Hydrogen production including using plasmas

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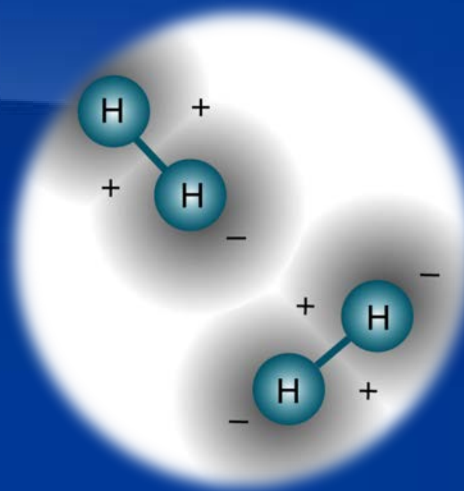
History of Hydrogen

- Diatomic molecule: $\mathbf{H_2}$
  - ✓ Colourless and odourless gas
  - ✓ Highly combustible



- Energy vector
  - ✓ Not a source of energy
  - ✓ Needs to be generated like electricity
- Theophrastus Bombastus von Hohenheim
  - ✓ First to artificially produce hydrogen in early 16^{th} century
- Henry Cavendish
  - ✓ First to discover that water is produced when hydrogen is burned
- Lavoisier gave the name Hydrogen
  - ✓ In Greek translates to ‘water-forming’

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Hydrogen uses

- Production of chemicals
  - ✓ Fertilizers, methanol, ethanol and dimethyl ether
- Alternative metallurgical processes
  - ✓ Recovery of nickel and lead from their ores
- Oil industry
  - ✓ Refining and desulphurization
- Source of energy
  - ✓ Rocket fuel, IC engine fuel, high temperature industrial furnaces fuel
- Electricity generation
  - ✓ Fuel Cells: the most efficient use of hydrogen

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Hydrogen Economy

'when and how not if…..'

- The replacement of the overwhelming majority of petroleum fuels with hydrogen

- Majority of experts consider hydrogen technology to be a long term solution for energy and environmental concerns

Highly dependent on the availability of low cost and environmentally friendly sources of hydrogen

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Key hydrogen production processes

