DIFFER
Dutch Institute for
Fundamental Energy Research

CO_2-Neutral Fuels

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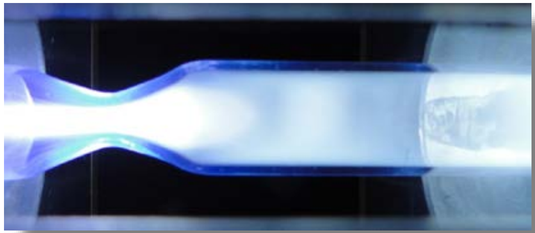
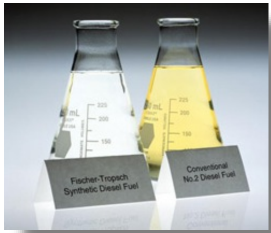
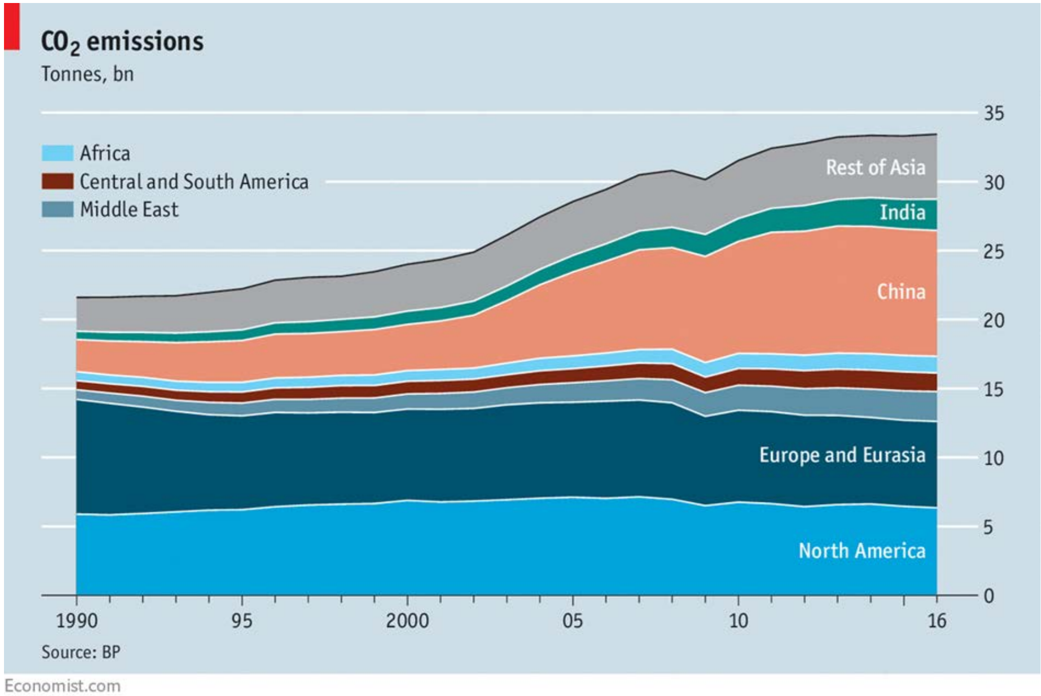
EERA
European Energy Research Alliance

Kopernikus-P2X





Driver of the Energy Transition
CO_2 Emission Reduction



- Global CO_2 emissions from energy use roughly flat in 2016 (source BP)
- Year-on-year increase of 0.1% is well below 10-year average 1.6%
- Improved energy efficiency and slowing global economy partly responsible

- China world's largest CO_2 emitter, but emissions fell by 41m tonnes in 2016
- India's 2016 CO_2 emissions increased by 114m tonnes
- In 2016 the Asia-Pacific region produced half of global CO_2 emissions, up from 25% in 1990

Source: Economist, Jun 17th 2017

Global CO_2 emission: EU 10.5 %, NL 0.5 %

NL CO_2 emission budget

- Power and Lightning (electricity) 26%
- Low temperature heat (domestic) 18%
- High temperature heat (industry) 19%
- Transport (cars, ships, planes) 17%
- Non-energy emissions (agriculture, waste, feedstock) 20%

typically 20:20:20:20:20

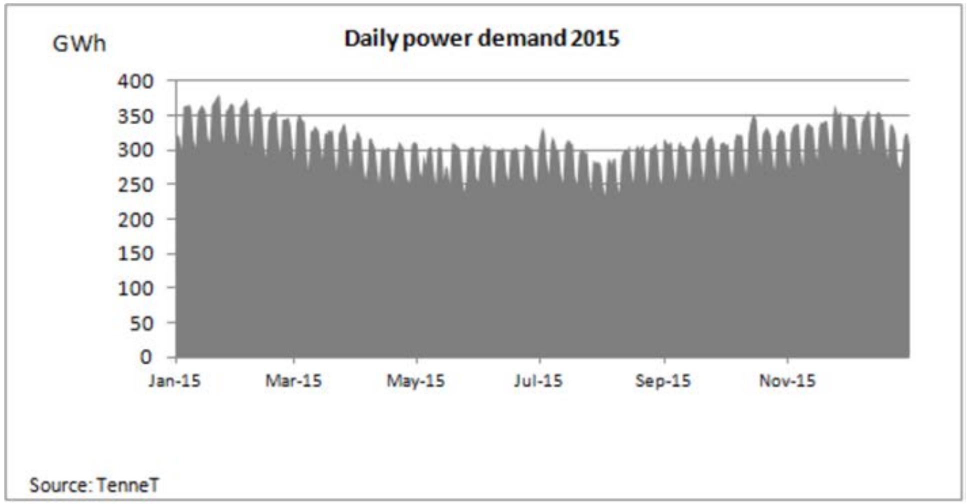
2050 CO_2 emission reduction targets

2050 UNFCCC agreement and EU Directives:

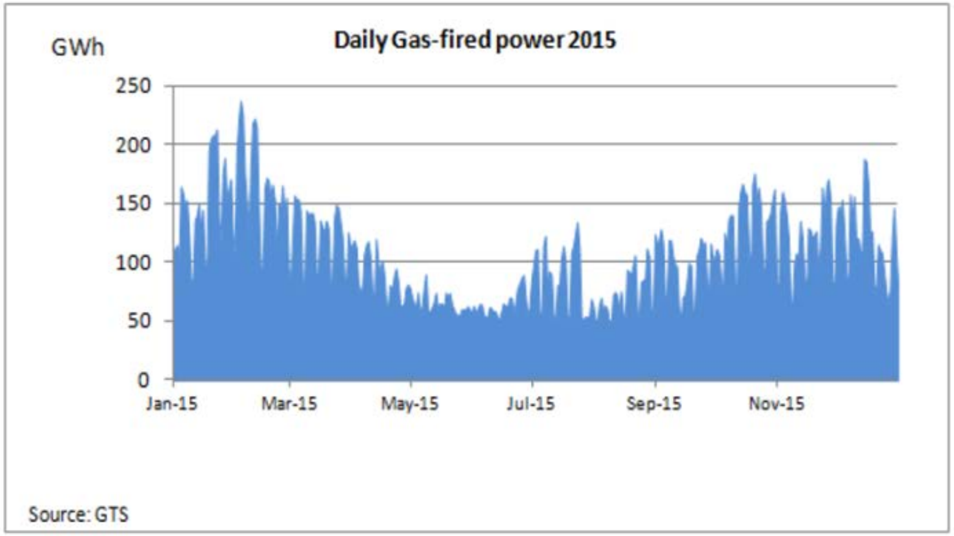
- CO_2 emission 80% to 95% below 1990 level
- Transportation: 60% CO_2 emission reduction
- Aviation: 40% sustainable fuel by 2050
- UN-ICAO: emissions 50% below 2005 level

Transportation sector: challenge to meet CO_2 reduction target, aviation being case in point

Energy Demand: The Netherlands (2015)

