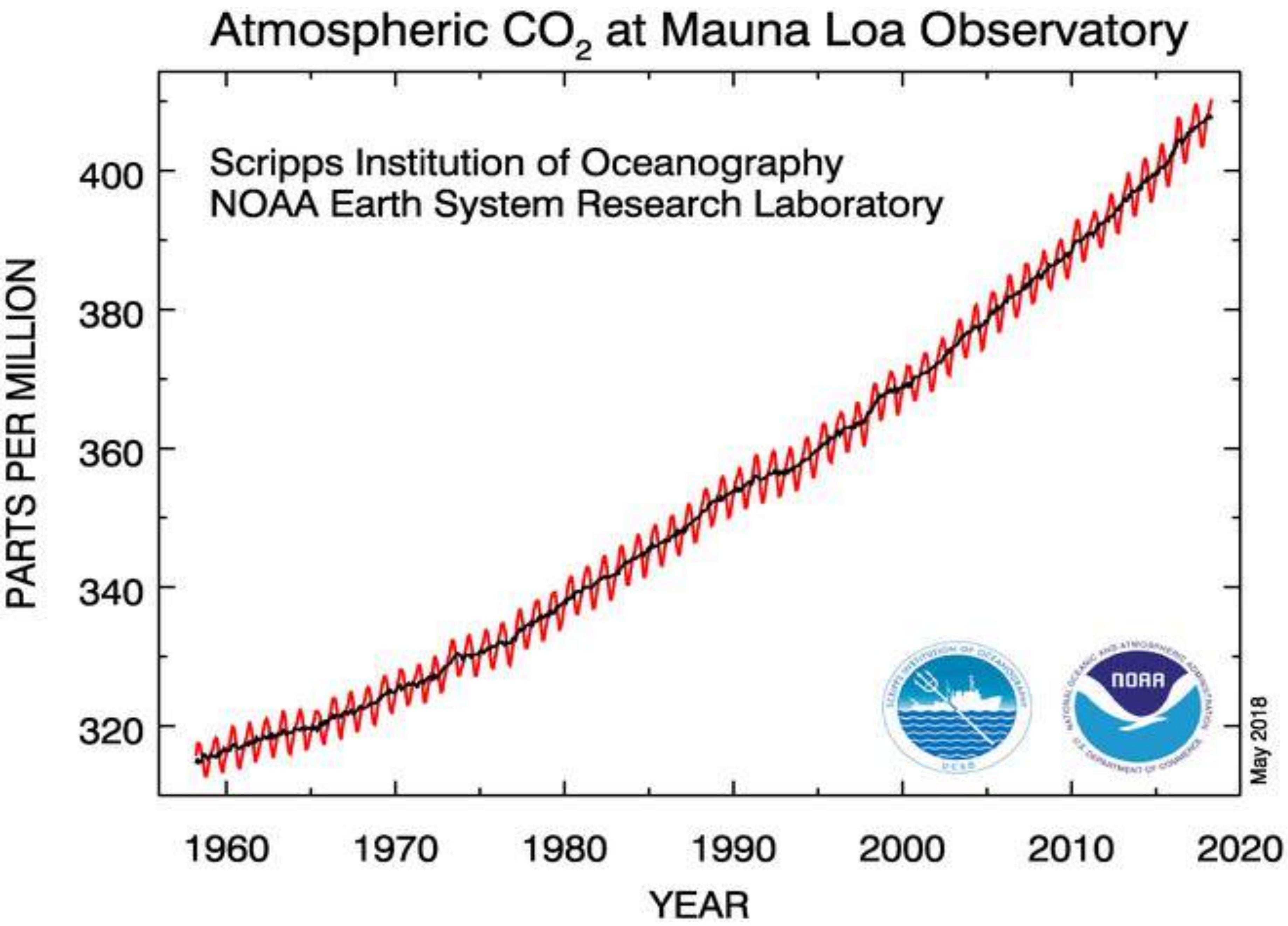


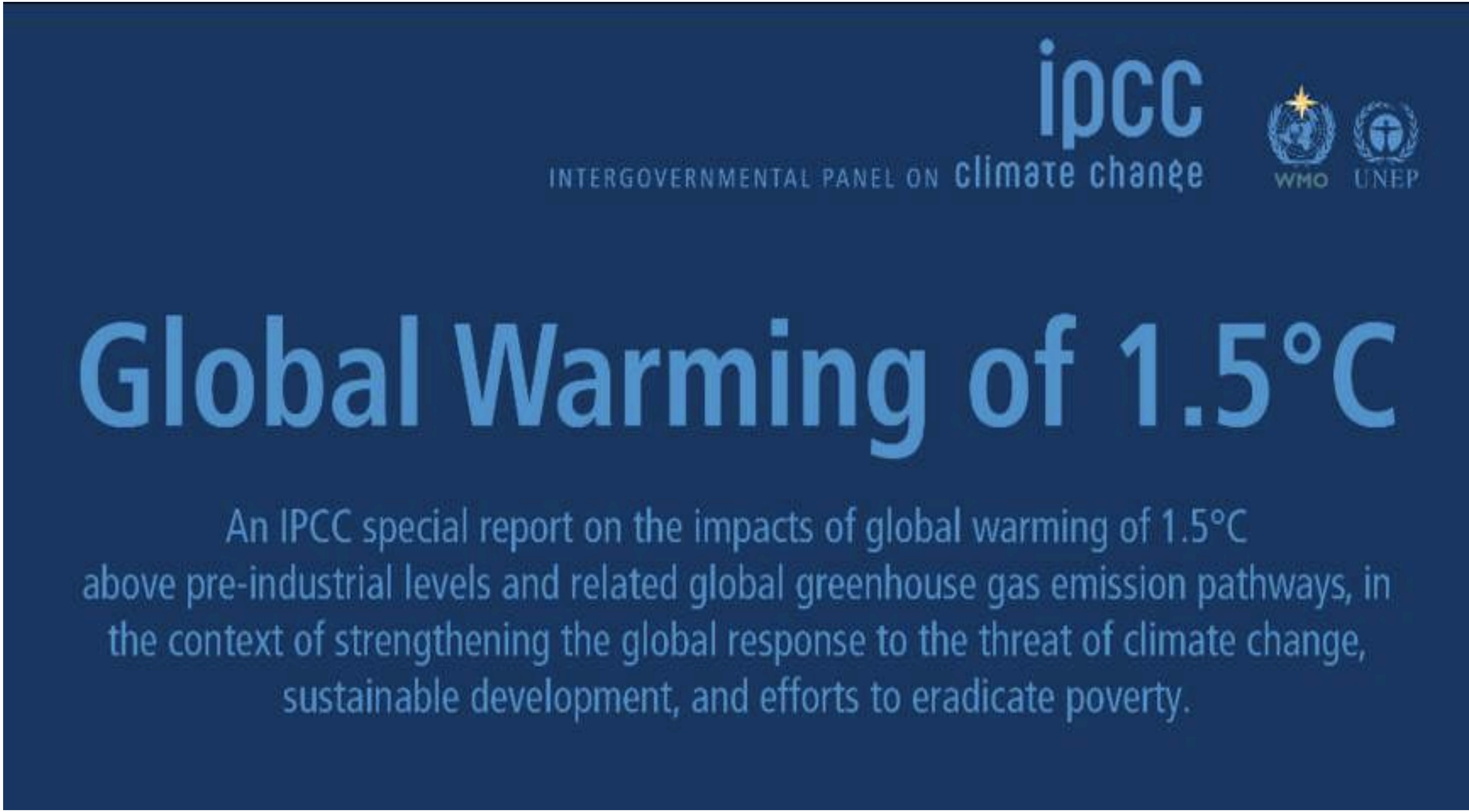
SOURCE: http://www.climatecentral.org/gallery/graphics/co2-and-rising-global-temperatures



Source: Earth Syst. Sci. Data, 8, 1–45, 2016 Global Carbon Budget 2016 Corinne Le Quéré et. al.

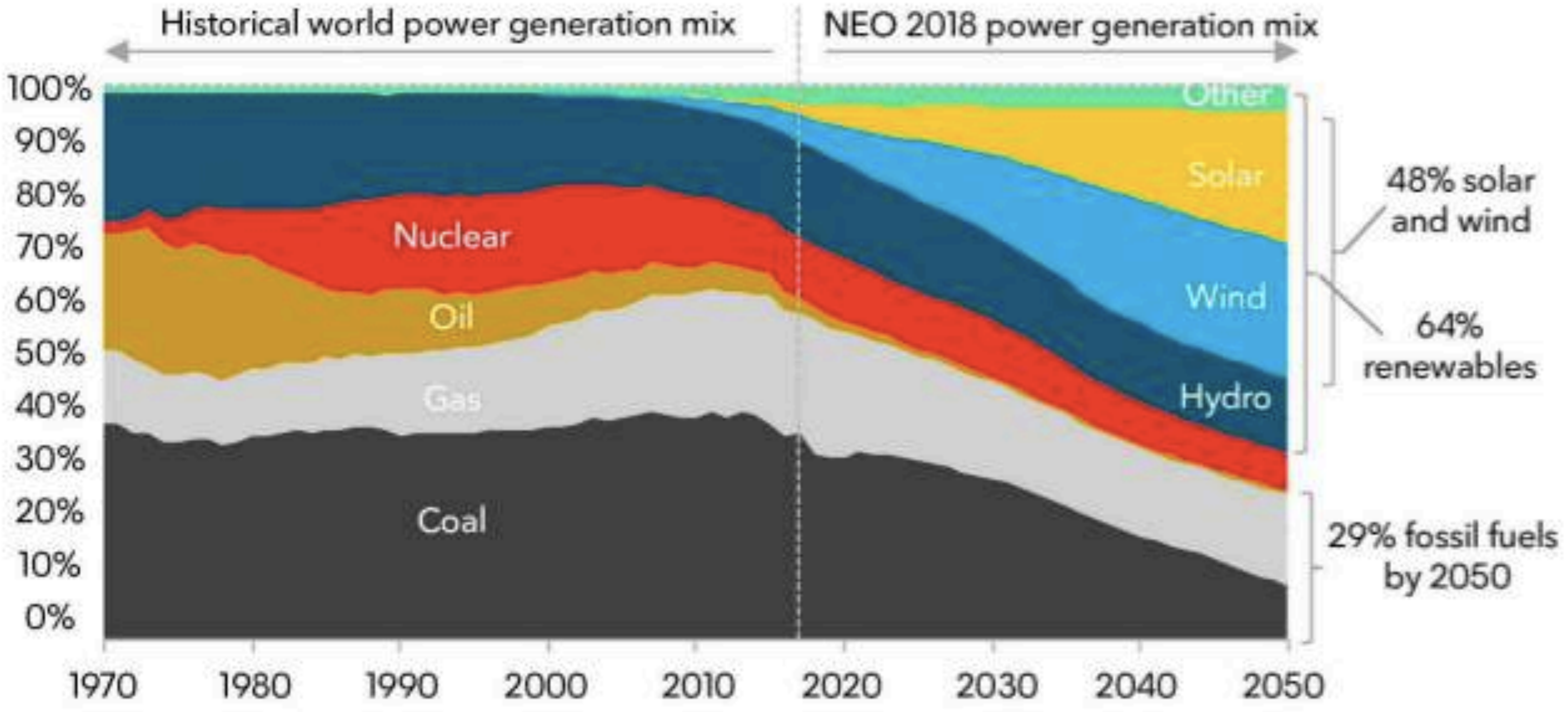
Above
410 ppm
for the first
time in
April 2017