Hydrogen can be generated from numerous of sources and processes

1. Water electrolysis

2. Biomass gasification

3. Methane reforming
   - ✓ Steam methane reforming
   - ✓ Thermo-catalytic decomposition

4. Plasma assisted gaseous hydrocarbon reforming

5. Comparison of reformer performance

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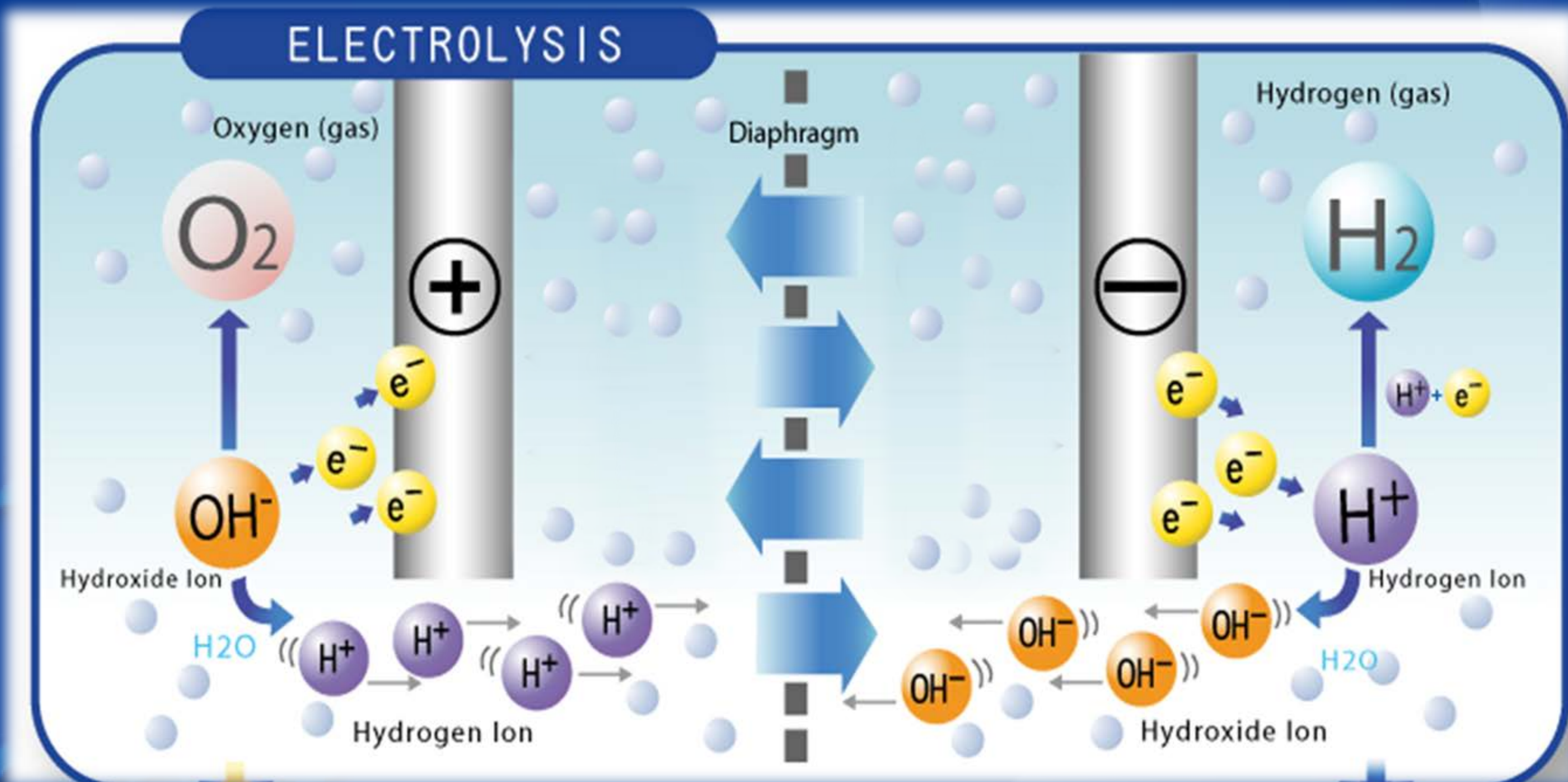
Water Electrolysis