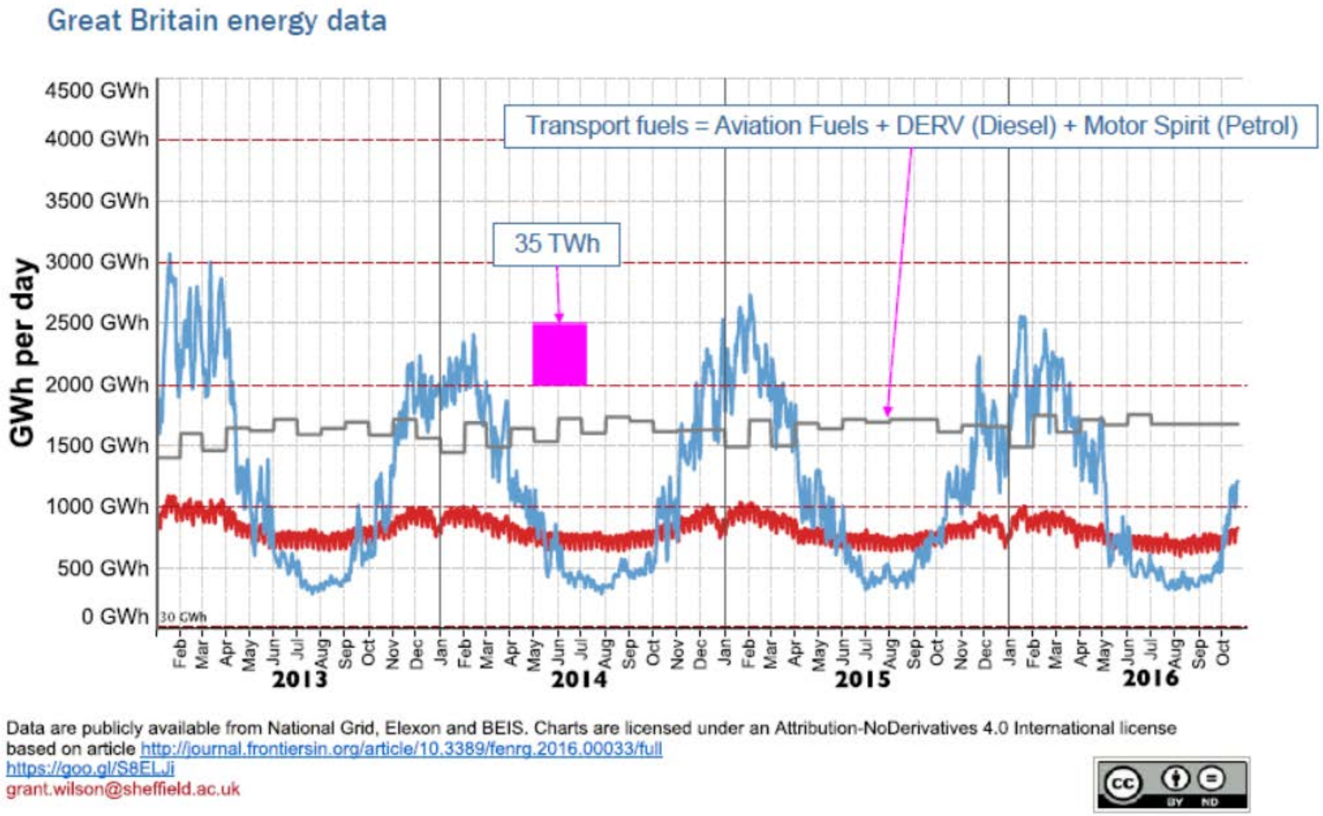


Electricity demand almost flat throughout the year ± 10% [GWh/day]



Gas demand (mainly heat): seasonal variation factor 4 [GWh/day]

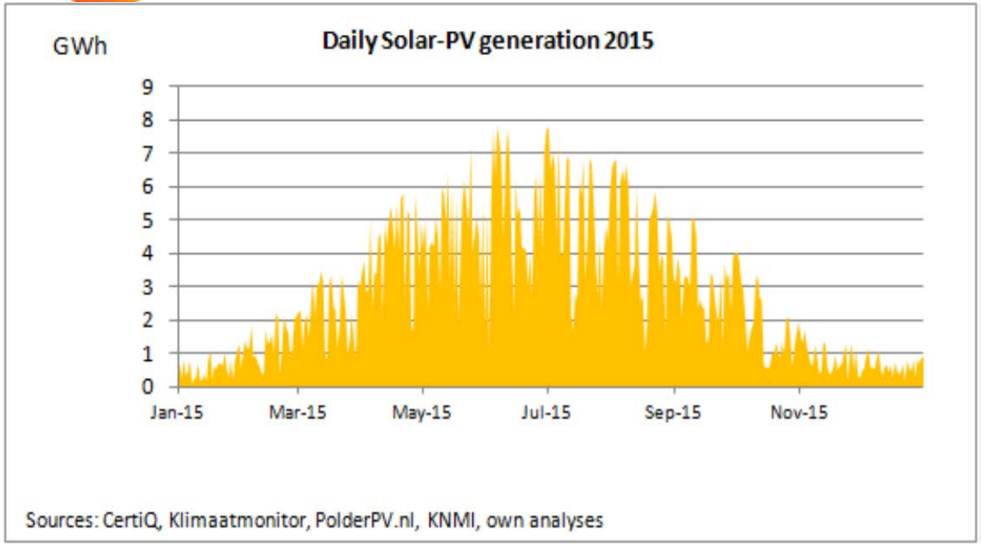
UK energy demand: Electricity, Gas and Transportation

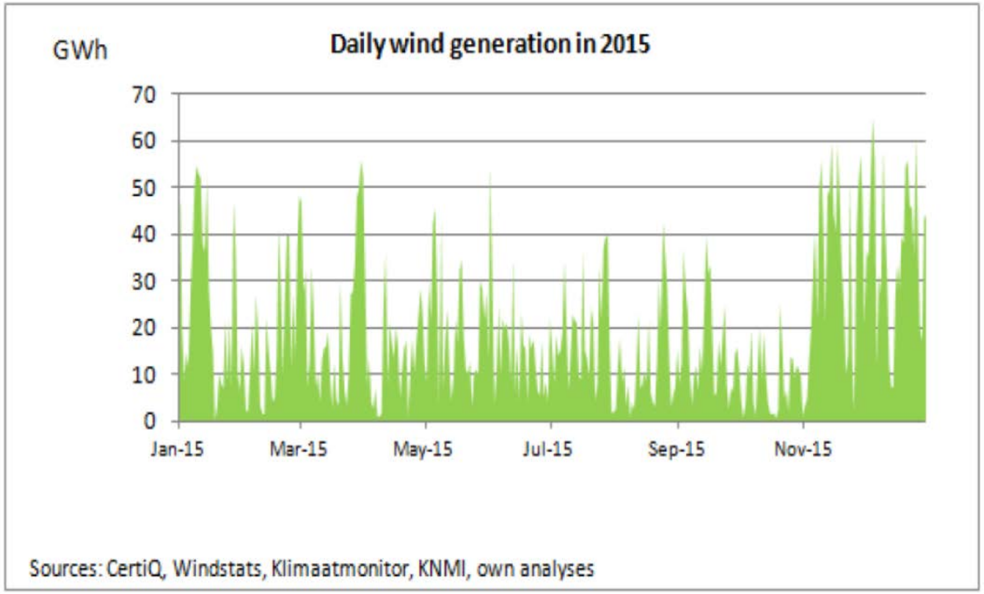


Seasonal and inter annual energy demand UK

- Transport: approx. flat over the year
- Electricity: ± 10% seasonal variation
- Gas: factor 5 seasonal variation and 2x electricity demand

Supply of Renewable Electricity - NL 2015





Sun: out of phase with seasonal heat demand at N-EU latitude
Winter insolation 10% of summer

In phase with diurnal demand, but not quantitatively: surplus during day, shortage at night

Wind: seasonal variation factor 2 to 3 in phase with heat demand but not quantitatively.
intermittent, with large dynamic range (factor 100)

Mix sun and wind 75%-25% projected by IEA not optimal

Figures in GWh/day

Projected Surplus Renewable Electricity

Current renewable energy scenarios rely on PV and Wind electricity
This leads to surplus electricity, whilst back-up power is still required