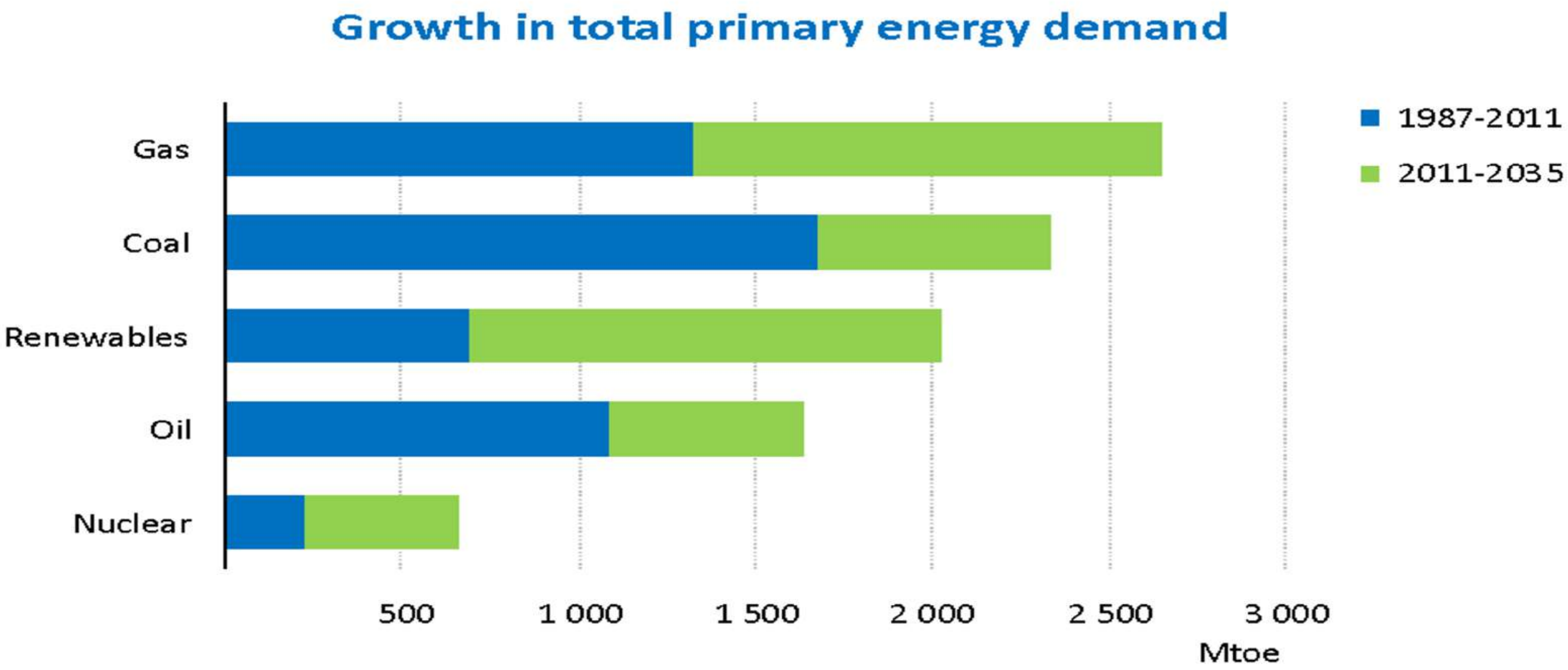
Source: IPCC website www.ipcc.ch

Power generation mix



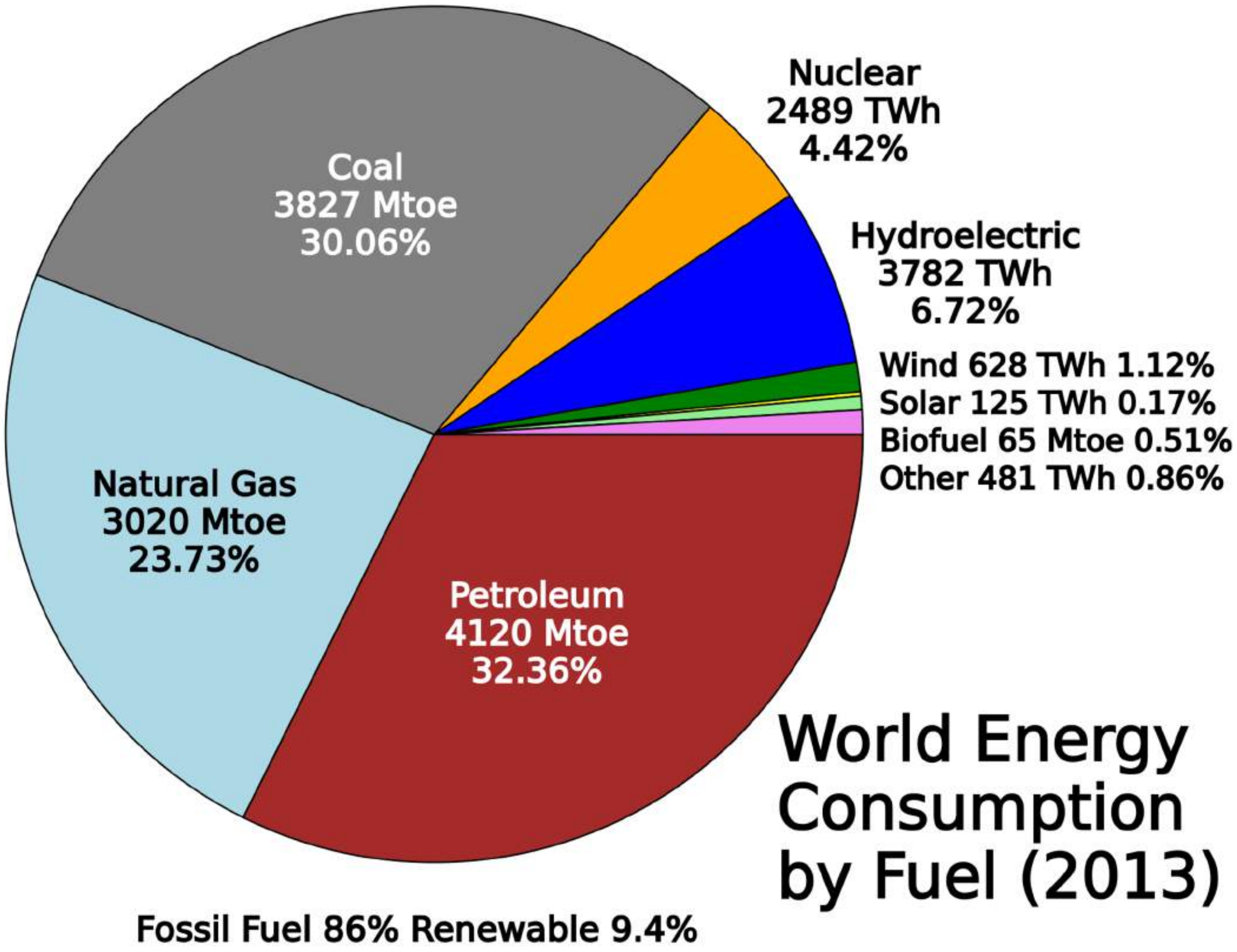
Source: Bloomberg NEF

A mix that is slow to change

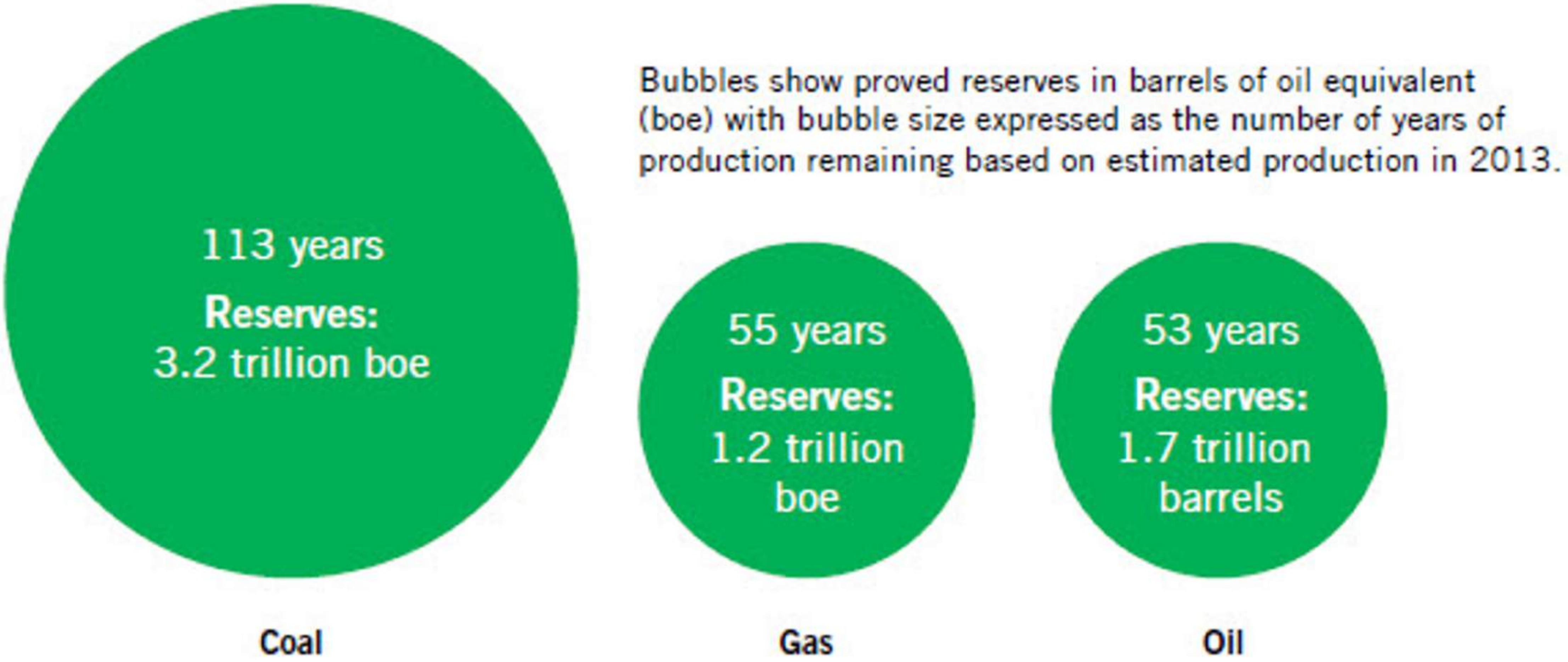


Today's share of fossil fuels in the global mix, at 82%, is the same as it was 25 years ago; the strong rise of renewables only reduces this to around 75% in 2035