Splitting water or steam into hydrogen and oxygen

$$2H_2O + \text{electric field} \rightarrow 2H_2 + O_2$$

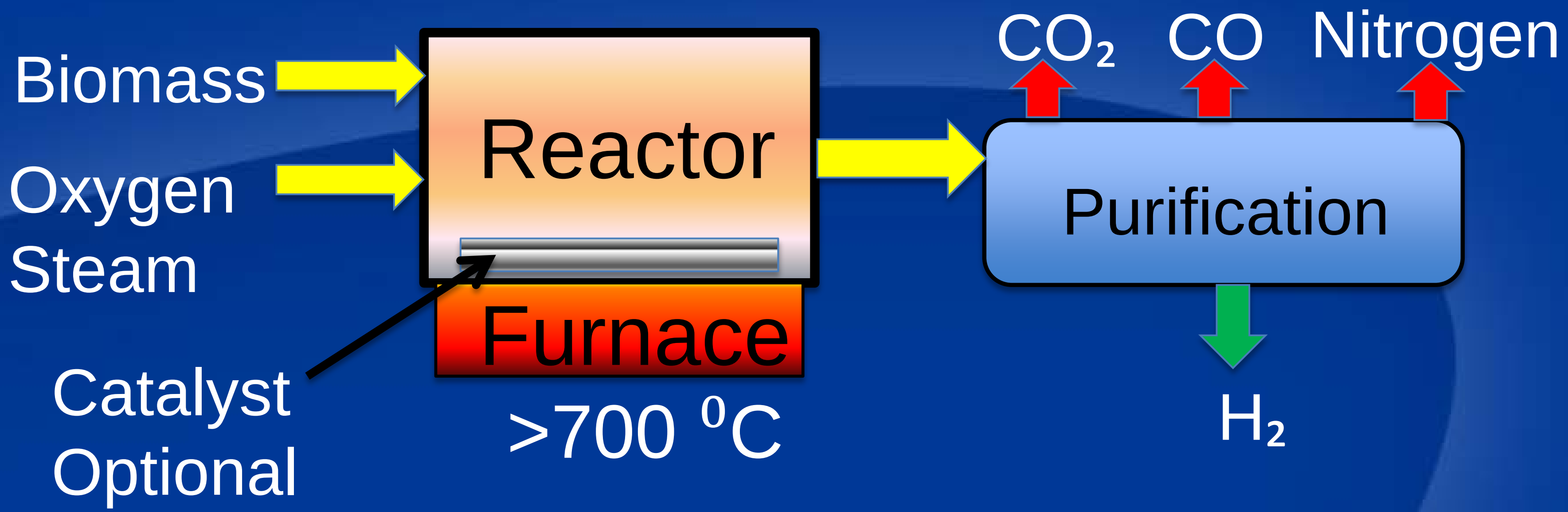


Water electrolysis: applications in hydrogen fuelling stations

- Hydrogen fuel station at Honda R&D Americas, Inc., Torrance, CA (Photo: Honda R&D Co., Ltd)
- Electricity for electrolysis is generated by solar power
- Carbon neutral and renewable hydrogen

- Hydrogen bus refuelling station, Iceland
- One of the first hydrogen fuelling stations in the World

Biomass Gasification



- Efficiencies 30 - 50 %
- Key disadvantages
  - ✓ Produces a significant amount of tar in the product gas
  - ✓ Low thermal efficiency due to moisture in biomass
  - ✓ Plant location has to be close to biomass source

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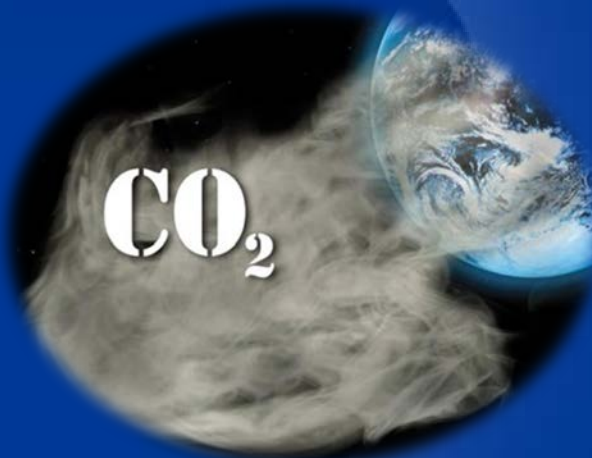
Biomass Gasification

- World's largest biomass gasification plant in Vaasa, Finland, supplied by Metso
- Use non-recyclable waste

- Biomass gasification plant in Middlesbury , Vermont, US

Steam Methane Reforming

- 48 % global hydrogen production
- Advantages
  - ✓ Most extensive industry experience
  - ✓ High system efficiency at 83 %
  - ✓ Natural gas pipeline infrastructure existent



- Disadvantages
  - ✓ High carbon dioxide emissions
  - ✓ 13.7 kg CO_2 per 1 kg of hydrogen
  - ✓ Capital equipment costs, operation and maintenance costs, must be reduced, and process energy efficiency must be improved in order to meet hydrogen cost targets