Netherlands
- 2025: 1.5TWh (12GW wind)
- 2050: 30-55TWh

Germany
- 2035: 34.5 TWh
- 2050: 110-148 TWh

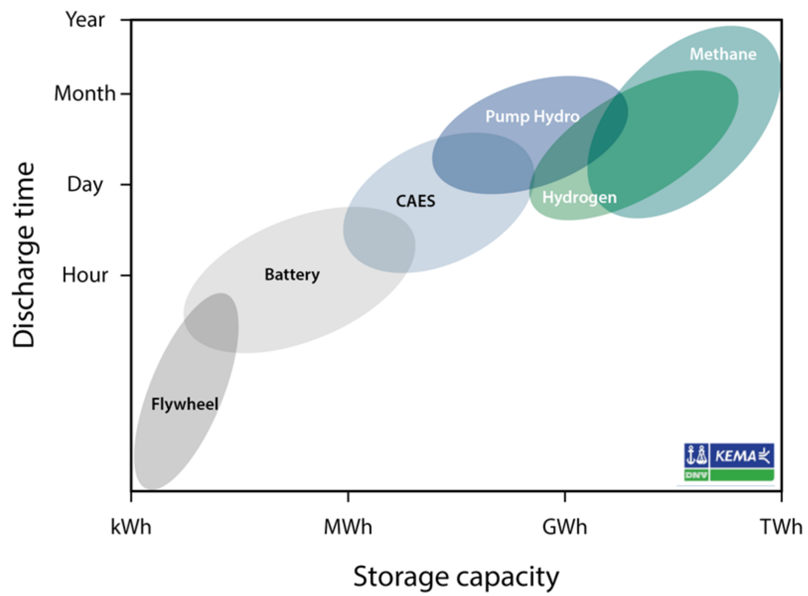
France
- 2030: 15 TWh
- 2050: 44-91 TWh

Need for large scale electricity storage on time scales ranging from msec to inter-annual in order to match renewable electricity supply with demand

Energy Supply by Renewables

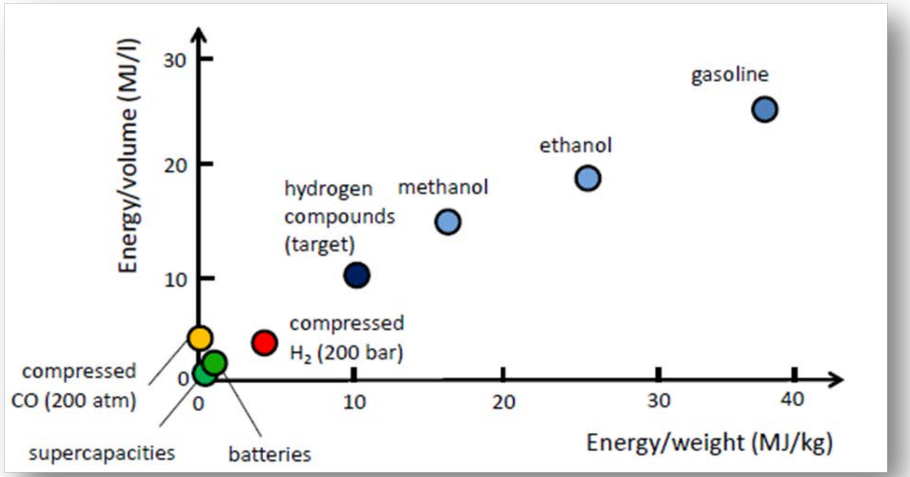
Two concepts:

- **Direct conversion** Solar photons into Fuel (Artificial Photosynthesis). Early days.
- **Indirect conversion** solar to electricity (PV, wind, waves, rivers). Followed by Electricity to Fuel = **Power to X**
- This P2X scheme is more advanced compared with AP
- As electricity makes up only 20% of demand, conversion into other energy sectors is needed: **Sector Coupling**
- Difficult to meet heat demand by renewable electricity: Capacity of the grid to be increased 3 to 5 times. Electricity transport is costly compared with gas (factor 20-40), whilst running idle half of time
- Difficult to meet transportation demand by electricity. Urban transport feasible, but long haul transportation probably not.



Energy Storage Capacity and discharge power

Chemical Energy Storage
Energy density and
Specific energy high



Sustainable Aviation Fuel - Hydrogen

Hydrogen low volumetric energy density: 3000 below **kerosene** limits storage, transport and usage as a fuel

- liquefied at 20K still factor 3.7 lower energy density,
- pressurised at 700 bar factor 6.4 lower energy density
- Safety aspects: highly flammable
- LH2 Aircraft gas turbine redesign/qualification to operate cryogenic fuel
- New fuel system, new ground handling and storage (boil-off).
- Fuel to be stored in fuselage rather than wings, because of volume and heat transfer.
- Increased drag and fuel consumption
- Reduced lift-off weight

DLR H2 Antares
Hydrogen Fuel Cell powered
one seater glider
36 kW PEM Fuel Cell @ 80 kg
10 kWh battery 45-60kW @ 50kg

Sustainable Aviation fuel - Batteries

Batteries good for Urban transport, no air pollution, no noise, future self-driving/ride sharing/big-data also electricity dependent

Long Haul Transportation: Energy density most advanced Li-ion battery is factor 14 lower than kerosene, by weight factor 50 lower
Battery powered airbus 380 needs 14.000 ton battery, instead of 260 ton kerosene > It will never take off
Long haul road transport, shipping and aviation are unlikely to be powered by electricity or hydrogen in the 2050 time frame

Current EU Policy directed at **bio fuel**. However, biofuels do not meet sustainability and resource requirements set by projected 2050 global fuel demand. Example: 5 m barrels kerosene per day for jet fuel alone.
Social Acceptance problem: Fuel vs. Food vs. Flora trilemma

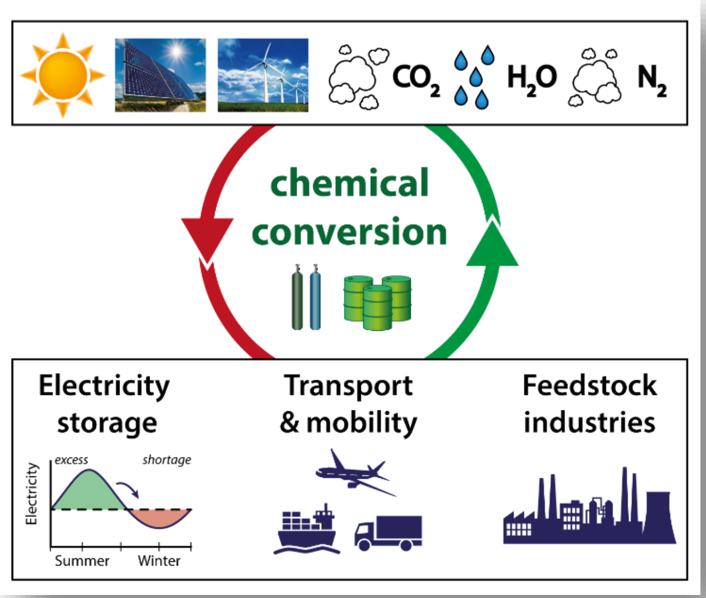
CO_2 Neutral fuels

CO_2 Neutral Fuels offer an Alternative Sustainable Fuel
Characterised by high energy density and existing infrastructure for Energy Storage, transport and distribution

Hydrocarbons synthesised from water and air

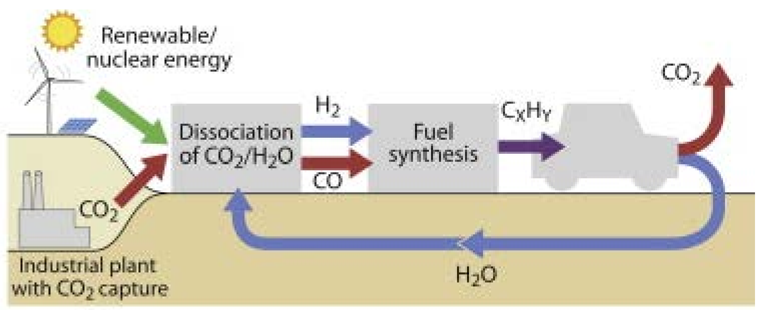
- powered by Renewable Electricity
- CO_2 recirculation after use

Power2X connects sectors: electricity to gas, to oil and to chemical sector.
Solves surplus, storage and transport by electricity