85% of the world energy demand is met by non-renewable fossil fuels



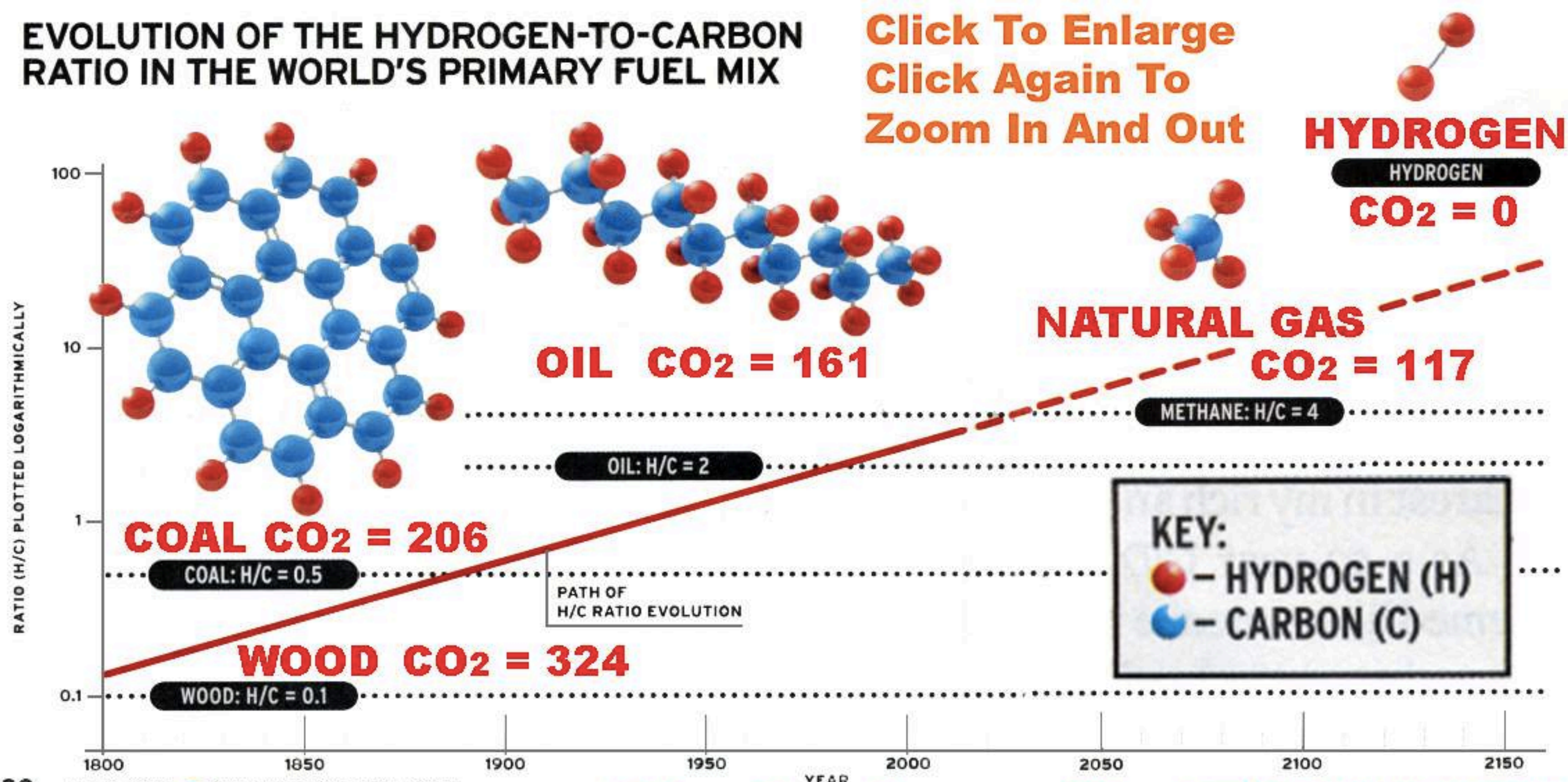
Accessibility
Broad applications
Transportation fuel
Portability
Storage



Source: BP, 2014. *Statistical Review of World Energy.*

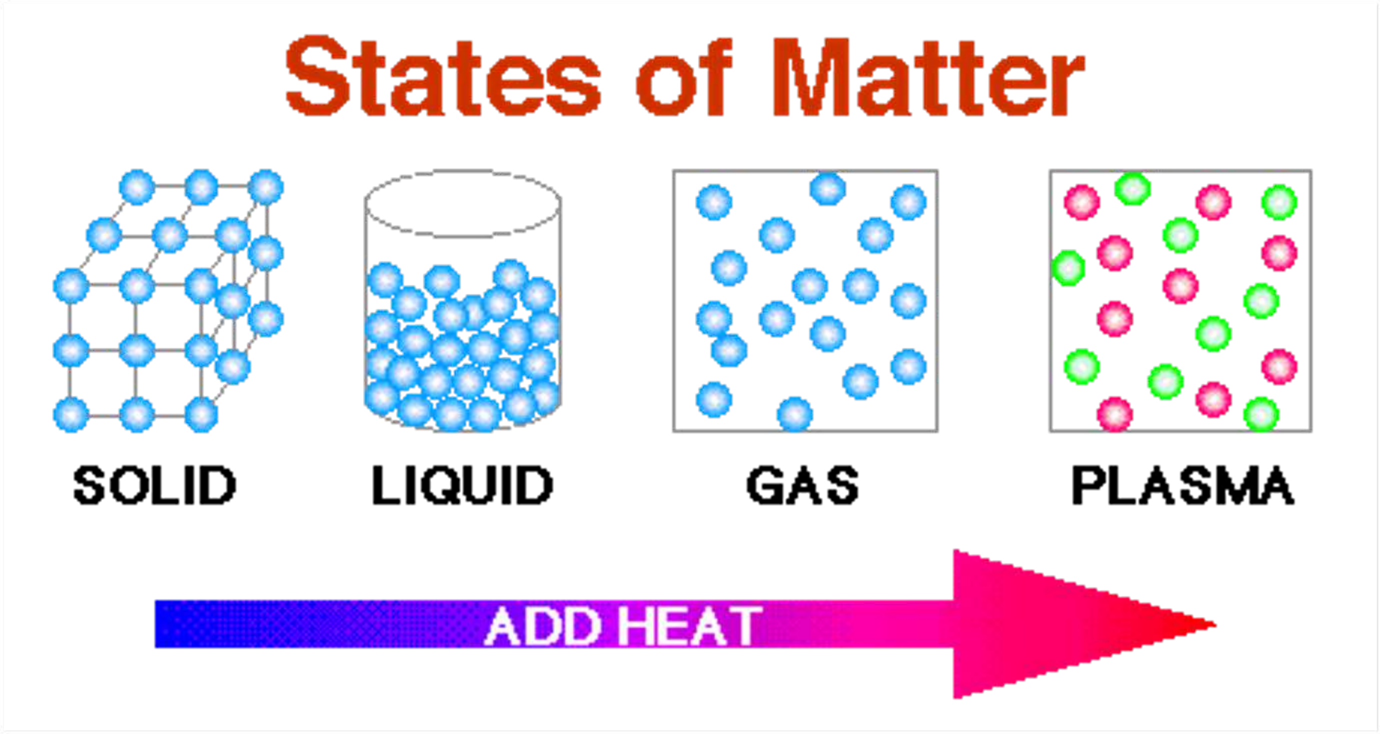
OPTION 1: DECARBONIZE FUEL

DECARBONIZATION: PROCESS OF REDUCING CARBON INTENSITY IN ENERGY UTILIZATION



ILLUSTRATIONS by BRYAN CHRISTIE DESIGN

CAN PLASMA BASED TECHNOLOGIES HELP IN DECARBONIZING FUELS?



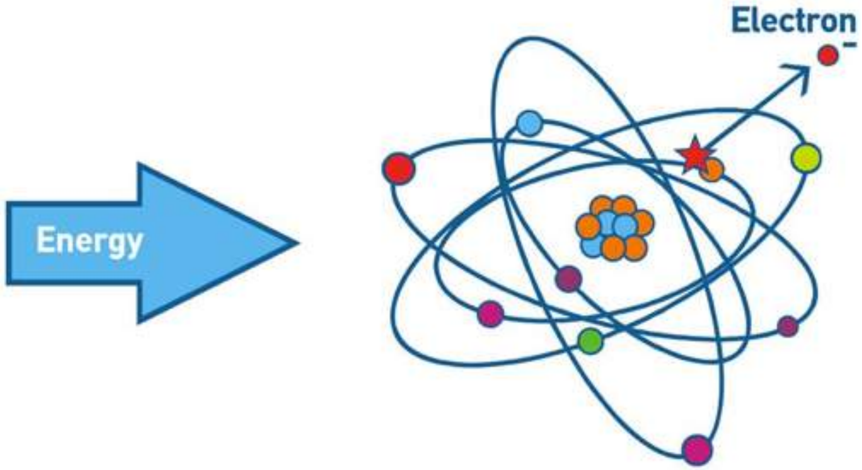
Cloud of electrically charged particles.

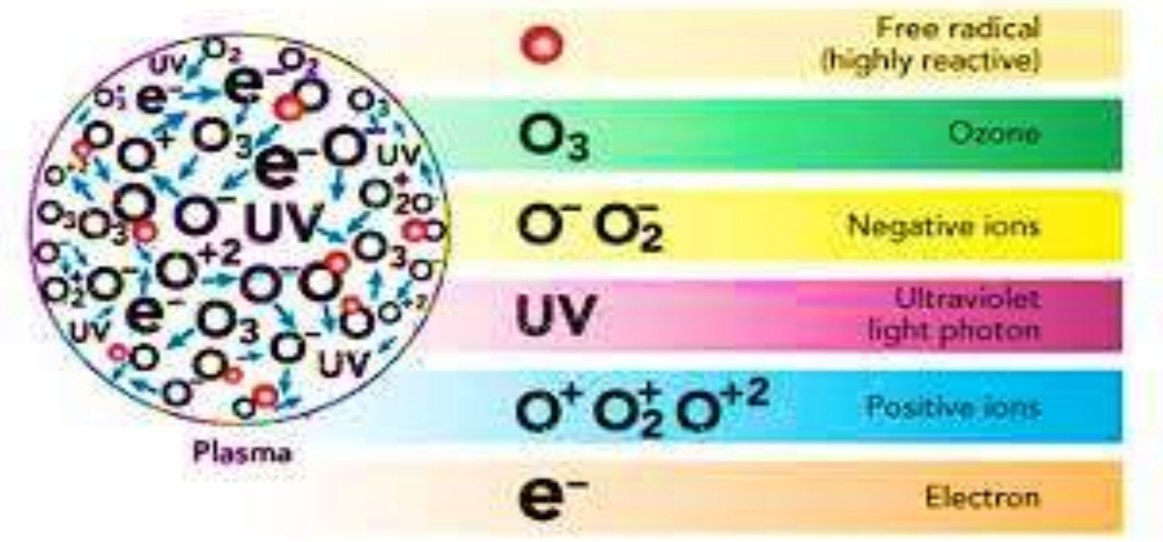
Coulomb interaction between the particles control dynamics.

Leads to collective effects like oscillations, waves, instabilities and self organization.

Most of the matter in the Universe exists as Plasma.

Sun, solar wind, stars, galactic space are all made of plasma.