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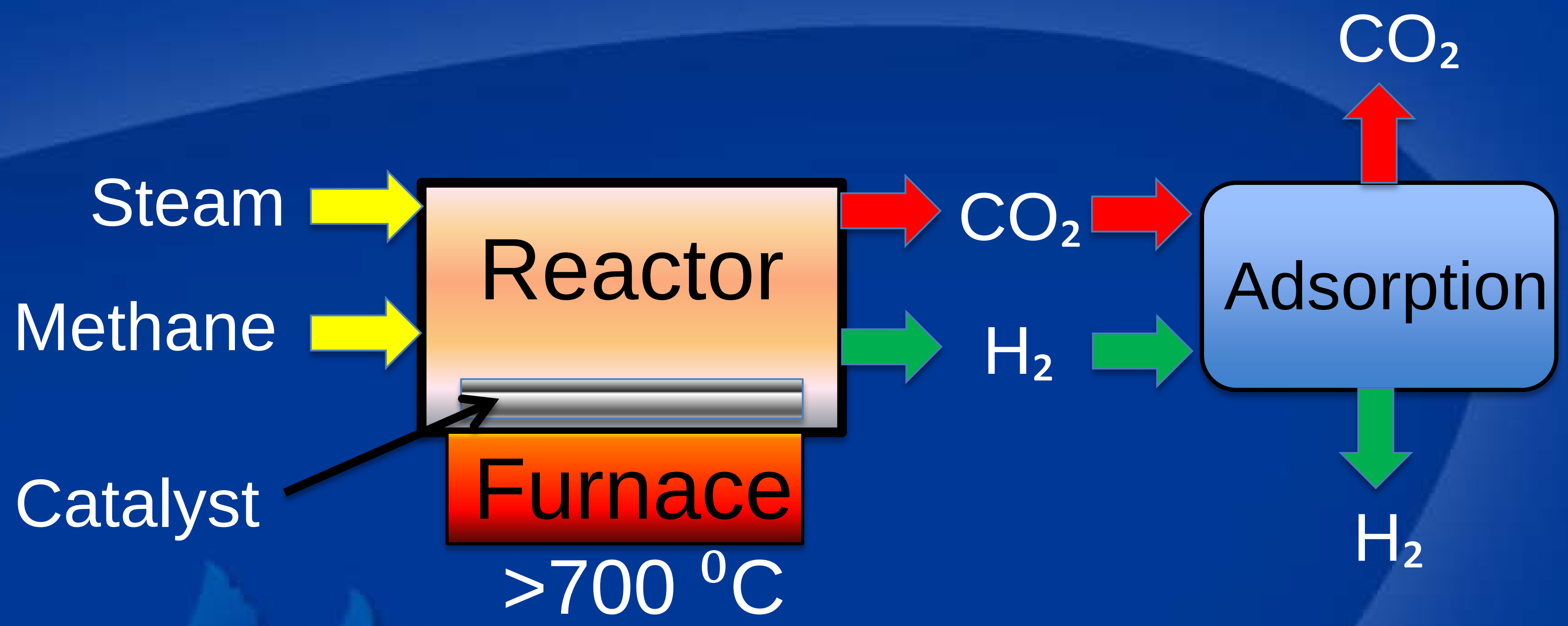
Steam Methane Reforming



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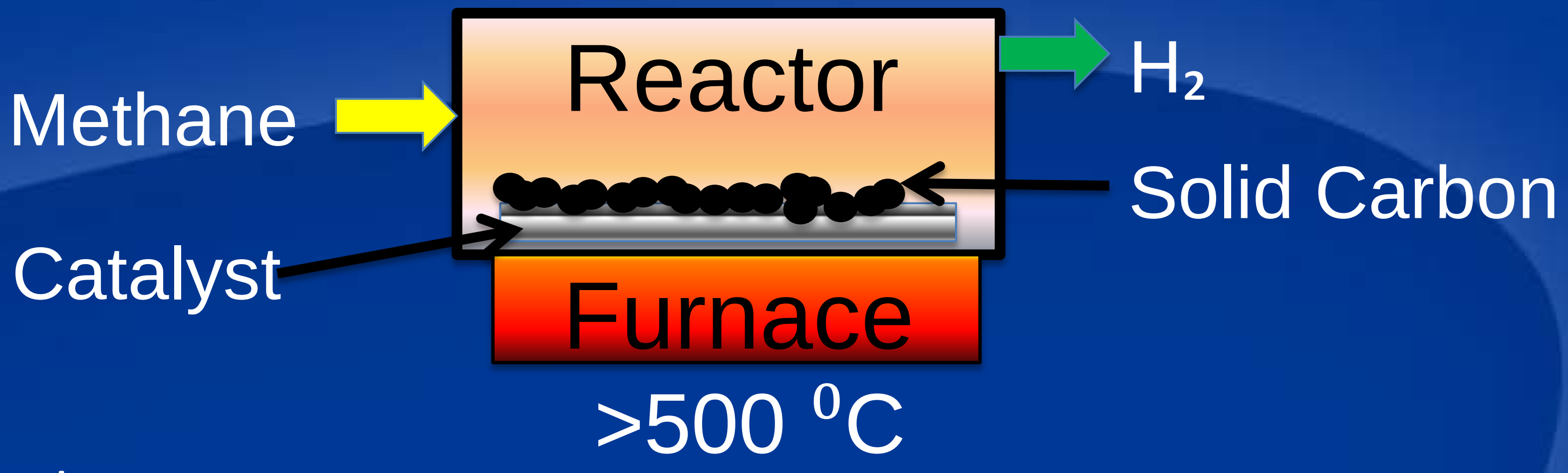
Thermo-catalytic methane decomposition



- Advantages
  - No COx production
  - More economical than SMR with carbon capture

- Disadvantages
  - Carbon deposition deactivates and damages catalyst
  - Catalyst regeneration is an expensive process and generates carbon dioxide