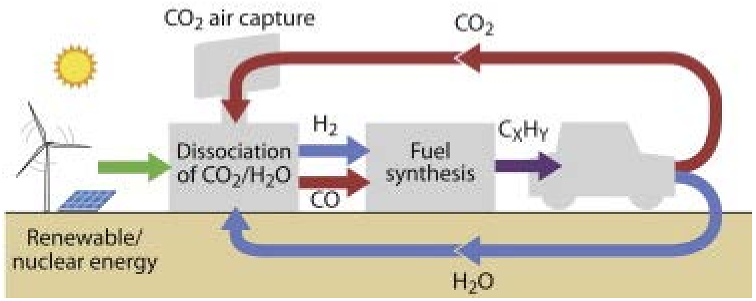
Carbon neutral fuel cycle: P2X – CCU

Point source capture of fossil CO_2
→ not climate neutral, emission delayed



Power-to-X
X = gas or liquid fuel or chemicals

Direct air capture of CO_2
→ climate neutral fuel cycle



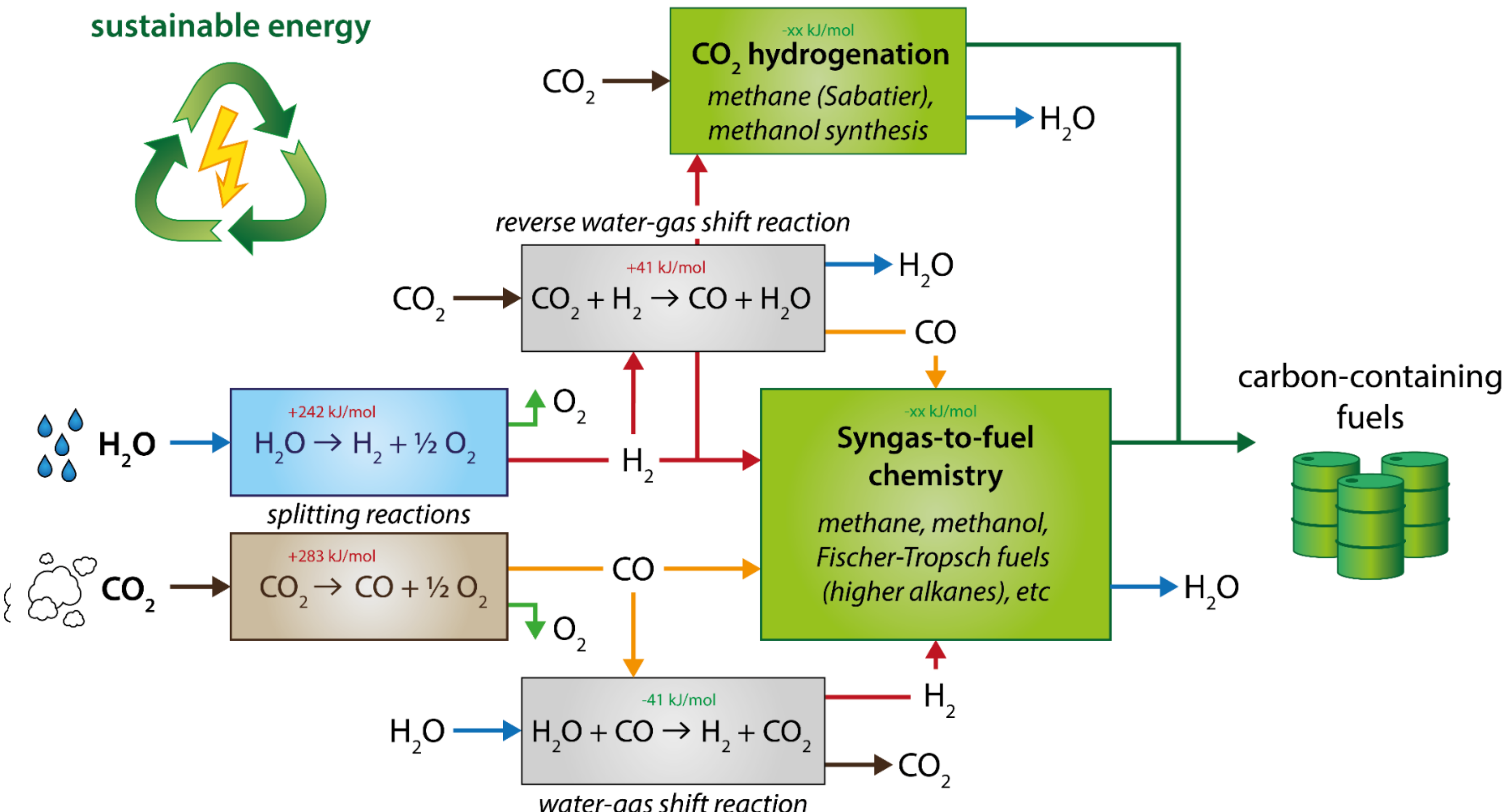
P2X + CCU
CCU: carbon capture and utilisation

Graves et al., Ren. Sustain. Energy Rev. **15**, 1, (2011)

P2X is most critical part both technically and economically

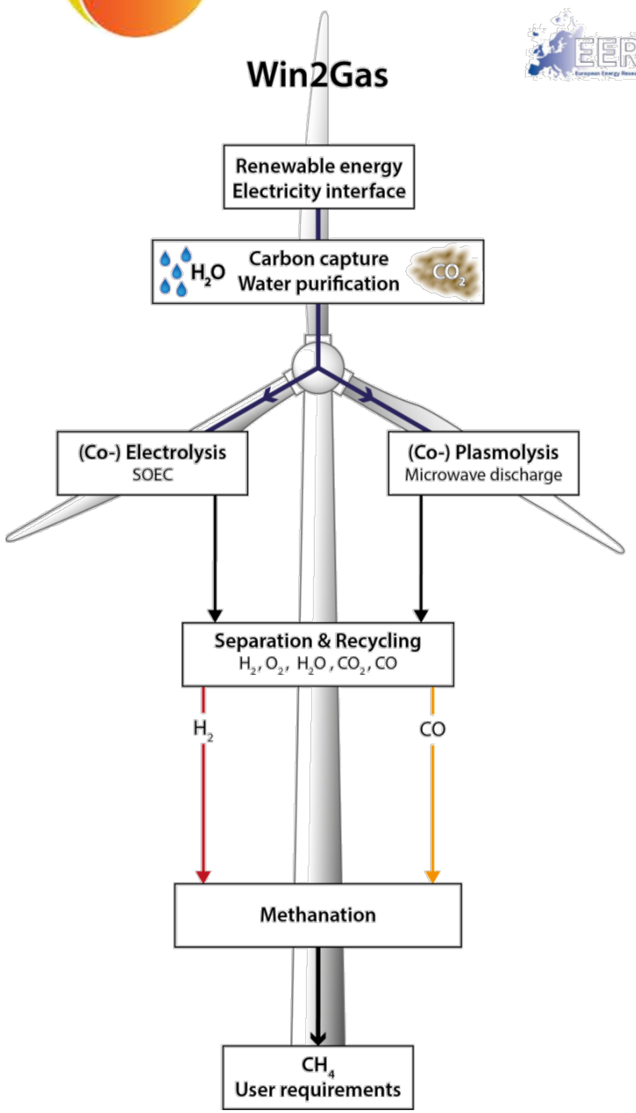
Technology benchmark: costs of H_2
- Electrolysis >6 €/kg H_2 (fossil fuel <1 €/kg H_2)
- CO_2 capture: point source 40 €/tonne, direct air 400 €/tonne

From H_2O and CO_2 to sustainable hydrocarbons



reaction enthalpies calculated for gaseous products at standard conditions

Sustainable Aviation Fuel



Input: surplus wind electricity followed by **P2G**
Output: synthetic methane
for **long-term, large-scale storage**
Feedstock: CO_2 and H_2O
Storage capacity Dutch gas system 552TWh
Recycling CO_2 emitted by re-capture from air

Research challenge: raise TRL from 2 to 5
CO_2 direct air capture, Efficient CO_2 and H_2O splitting by electrolysis and plasmolysis,
Gas separation

Sustainable aircraft grade Kerosene from Water and Air powered by Renewable Electricity,