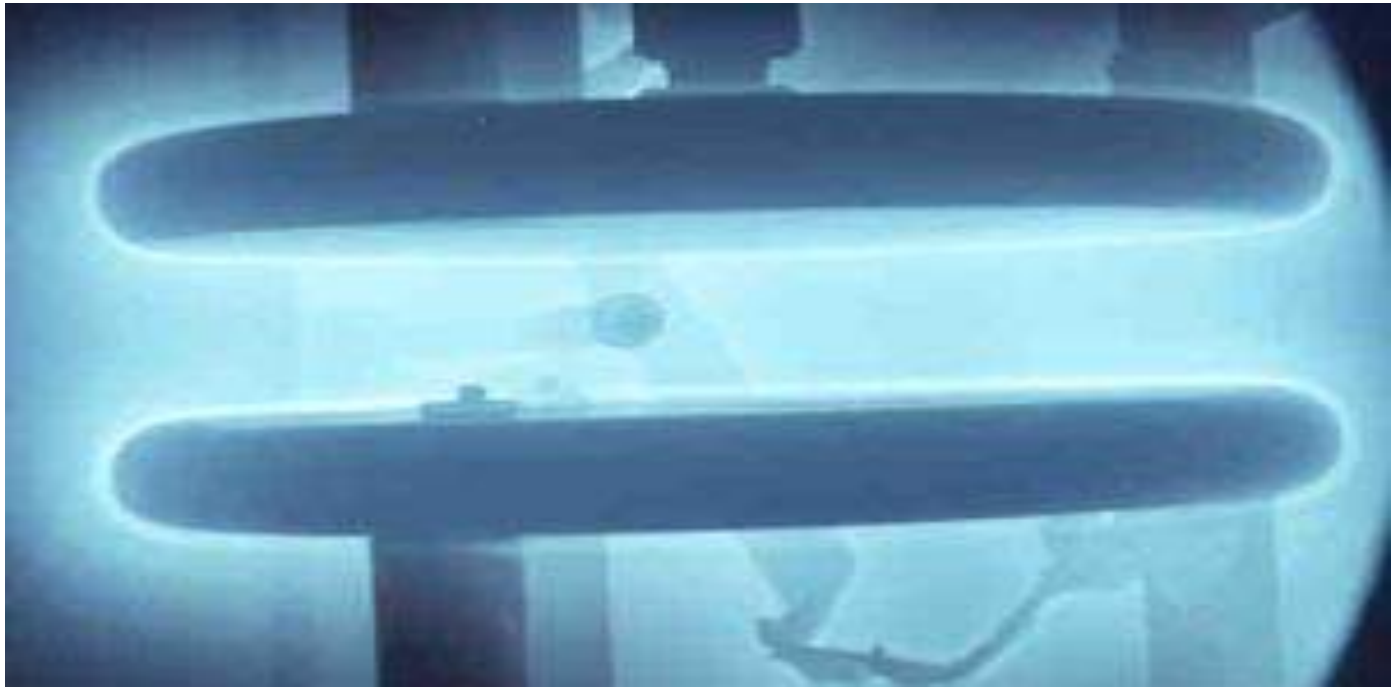
Energetic electrons knock off electrons of an atom and ionize it.

If the gas is situated in an electric field, the product electrons can be accelerated to gain energy and produce more ionization.

Repeated many times, this process leads to conversion of the gas into a plasma.

Energy flows from the electric field to the electrons and through collisions, to ions and neutrals.

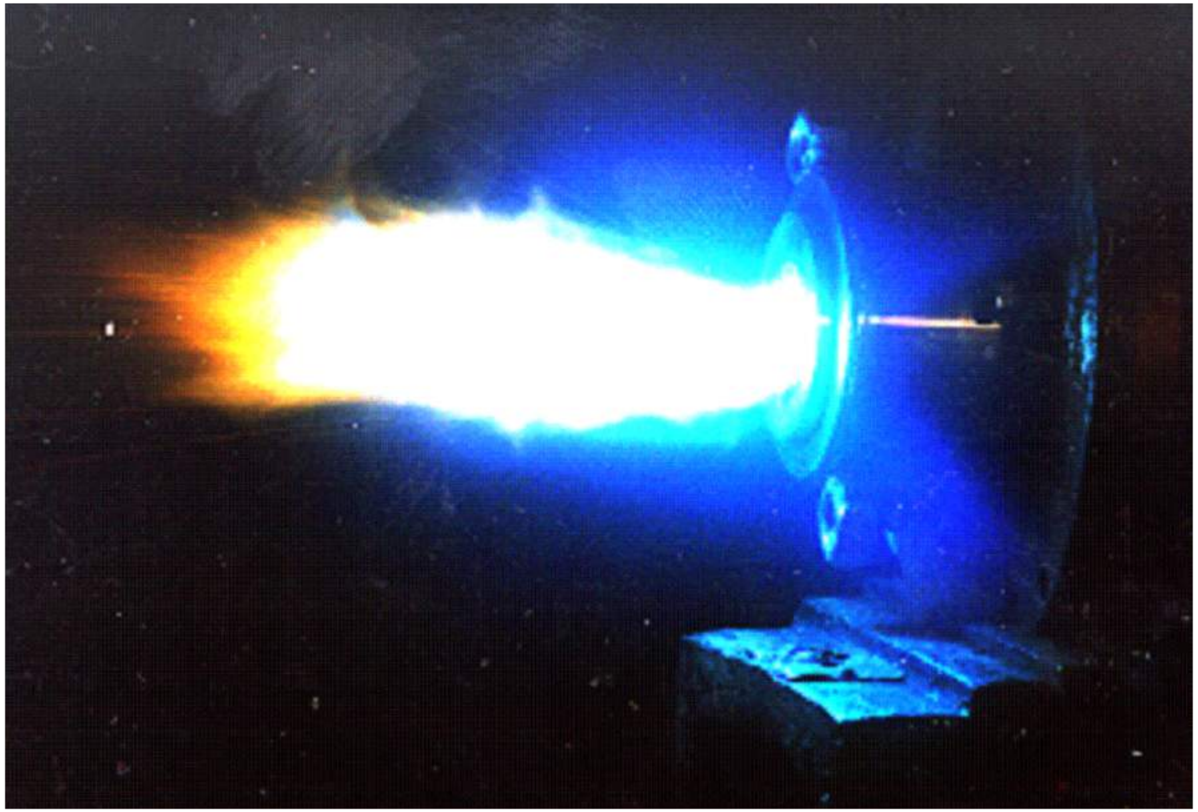
At low pressure, with infrequent collisions, the electrons are hot whereas the ions and neutrals are cold. The plasma is called non-equilibrium or cold plasma.



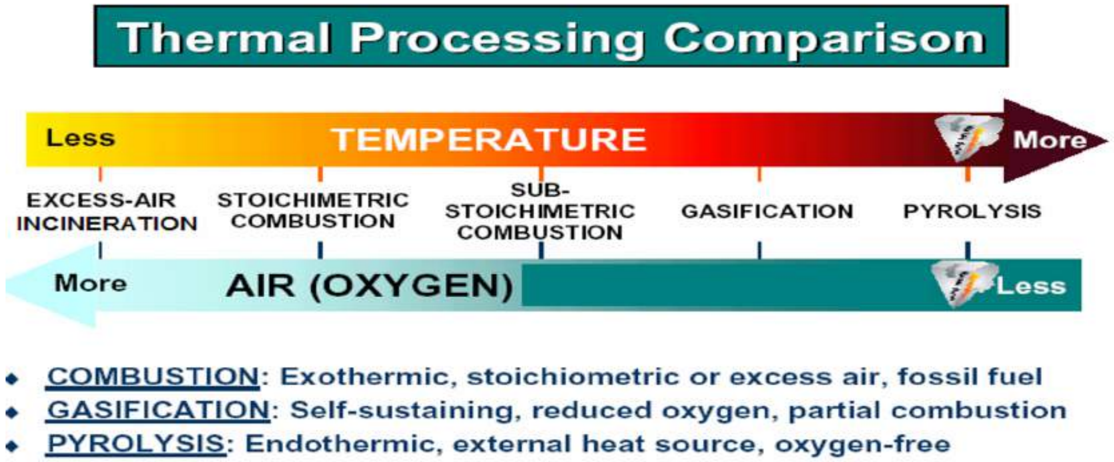
Plasma environment has high chemical reactivity because of the presence of free electrons.

Exotic Chemistry!

At high pressure, electrons and ions thermalize, producing hot plasma with temperatures of the order of 20,000 Deg K



PLASMA TORCH



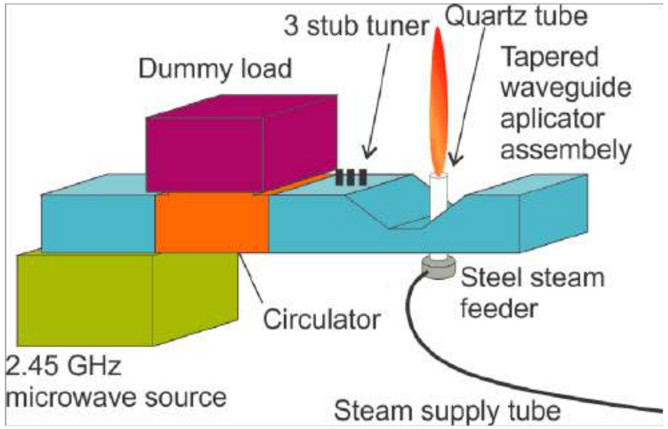
Heat causes organic material to disintegrate forming fragments promoted by the high chemical reactivity of the plasma environment. Most likely products are H, CH_4, C_2H_6, CO etc. 10% remain as Char/Ash