Thermo-catalytic methane decomposition: solid carbon value

- Solid carbon is easier to harvest
- Variety of uses
  - ✓ Ferroalloy industries
  - ✓ Building materials
  - ✓ Electricity
  - ✓ Fertiliser
- Commercial value
  - ➢ £ 200/tonne for Low Quality (LQ) e.g. carbon black
  - ➢ £ 1000/tonne for High Quality (HQ) e.g. nanotubes

Boeing 787 Dreamliner made 50 % of carbon fibre material

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Research at Brunel University: Plasma assisted hydrogen production

Energy and free radicals used for the reforming reaction are provided by a plasma

- Conventional methodologies can be adopted
  - ✓ Plasma replaces catalyst and high temperatures
- At Research and Development Stage
- Very competitive system potential

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Plasma – The Fourth State of Matter

Plasma is a term used to describe an ionized gas

- Highly reactive system
- Charged particles, excited atoms and molecules, active atoms and radicals

- Comprises the majority of the universe
  - The solar corona, solar wind, nebula and Earth's ionosphere

- The best known natural plasma is lightening

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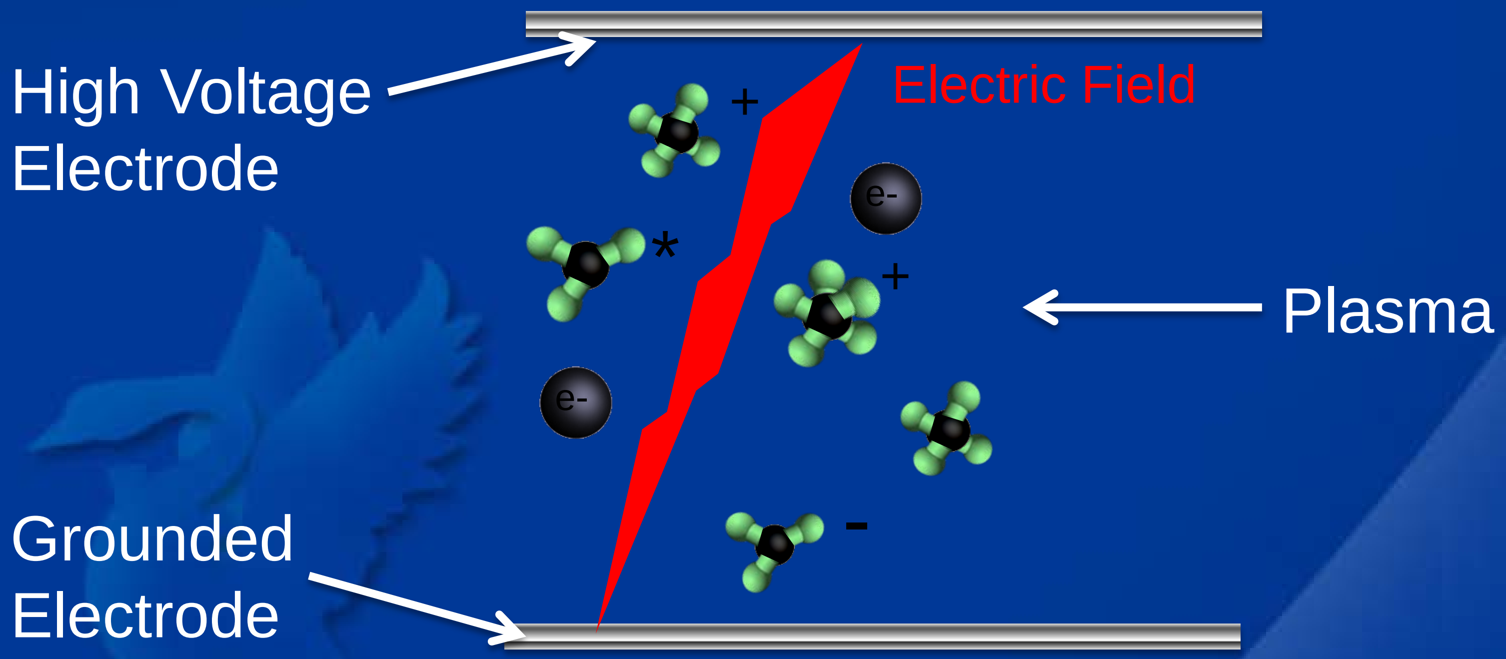
Man-Made plasmas