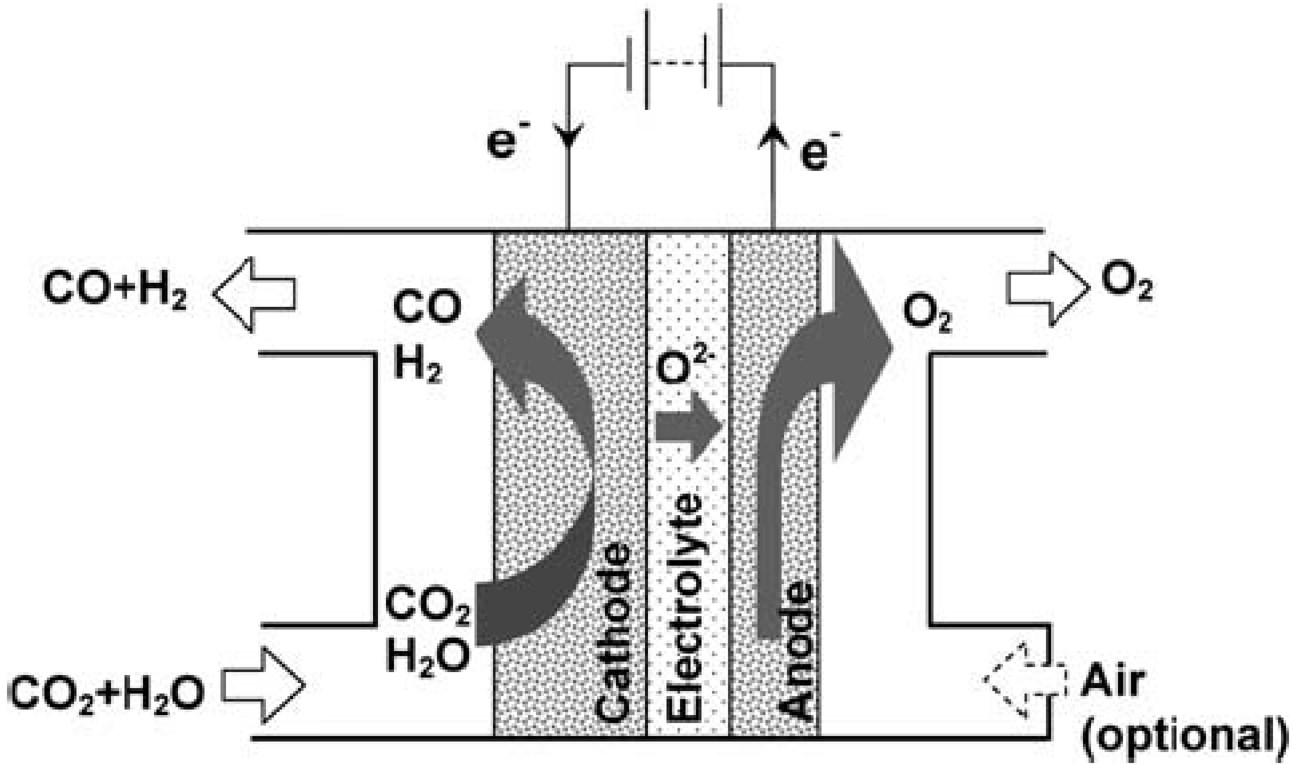
through splitting CO_2, formation Syngas and Fischer-Tropsch synthesis.

Splitting H_2O and / or CO_2 by electrolysis

- **Alkaline** electrolyte (100 yrs large scale mature technology)
  - Power density low (< 0.5W/cm^2)
  - Low hydrogen output pressure (< 30bar)
  - Safety (caustic electrolyte)
- **PEM** (polymer electrolyte membrane), pre-commercial
  - Power density ~1W/cm^2
  - Rapid dynamic response
  - Degradation membrane
  - Catalyst material Pt, Ir (Scarce)
  - MW unit (Siemens)
- **SOEC** (solid-oxide electrolyser cell)
  - High power density, energy efficiency, output pressure
  - High Temperature operation (800°C and pressure 50-100 bar)
  - Co-electrolysis H_2O and CO_2
  - Degradation under high current density operation

Principle of Solid Oxide Electrolysis Cell

External dc voltage pumps O^{2-} ions from porous **cathode** (Ni/YSZ) through dense solid **electrolyte** (YSZ = Yttrium Stabilised Zirconium) to porous **anode** (LSM/YSZ = $La_{1-x}Sr_xMnO_3$/YSZ)

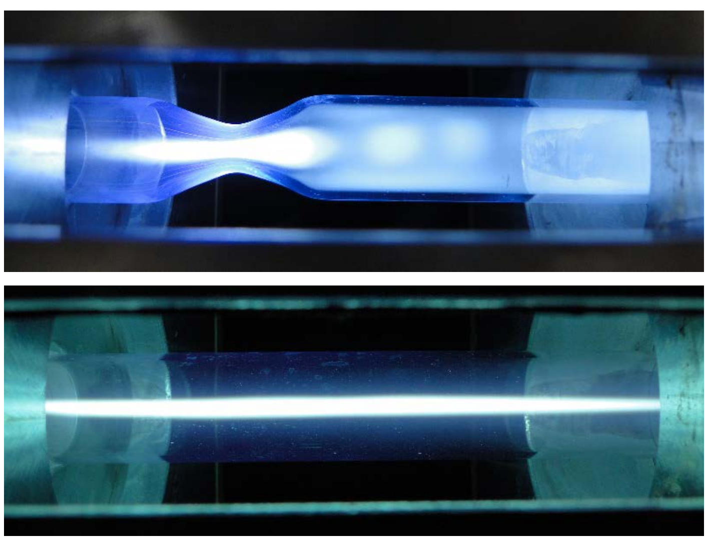


Why plasma for CO_2 conversion?

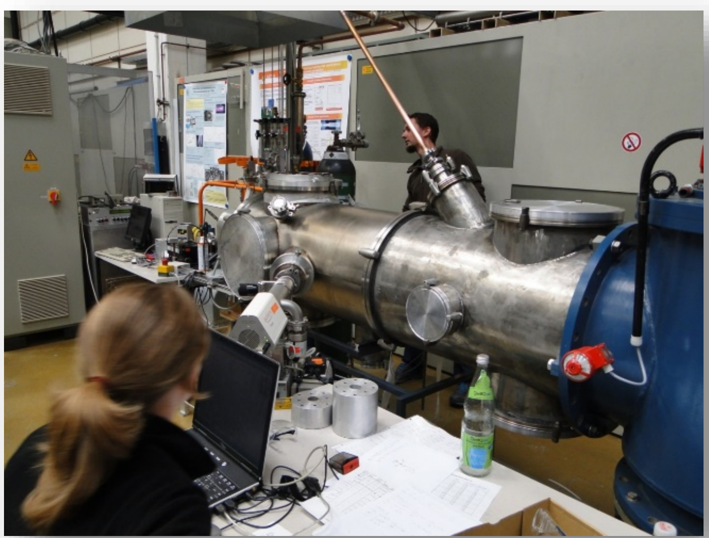
Characteristics of CO_2 plasmolysis

Ease conditions for CO_2 splitting by channelling energy in molecular vibration to break chemical bond, not to heat the gas (non-equilibrium)

- Energy efficiency comparable to Electrolysis (~60% demonstrated)
- High productivity: large gas flow and power flow density ($45 W/cm^2$)
- Fast dynamic response to intermittent power supply
- No scarce materials employed (Pt catalyst in PEM)



30 kW @ 915 MHz



RF plasma discharge

Out of equilibrium $T_{vib} > T_0$ chemistry

Chemical reaction scheme

$CO_2 \rightarrow CO + O$ (ΔH=5.5 eV)

followed by reuse energetic **O** radical

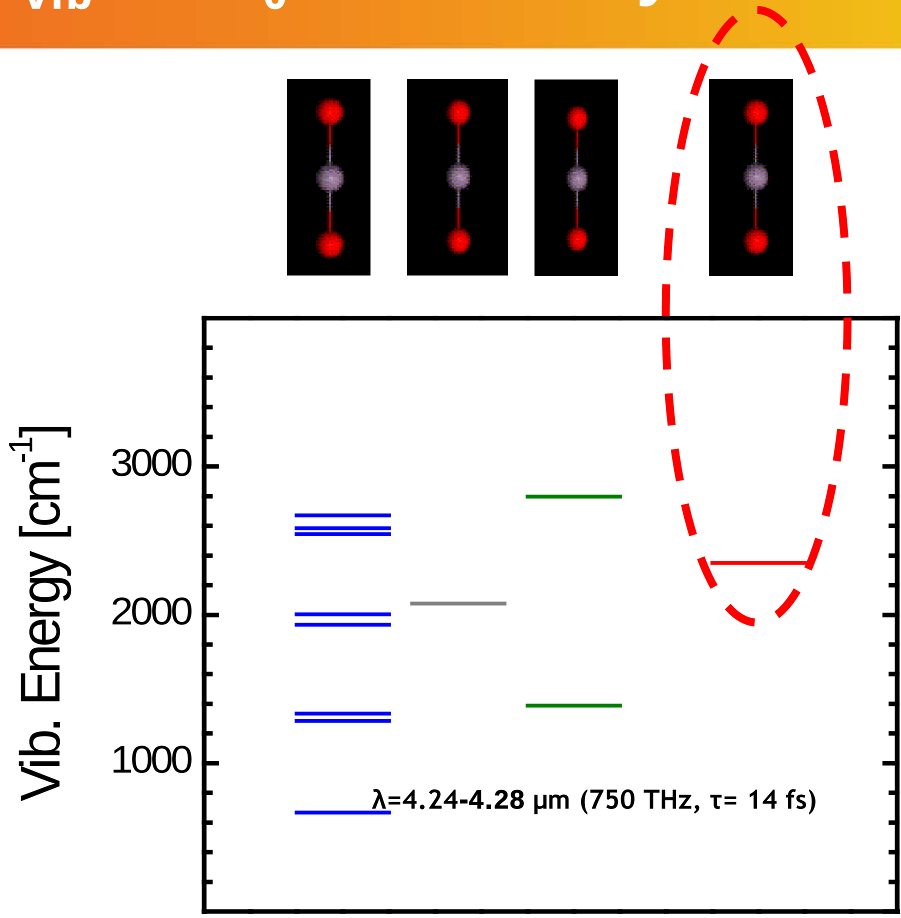
$CO_2 + O \rightarrow CO + O_2$ (ΔH=0.3 eV)