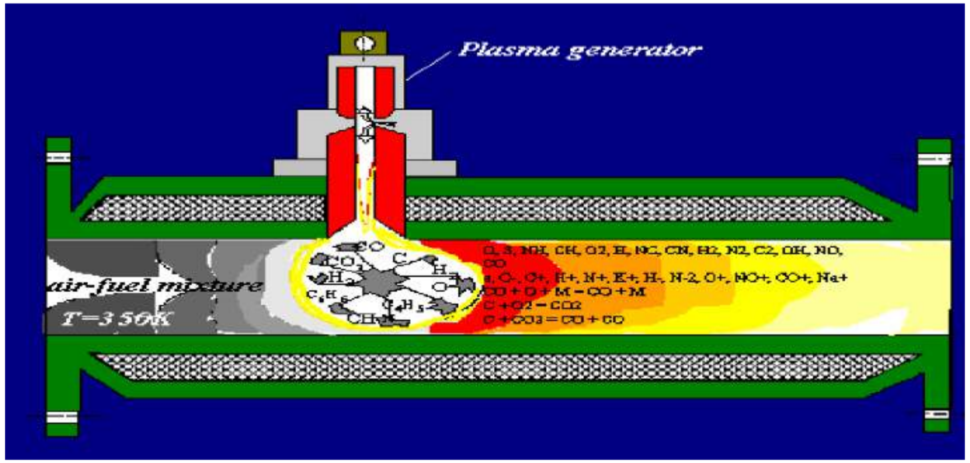
PLASMA TECHNOLOGIES FOR FUEL DECARBONIZATION

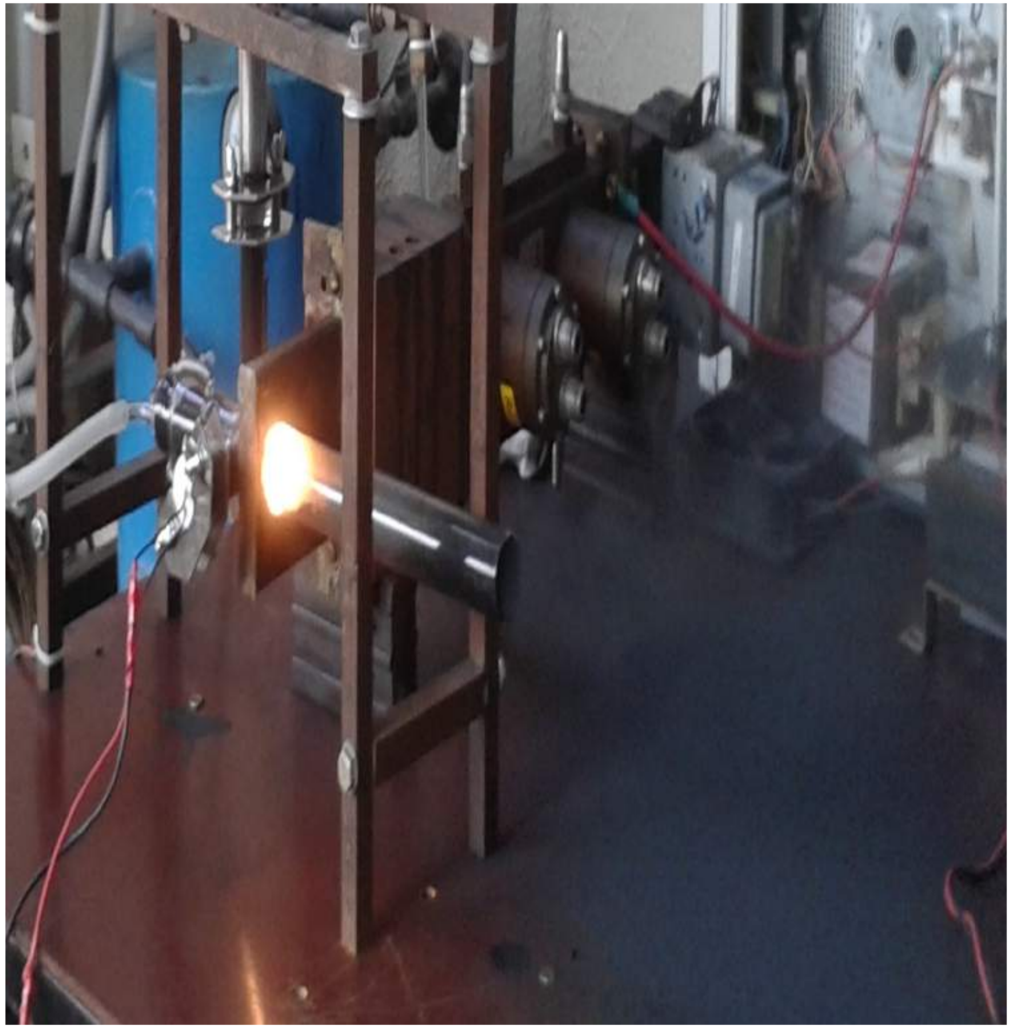
GASIFICATION

50-100 micron particles fragment into 5-10 micron particles and are volatalized to produce CO, CO_2, H_2, N_2, CH_4, C_6H_6 etc.

5kW Plasma Coal Gasification activity at FCIPT







PLASMA TECHNOLOGIES FOR FUEL DECARBONIZATION

FUEL REFORMING

Partial Oxidation: $CH_4+0.5O_2=CO+2H_2$ (-35.6 kJ/mol)

Water Gas Shift: $CO+H_2O=CO_2+H_2$ (-41.2)

Methane Oxidation: $CH_4+2O_2=CO_2+2H_2O$ (-802.2)

CO Oxidation: $CO+0.5O_2=CO_2$ (-283)

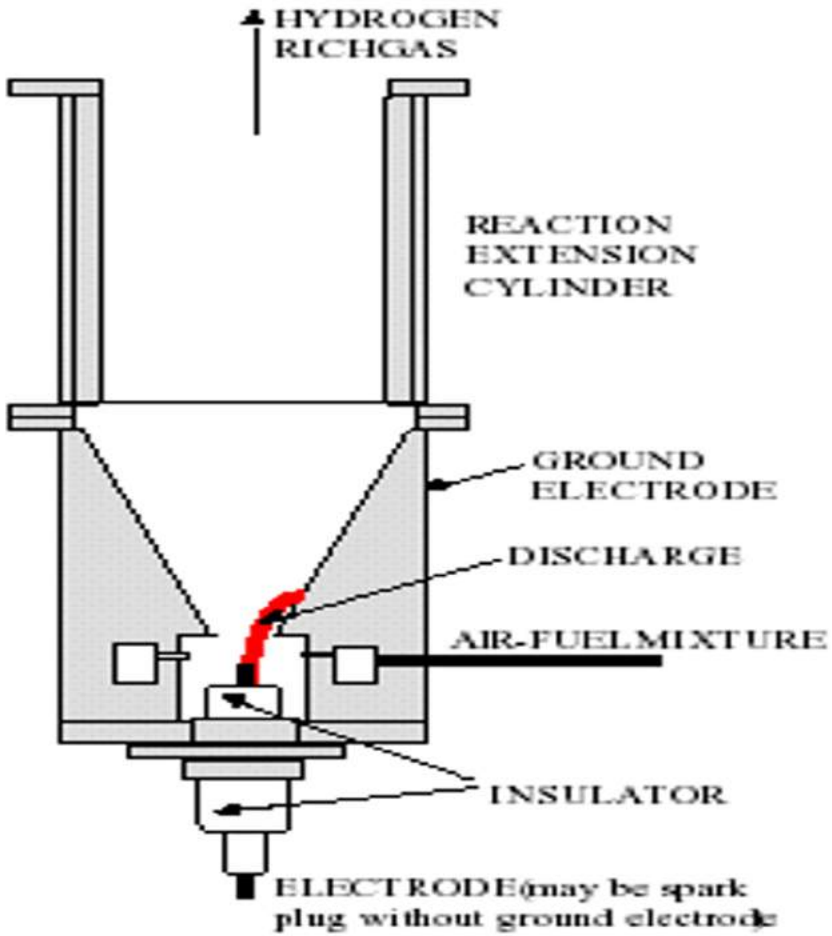
CO Methanation: $CO+3H_2=CH_4+H_2O$ (-206.2)

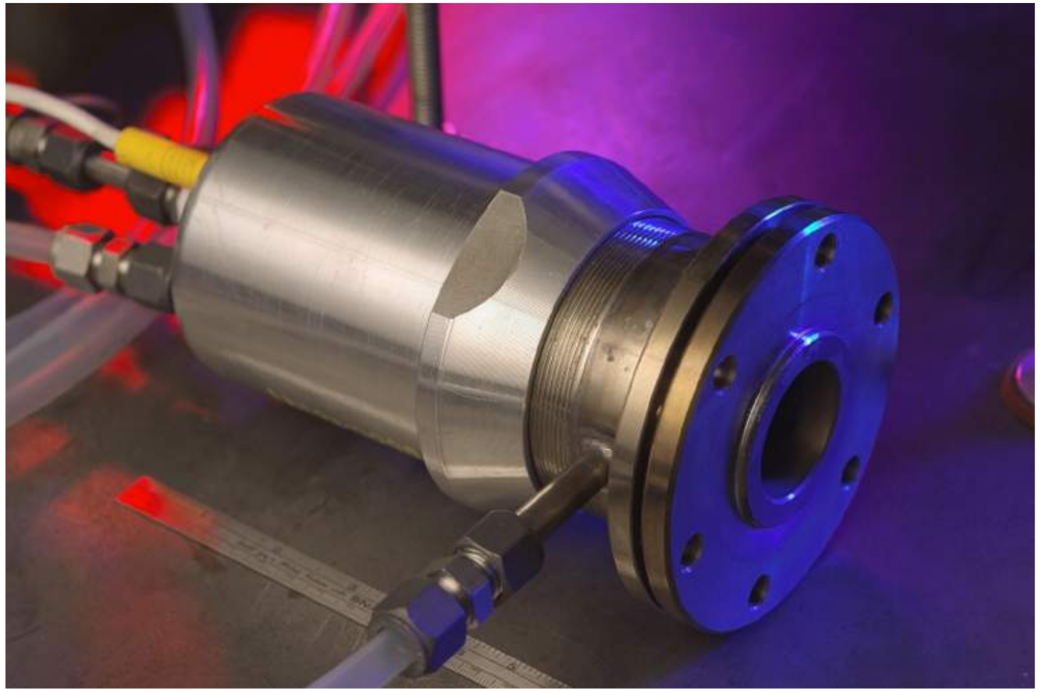
CO2 Methanation: $CO_2+4H_2=CH_4+2H_2O$ (-165)

- Steam Reforming: Convert Methane into H_2
- At high temperature and in the presence of metal based catalyst (Nickel), steam reacts with Methane to yield CO and H_2 through the following reactions:
- $CH_4+H_2O = CO + 3H_2$
- $CO + H_2O = CO_2 + H_2$

- CO_2 must be sequestered

Compact, lightweight, fast, controllable, arc plasma based reformer for onboard fuel reforming can be a viable transportation technology





70% conversion efficiency,
Power 50-300 W
H2 flow rate 30-50 liters/min
Volume 2 liters

Direct Decarbonization

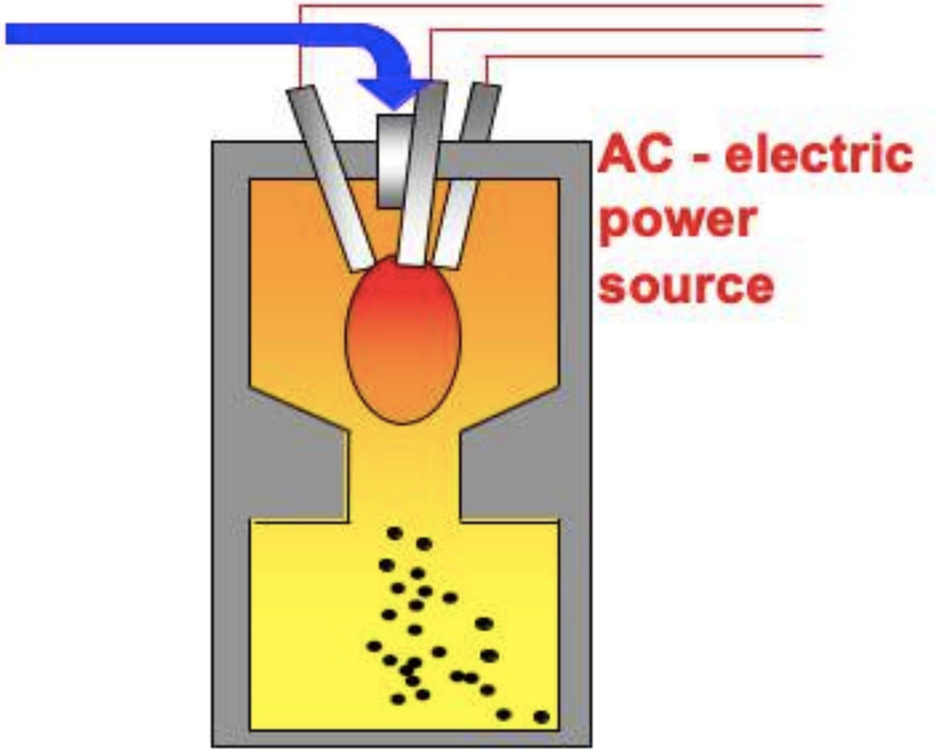
Laurent Fulcheri, Mines - Paris Tech, France

Methane reforming produces 4 tonnes of CO2 per tonne of H2

Alternative, dry process: CH4→ C + 2H2 (75:6kJ/mol)

High temperature (>1200 ◦ C).

Byproduct is valuable carbon black.