- Generated by supplying energy to a neutral gas
  - Thermal energy
  - Magnetic fields
  - Electric fields



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Plasma types

- Thermal plasma
  - High temperature: 10,000 K to 30,000 K
  - Very powerful
  - High energy consumption

Thermal plasma torch

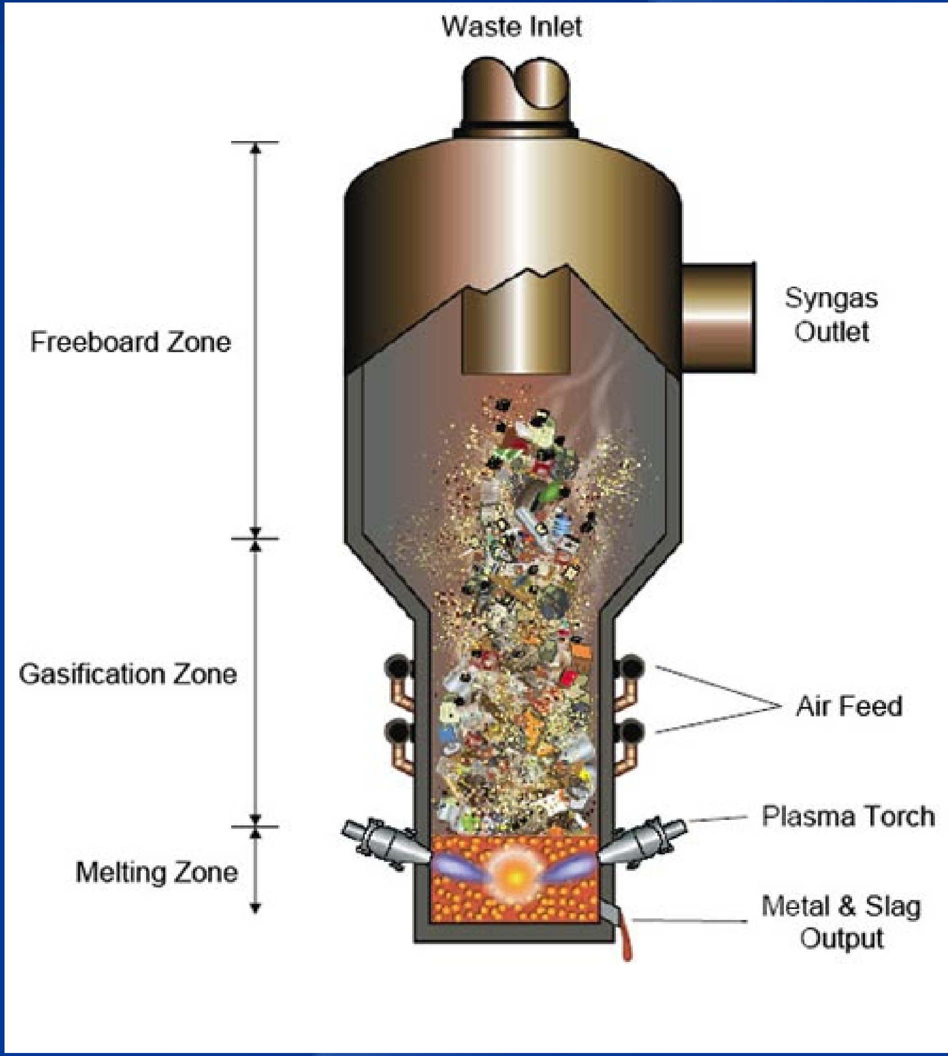
- Non-thermal plasma
  - Low bulk temperature: room temperature
  - Selective and energy efficient
  - Energetic and chemically active species