Net

$CO_2 \rightarrow CO + \frac{1}{2} O_2$ (ΔH=2.9 eV)

Efficiency to be increased by

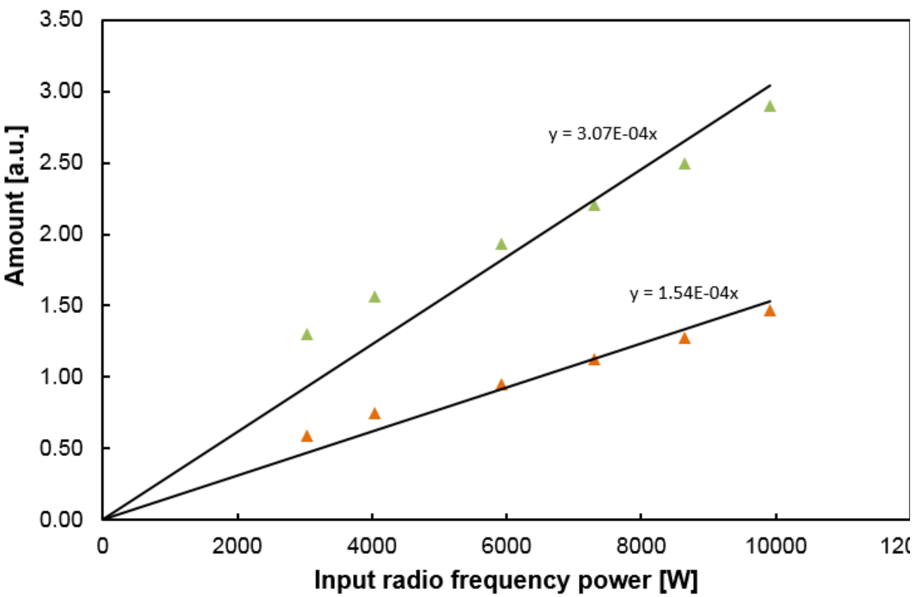
Concentration of electron energy on vibrational excitation of CO_2 in asymmetric stretch mode

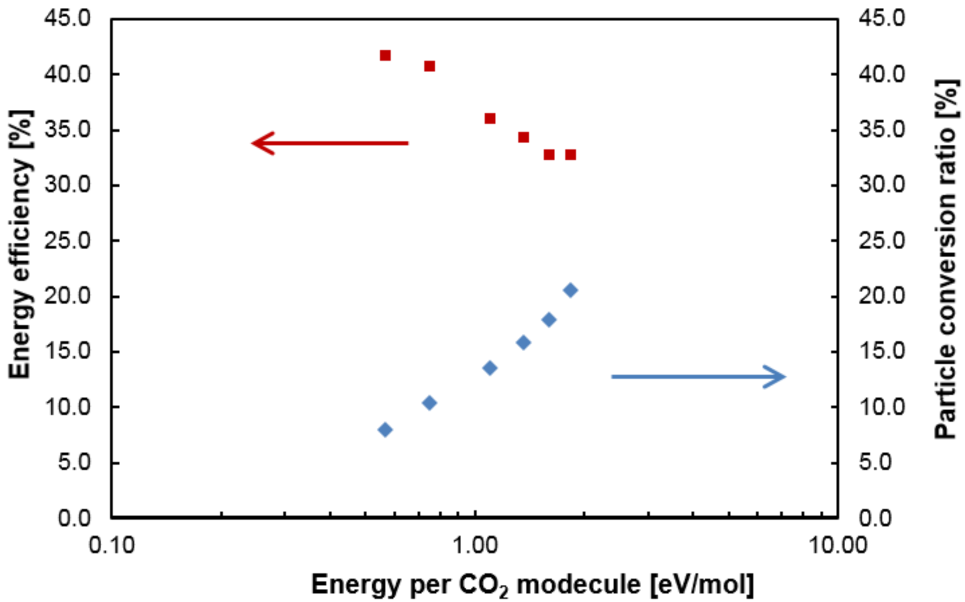


Arrhenius/Fridman:
Activation energy reduced by vibration energy

$k = A \exp (\alpha E_v - E_a)/kT$

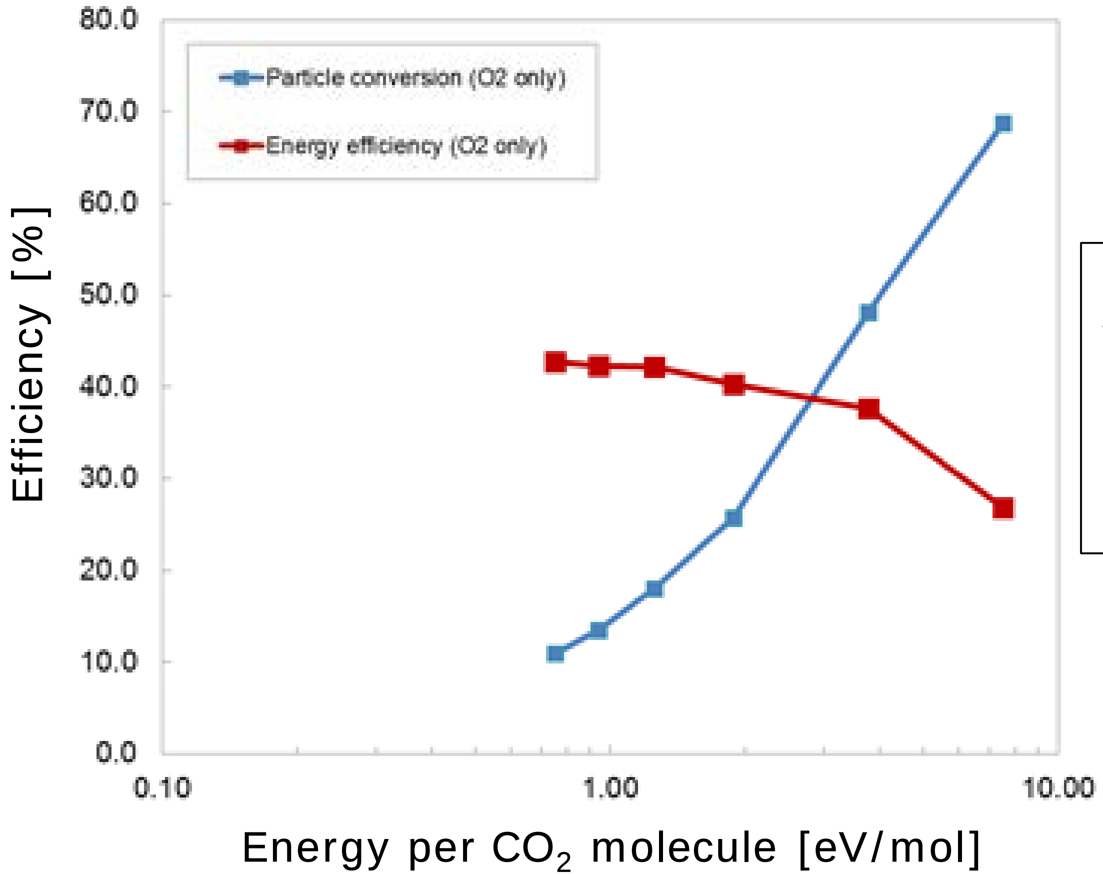
CO and O_2 production as function **RF Power**