Zero direct CO_2

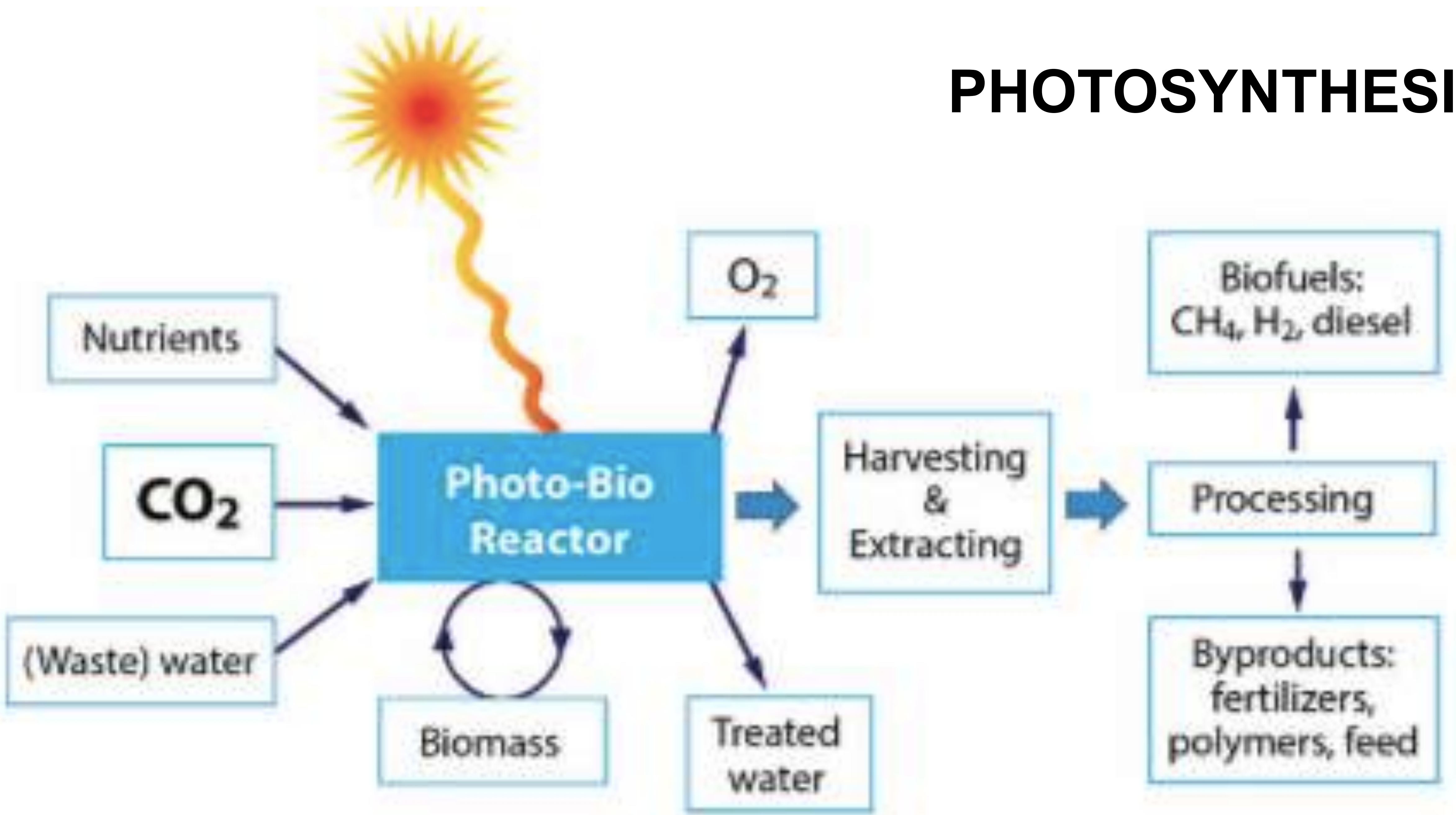
$2/kg Hydrogen DOE objective

OPTION 2

DECARBONIZING THE ATMOSPHERE

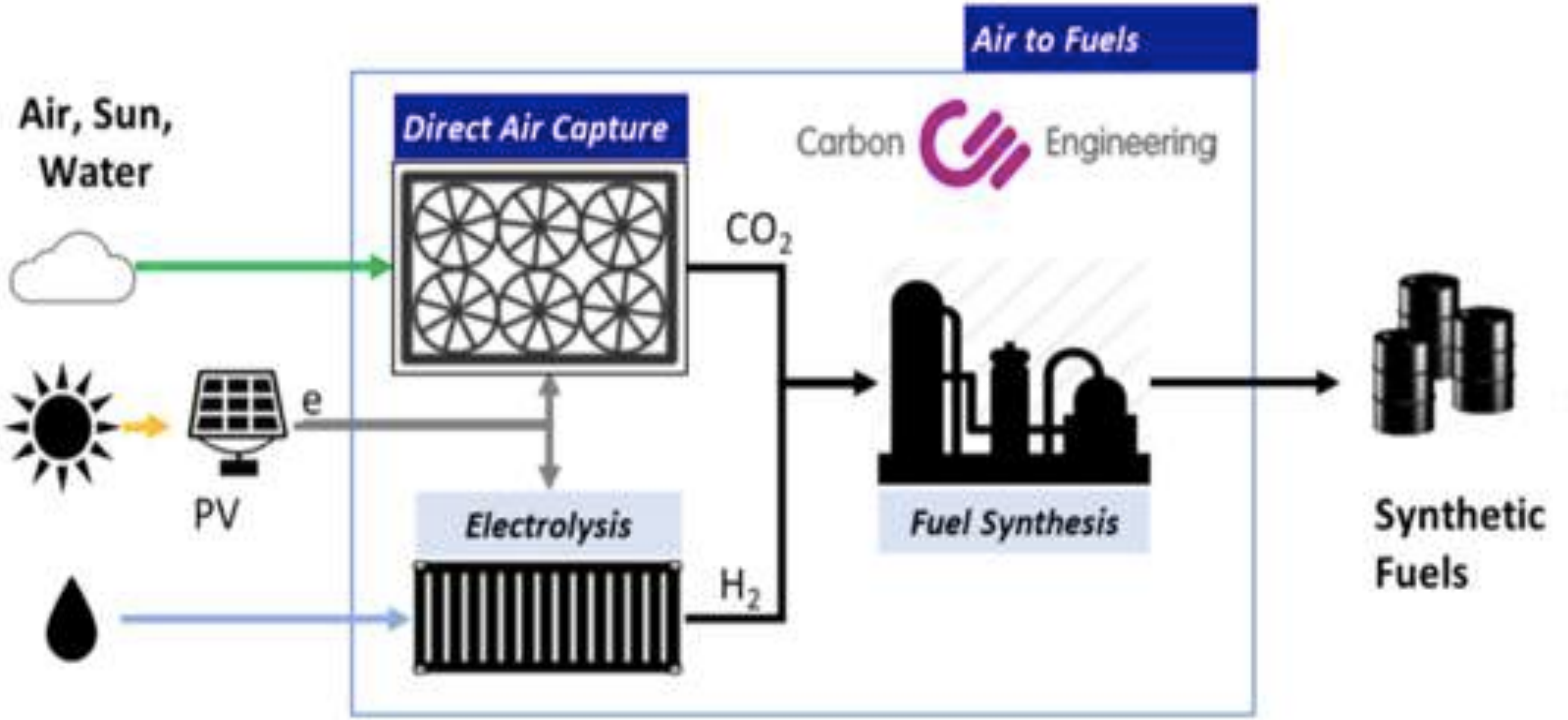
CAN WE REMOVE CO2 FROM THE ATMOSPHERE AND CONVERT IT INTO FUEL?

PHOTOSYNTHESIS



Carbon Engineering

AIR TO FUEL (A2F) PROCESS

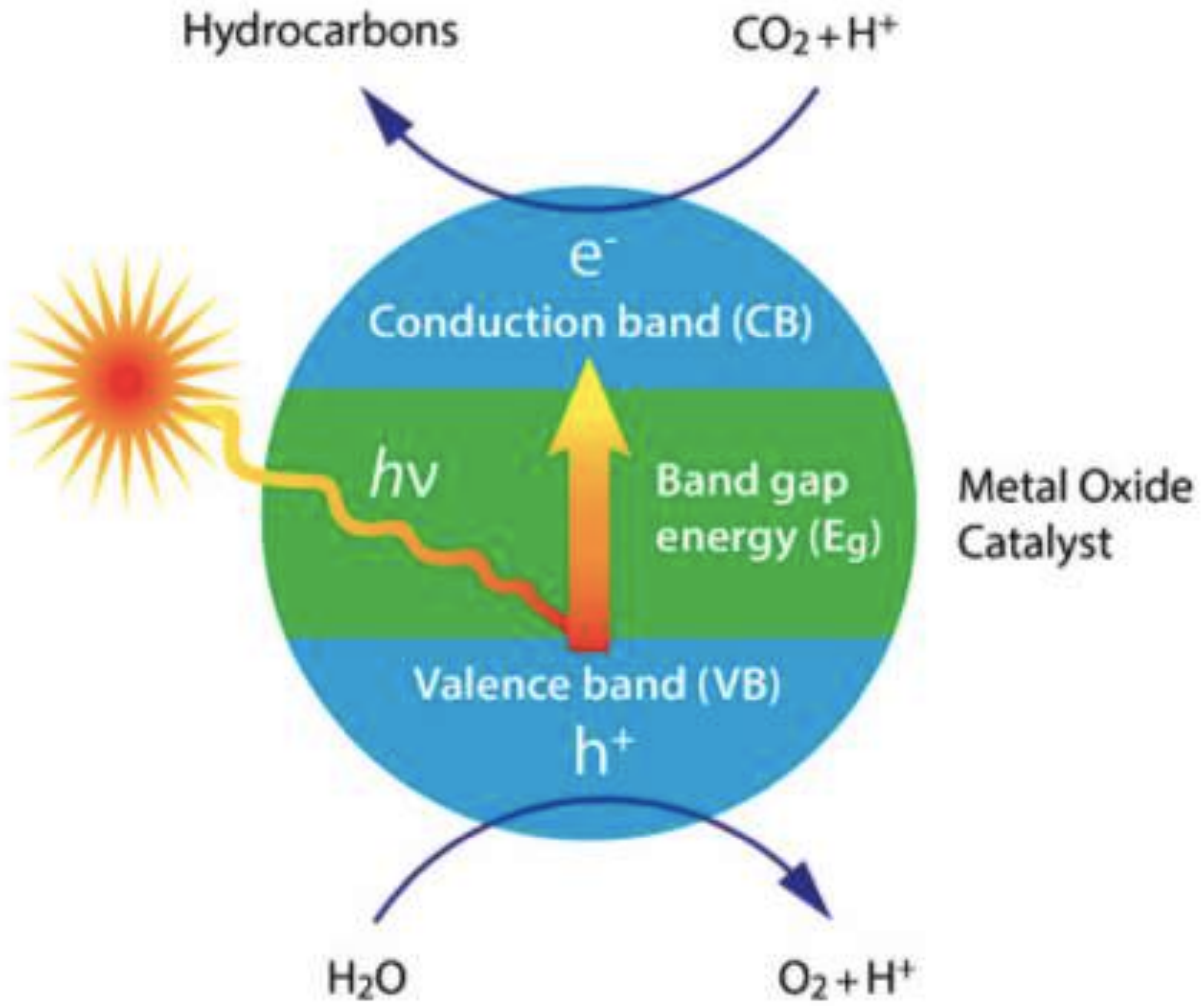


Cost: US$ 94 and $ 232 per tonne.