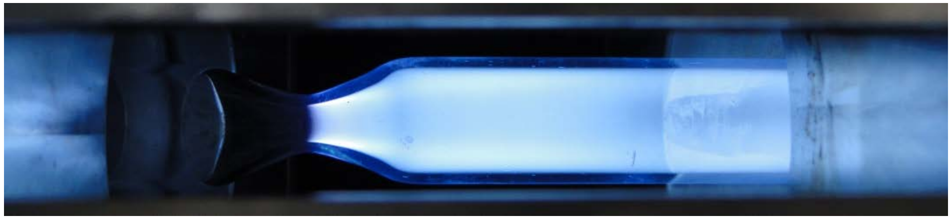
Experimental Results

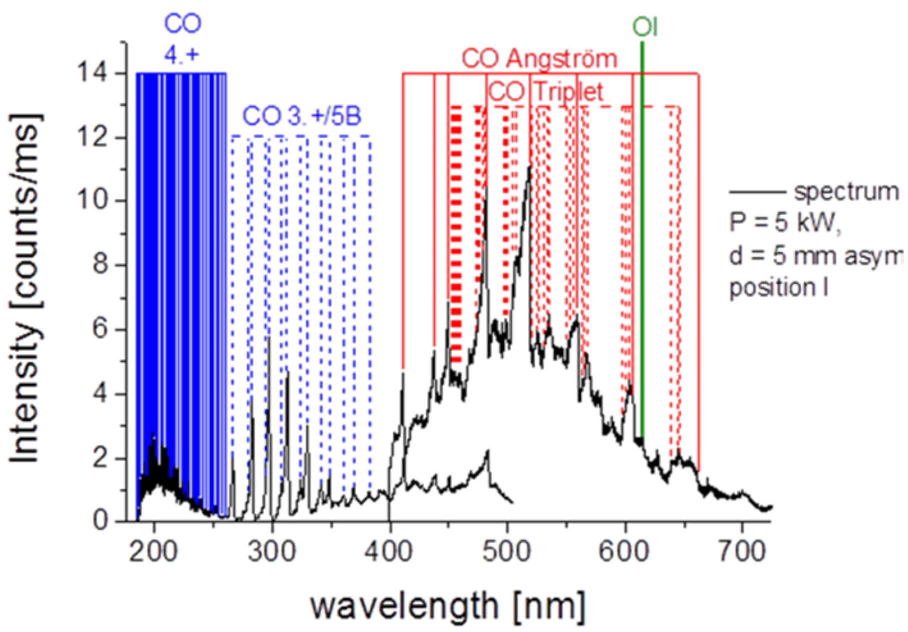
- CO production as function **Gas flow**

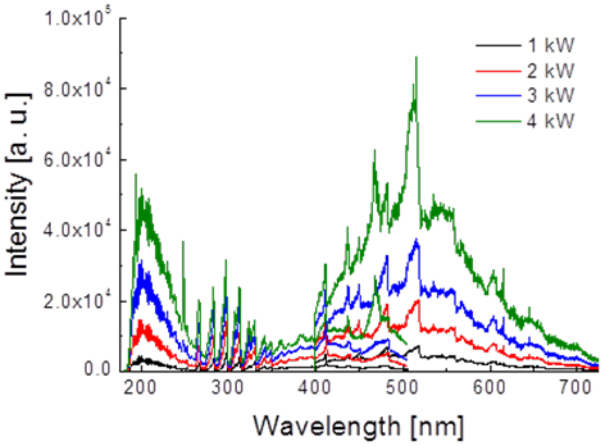


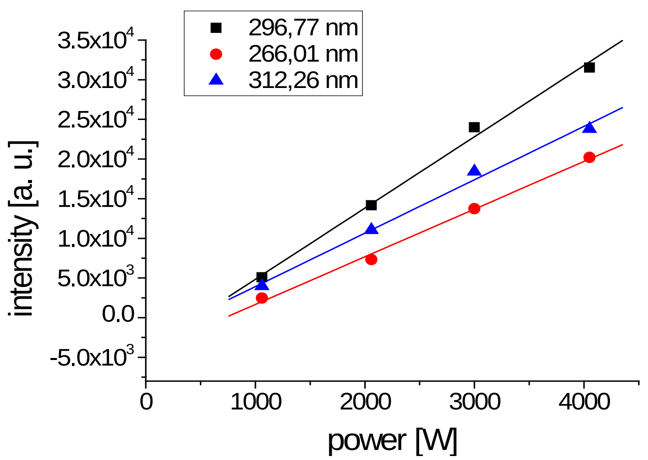
10 kW RF absorbed
75 slm CO2, conversion 10% CO
(non optimised for safety risk)
Pressure 500 mbar,
Energy Efficiency 30%

Optical Emission Spectroscopy



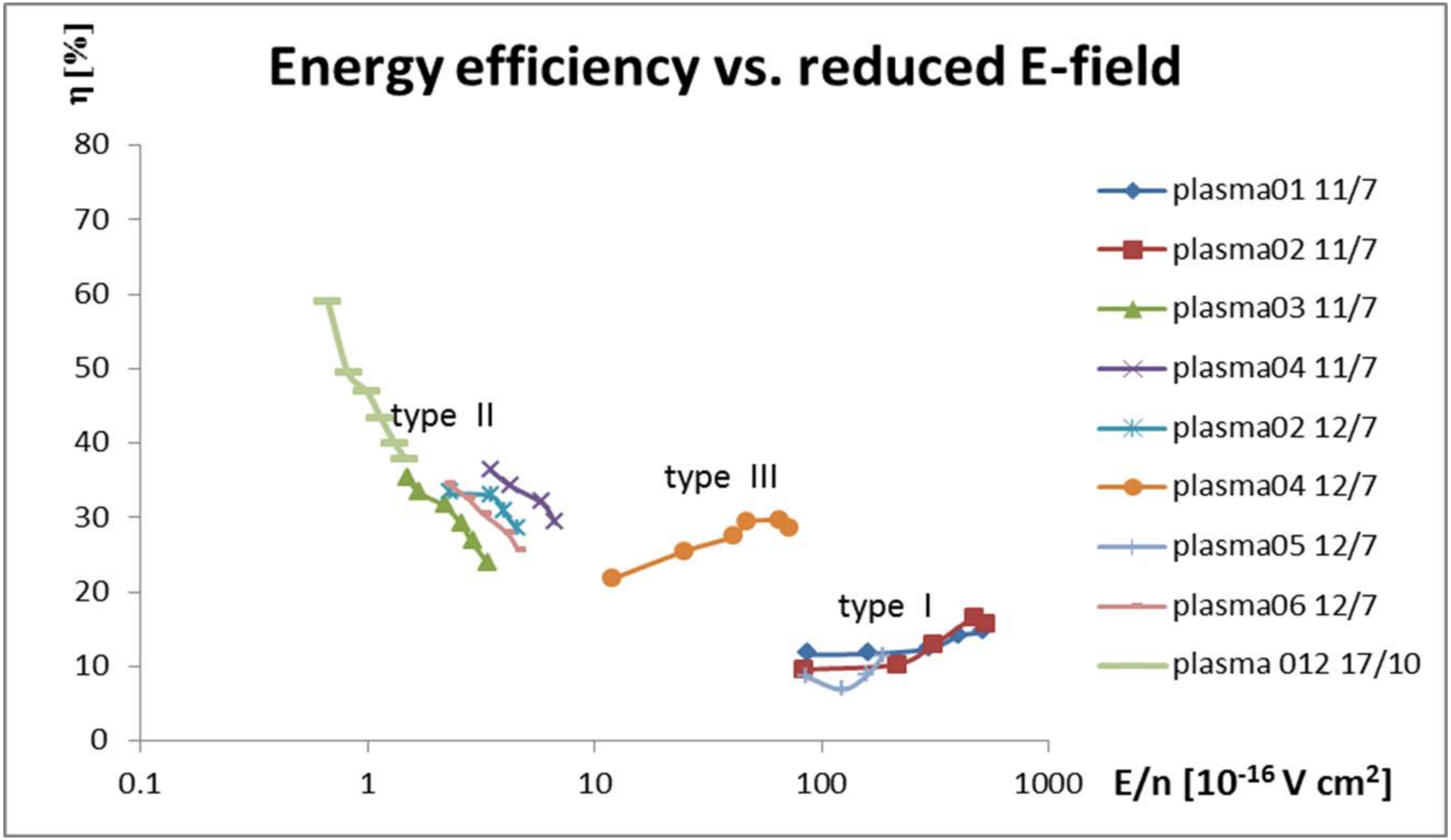




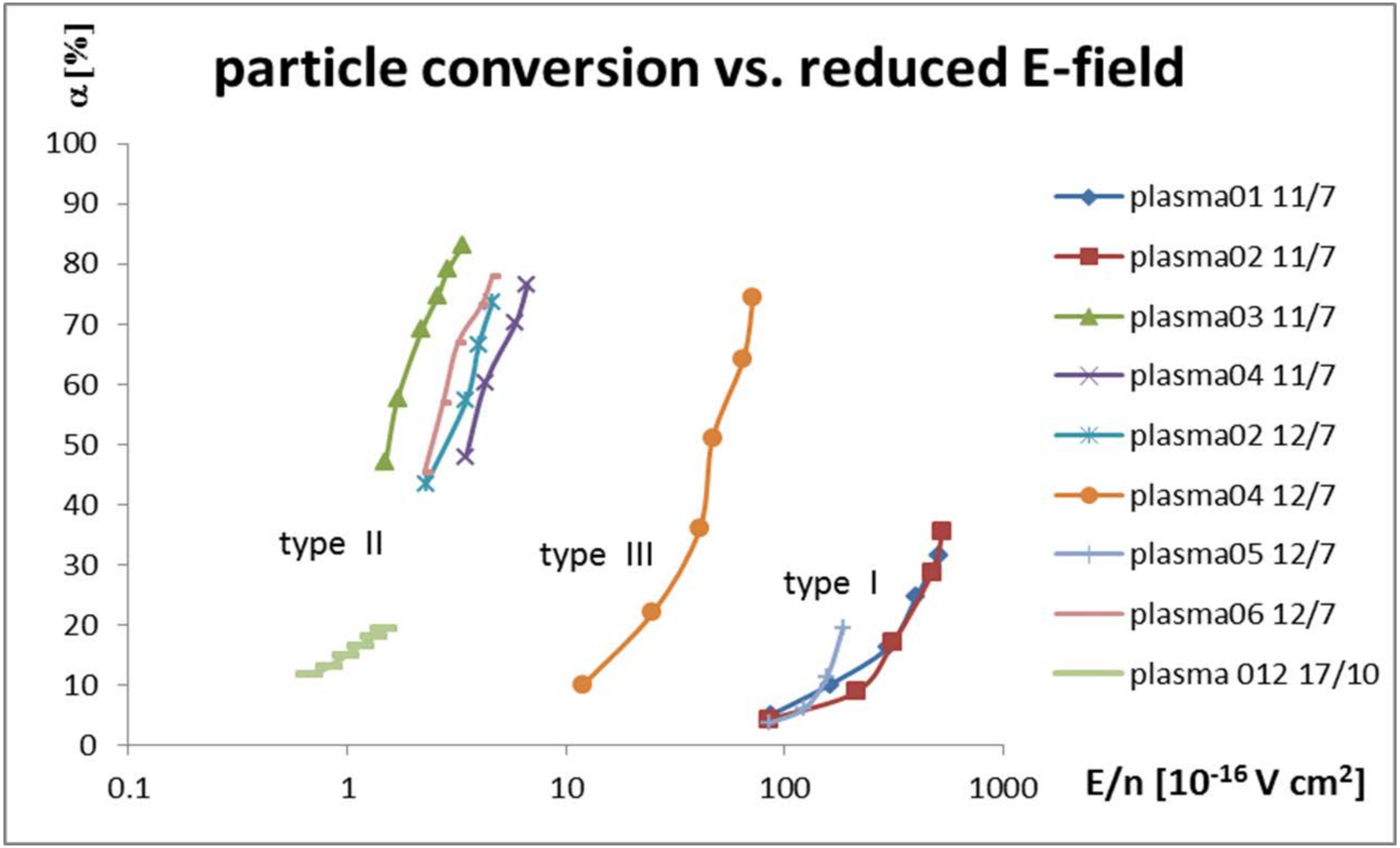


- CO 3rd positives, 4th positives, Angstrom and triplet bands identified.
- CO line intensity increases linear with power in supersonic regime

Experimental Results

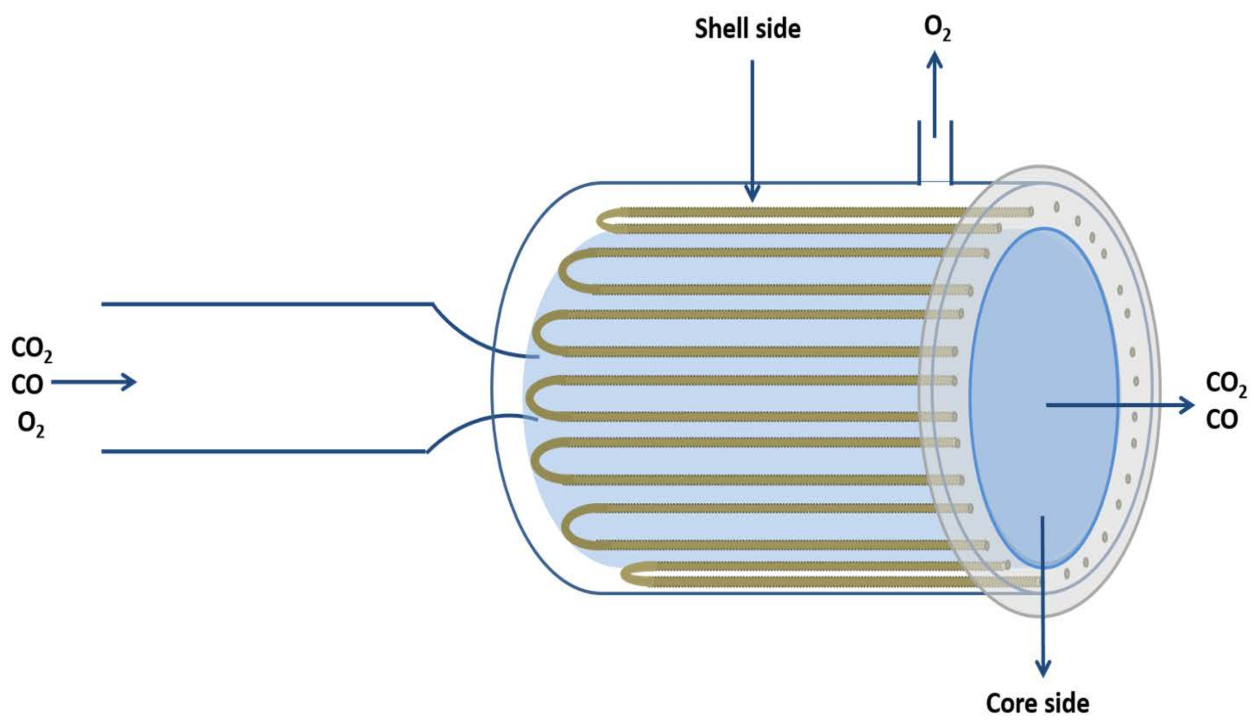


Experimental Results



Separation of CO, O_2, CO_2 mixture

SOC oxygen separation membrane integrated with plasma reactor.
Lanthanum based perovskites show superior oxygen flux
YSZ or SDC electrolyte sandwiched between perovskite electrodes:
LSM/YSZ or LSCF oxygen electrode, Ni/YSZ or LSCM plasma electrode.
Plasma sheath electric field meets with electrode polarisation critical I/F



Conclusions

- P2X can provide vast seasonal energy storage capacity and flexibility of supply from Renewable Electricity though sector Coupling
- P2X enables distributed small scale production plants (Ex. Ammonia or CO)
- P2X-CCU enables a CO_2 neutral fuel cycle based on hydro-carbons and existing infrastructure
- Technical challenge: innovation in CO_2 splitting and CO-O_2 separation
- Economic challenge: cost reduction, business case expected to emerge around 2030, when cost of CO_2 reach € 200/ton

Future Energy System

- Next 20 years: fundamental shift in the way energy is generated, stored, delivered, valued and purchased

- Critical element: conversion renewable electricity into fuel
- Coupling of renewable electricity to the other 80% of CO_2 emitting sectors, including low and high temperature heat, transportation and chemical feedstock

- Incremental improvement: role of Industry
- Novel concepts, game changers: role of fundamental energy research
- Driver: CO2 reduction targets, International (UNFCCC), EU directive (RED), National Policy. Targets for 2030 and 2050 are set, but
- Road to get there is largely unchartered

End of lecture

Thank you for your attention!

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