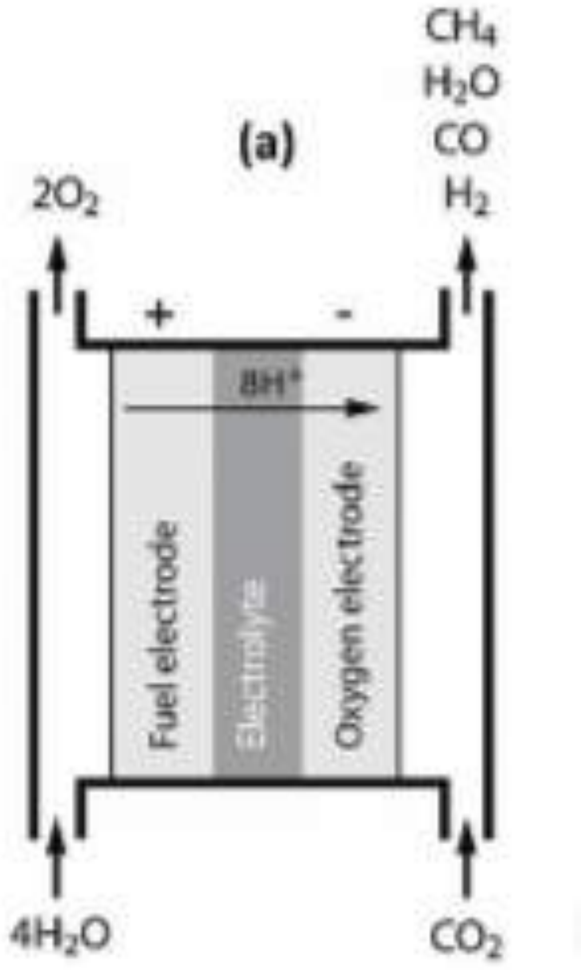
CE has a pilot in Canada since 2015

Source: The Economist Jun 7th 2018

PHOTOCATALYTIC REDUCTION



ELECTROCHEMICAL REDUCTION



	Use of rare earth metals	Renewable energy	Turnkey process	Conversion and yield	Separation step needed	Oxygenated products (e.g. alcohols, acids)	Investment cost	Operating cost	Overall flexibility
Traditional catalysis	Yes	–	No	High	Yes	Yes	Low	High	Low
Catalysis by MW-heating		Indirect						Low	Low
Electro-chemical	Yes	Indirect	No[b]	High	Yes[c]	Yes	Low	Low	Medium
Solar thermo-chemical	Yes	Direct	NA	High	No	No	High	Low	Low
Photo-chemical	Yes	Direct[a]	Yes	Low	Yes	Yes	Low	Low	Low
Biochemical	No	Direct[a]	No	Medium	Yes[d]	Yes	High /low	High	Low

Source: R. Snoeckx and A.Bogaerts, Chem. Soc. Rev., 2017,46, 5805

PLASMA DISSOCIATION OF CO2

WHY PLASMA?

Dutch Institute for Fundamental Energy Research The Netherlands

Institut für Plasmaforschung Universität Stuttgart, Germany

Department of Physics and Astronomy, West Virginia University, USA

Research group PLASMANT, University of Antwerp, Belgium

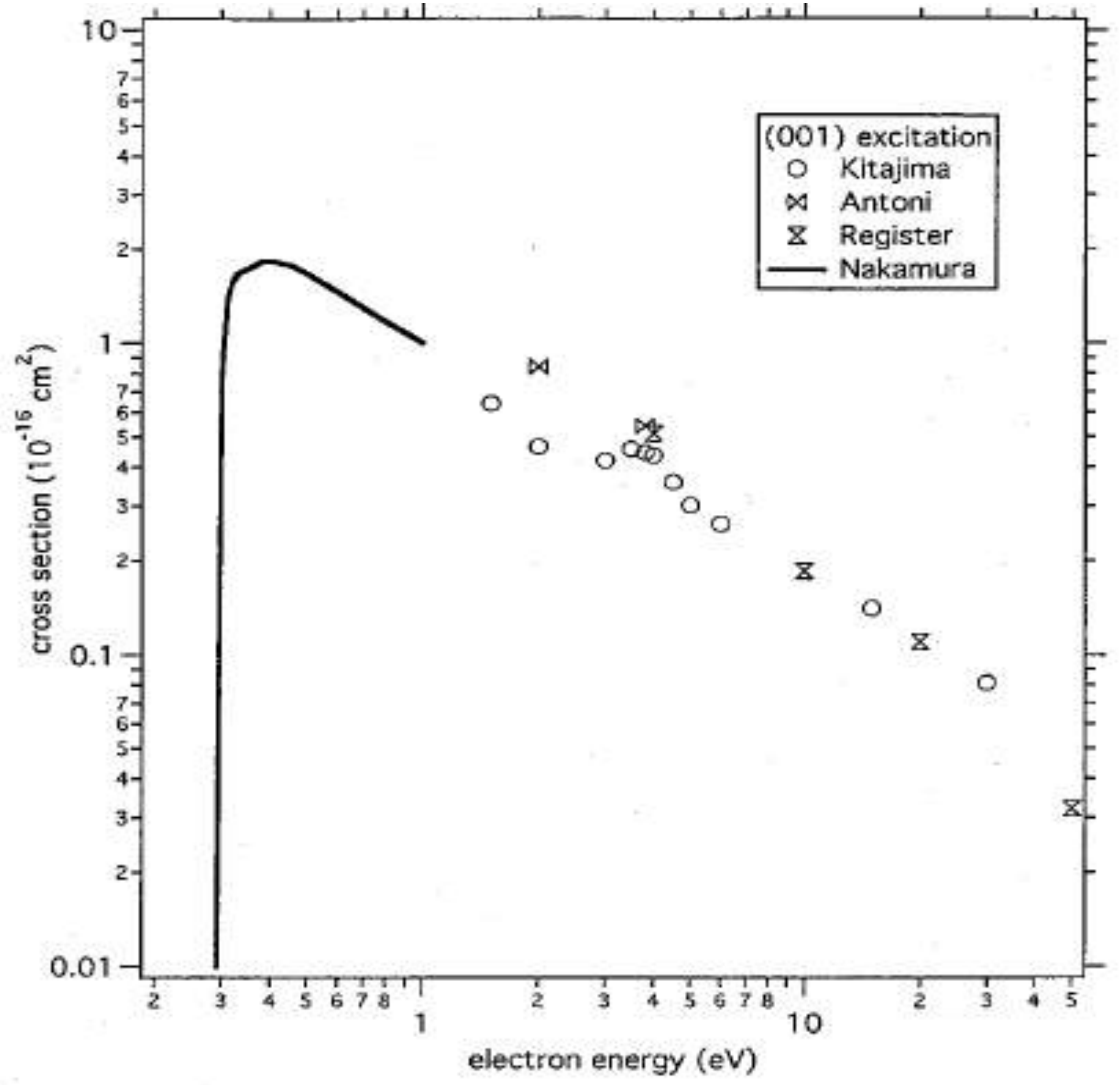
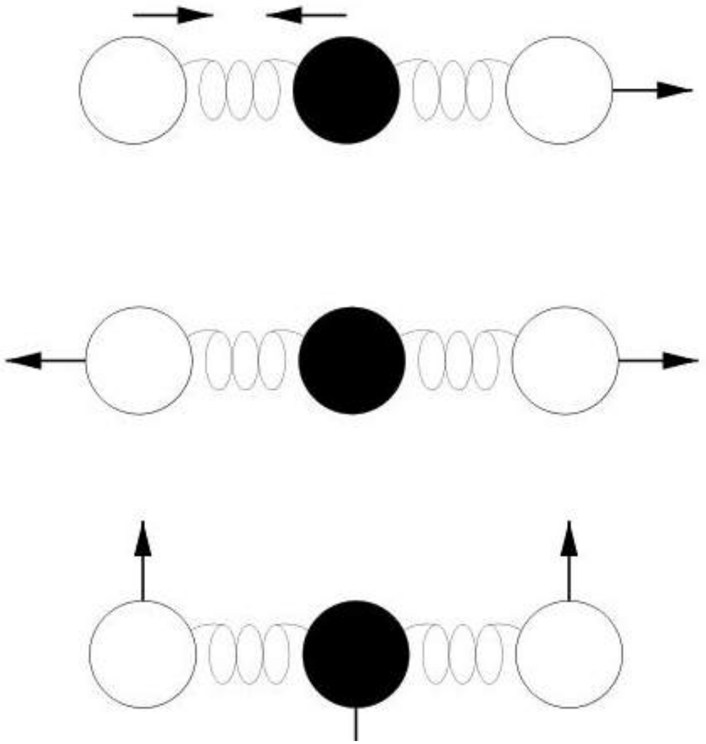
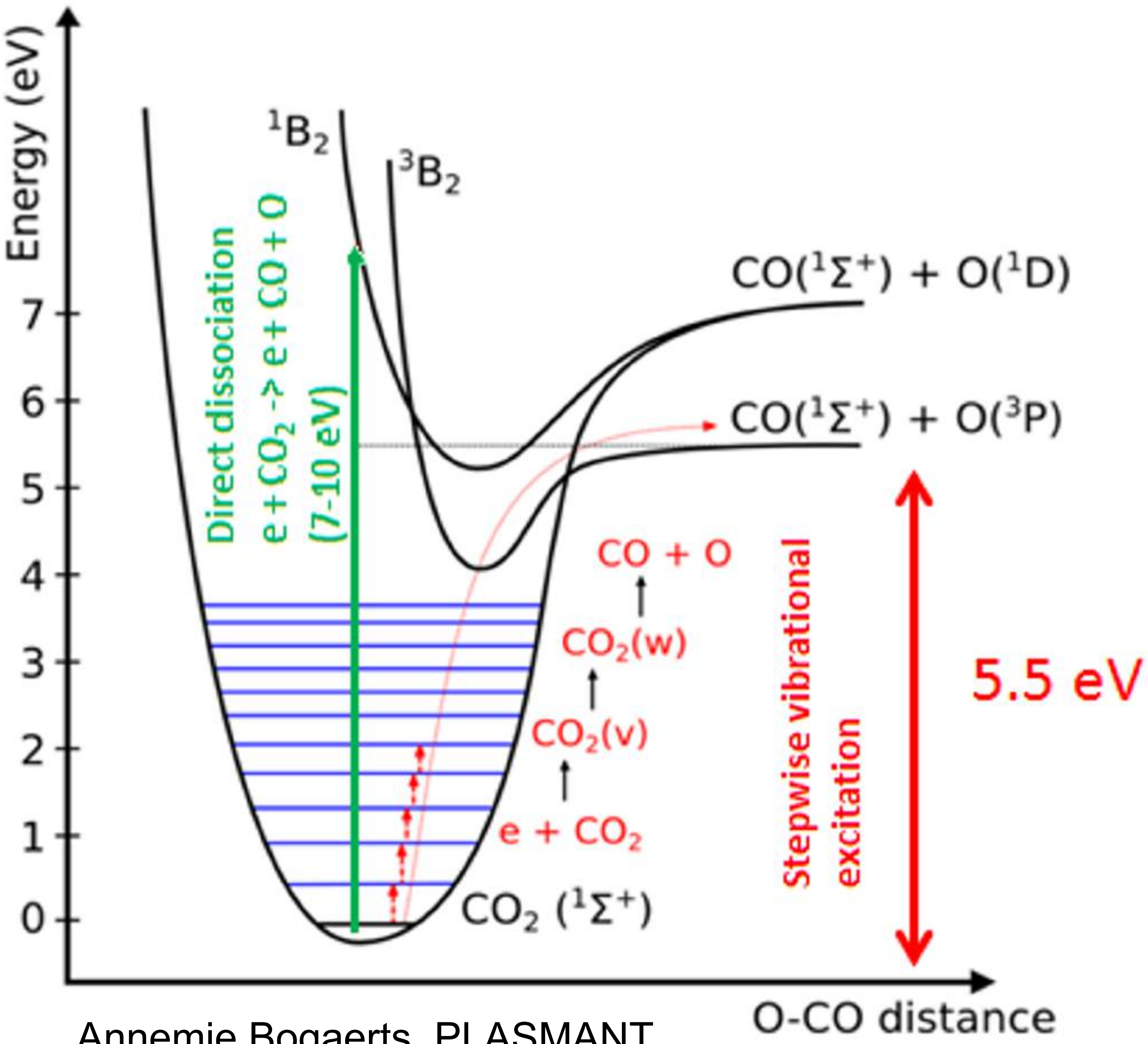


FIG. 7. Cross sections for the electron-impact excitation of the vibrational state (001) of CO_2. Comparison of the beam experiments by Kitajima *et al.*,[32] Antoni *et al.*,[33] and Register *et al.*,[26] and the swarm result of Nakamura[31] is shown.

CO2 DISSOCIATION BY STEPWISE VIBRATIONAL EXCITATION

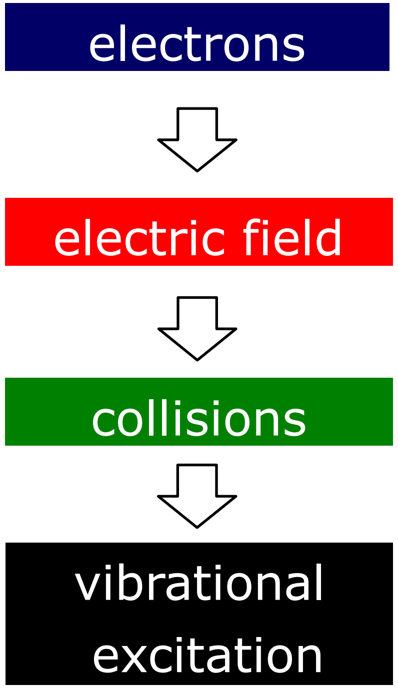
Ladder Climbing

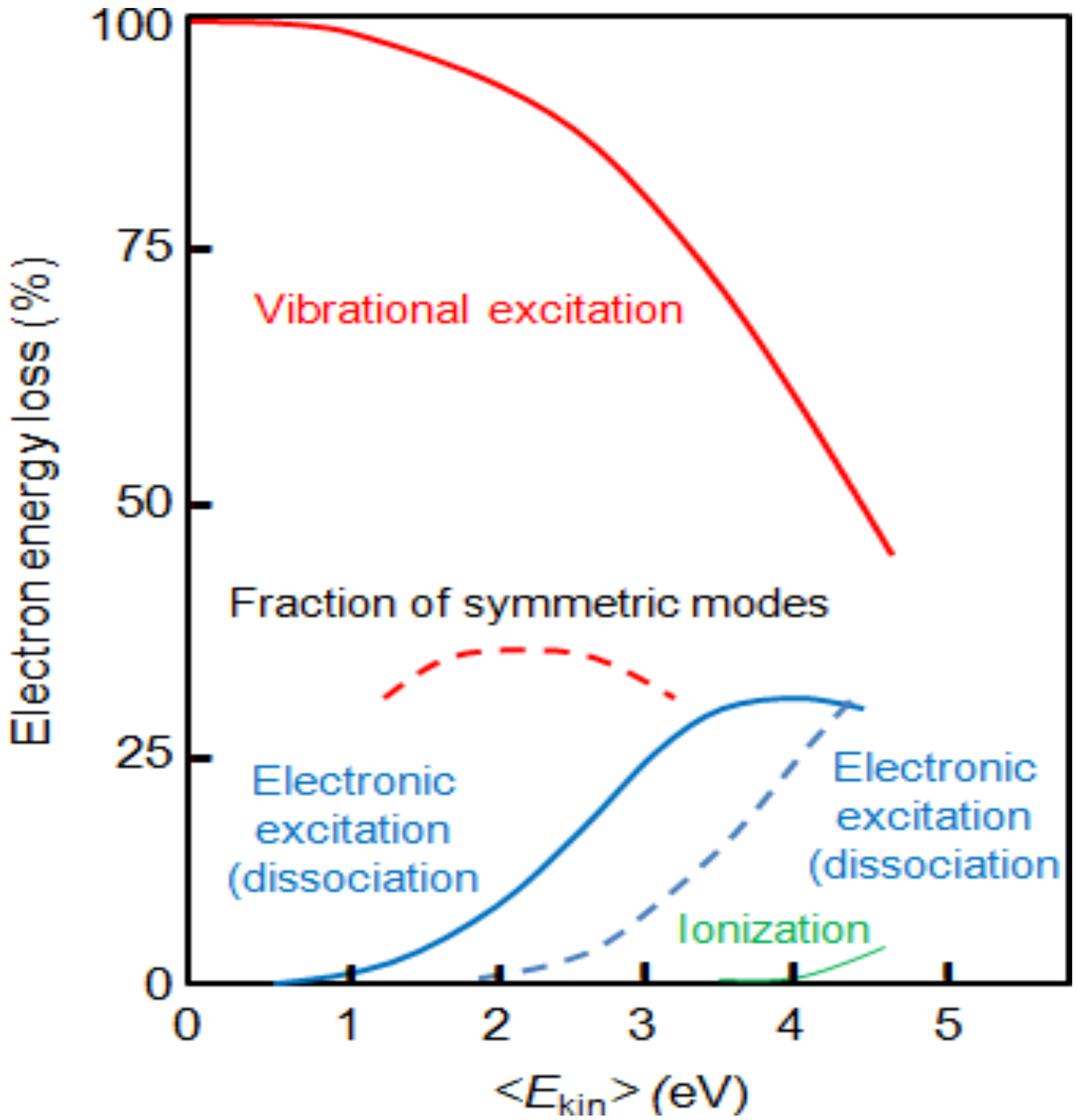




Annemie Bogaerts, PLASMANT, University of Antwerp

Electron energy loss depends on reduced electric field (depends on average electron energy)





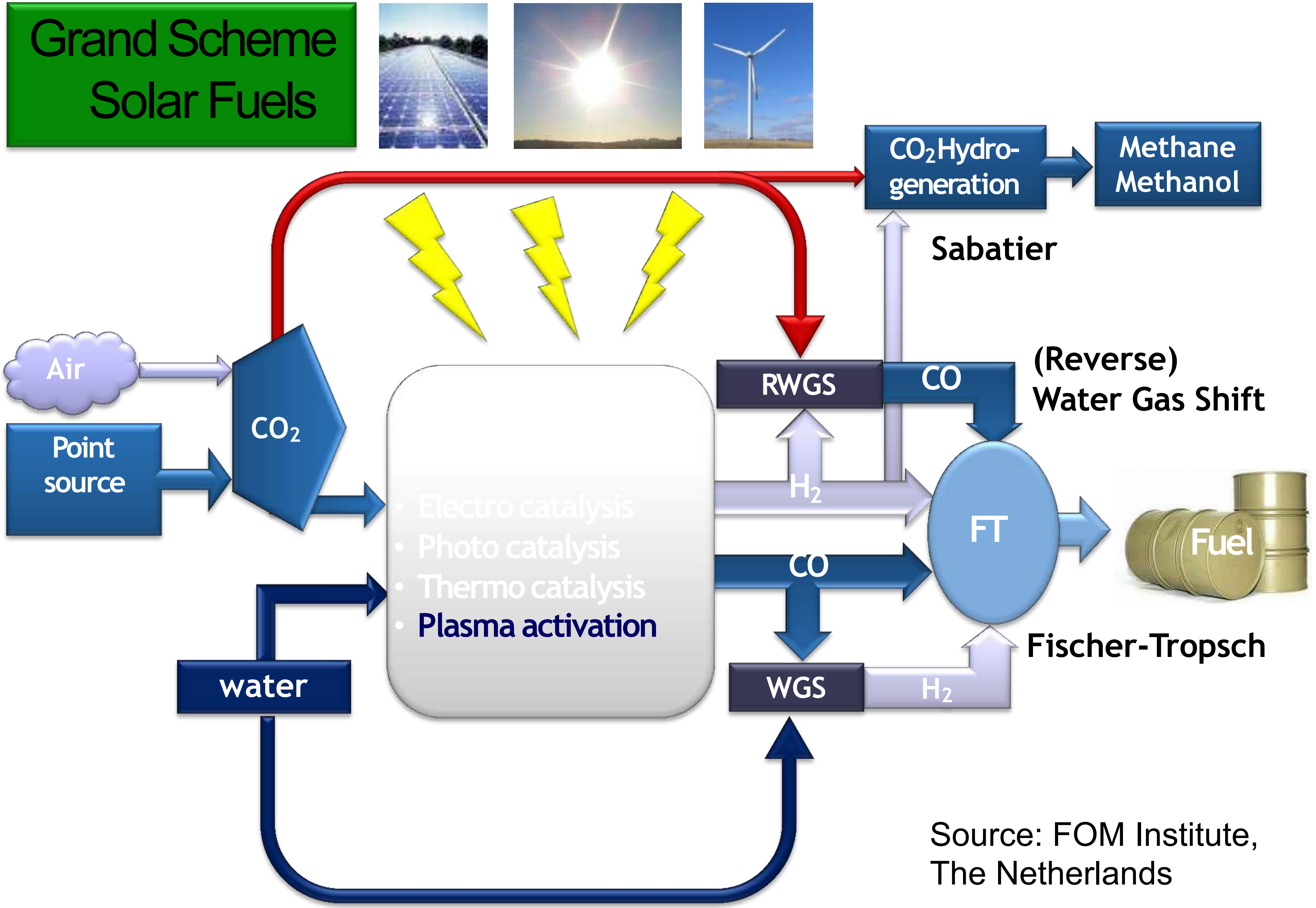
PLASMA DISSOCIATION OF CO2

WHY PLASMA?

- **On demand capability**
- **High energy efficiency (~60% demonstrated)**
- **High power density (45W/cm^3)**
- **Rapid ramping up and down (wrt high temperature SOEC)**
- **No scarce materials employed (Pt catalyst in PEM)**

	Use of rare earth metals	Renewable energy	Turnkey process	Conversion and yield	Separation step needed	Oxygenated products (e.g. alcohols, acids)	Investment cost	Operating cost	Overall flexibility
Traditional catalysis	Yes	--	No	High	Yes	Yes	Low	High	Low
Catalysis by MW-heating	Yes	Indirect	No	High	Yes	Yes	Low	Low	Low
Electro-chemical	Yes	Indirect	No[b]	High	Yes[c]	Yes	Low	Low	Medium
Solar thermo-chemical	Yes	Direct	NA	High	No	No	High	Low	Low
Photo-chemical	Yes	Direct[a]	Yes	Low	Yes	Yes	Low	Low	Low
Biochemical	No	Direct[a]	No	Medium	Yes[d]	Yes	High /low	High	Low
Plasma-chemical	No	Indirect	Yes	High	Yes[e]	Yes	Low	Low	High

Source: R. Snoeckx and A.Bogaerts, Chem. Soc. Rev., 2017,46, 5805



Source: FOM Institute,
The Netherlands

This monograph explores the pervasive role of plasma in some areas related to energy and environment. Plasma processing exploits the fact that plasmas occupy an extremely extended parameter space in density, temperature or chemical reactivity. Density can vary over 30 orders while temperature can vary over 10. Relevant time scales can vary from seconds to picoseconds. Plasmas can provide temperatures and energy densities higher than any other medium. High levels of transient and non-equilibrium conditions can prevail in plasmas. Certain plasmas can have short density and temperature scale lengths enabling fast quenching of chemical products. Plasma processing plays an important role in the realisation of modern photovoltaic devices used for converting solar energy into electricity. Atmospheric contamination from industrial and vehicular emissions is ameliorated through plasma mediated processes. The negative impact of waste in environmental degradation is reduced through plasma processes for waste to energy conversion. Hydrocarbon fuels are made carbon-lean and environmentally less damaging.

Prof. John Pucadyil served as Senior Professor and had occupied the Meghnad Saha Chair in Plasma Science and Technology at the Institute for Plasma Research in India. He has contributed significantly to the nucleation and growth of Plasma Physics and Industrial Plasma Applications in India. He lives in Kottayam, Kerala.

978-3-659-94524-3

Plasma Processes for Environment

Pucadyil

John Pucadyil

Plasma Processes for Energy and Environment

The Pervasive Role of Plasma Processing in Technologies for Clean Energy and Environment.

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