Non-thermal plasma hollow tube

Thermal Plasma Gasification of Biomass and Coal

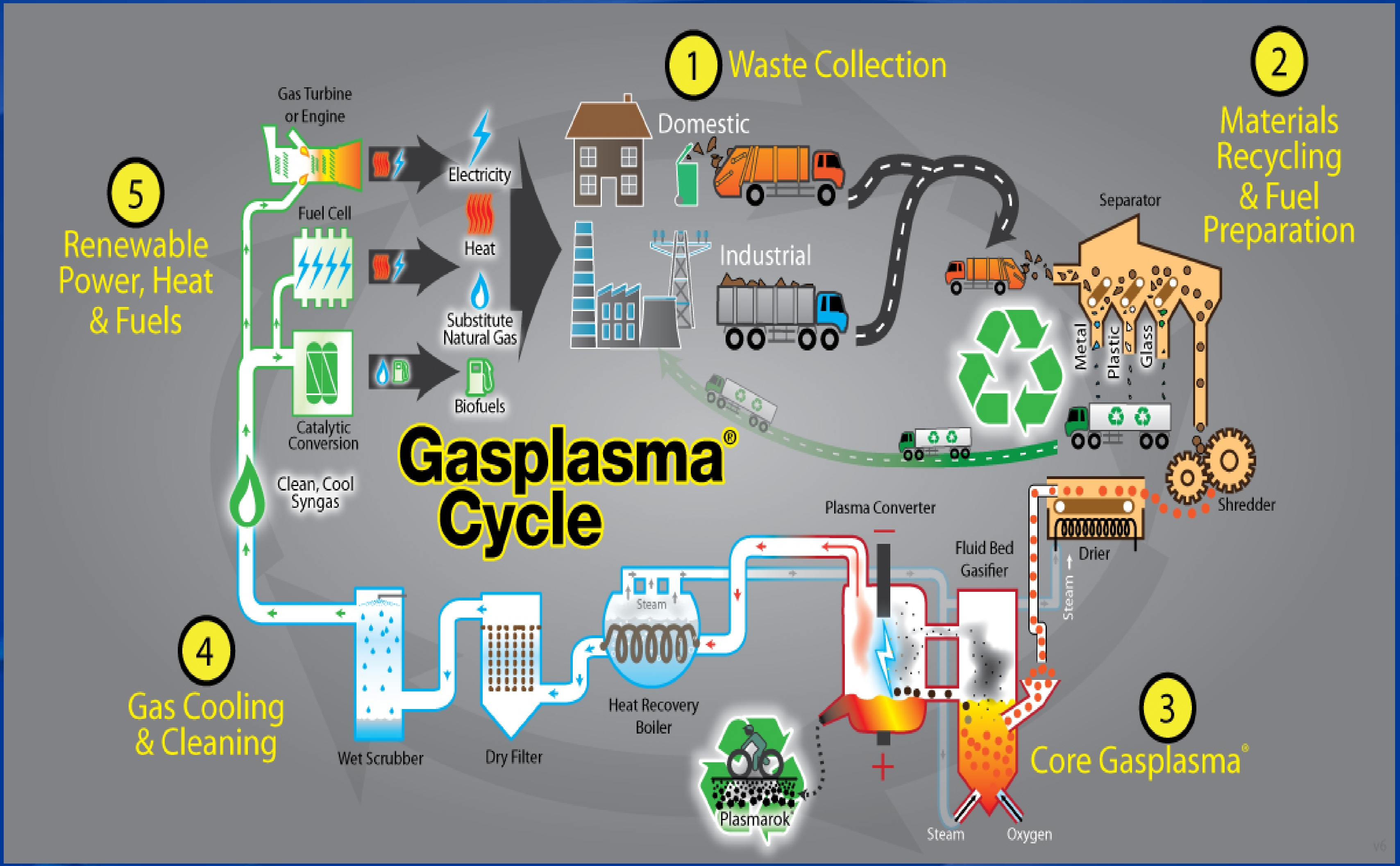
No other remediation technology can achieve the sustained temperature levels (> 7000 ^{o}C) or energy densities (up to 100 MW/m^{3})

- ✓ Hazardous & toxic compounds
- ✓ Acid gases readily neutralized
- ✓ Residual materials immobilized
- ✓ Vitrified slag as a by-product that is inert and safe to use as aggregate or for use in other applications



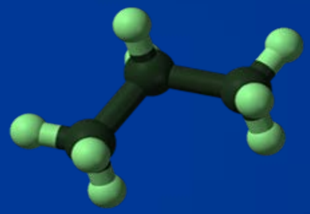
Commercial model developed by Alter NRG

Thermal Plasma Gasification of Biomass: Advanced Plasma Power UK



Research at Brunel University: Non-thermal Plasma assisted decomposition of gaseous hydrocarbons

- Non-thermal plasma advantages for hydrogen production
  - Eliminate catalyst use
  - Higher conversion efficiencies and specific productivity than catalytic reforming



- Decomposition of propane
  - Major constituent of liquefied petroleum gas
  - Liquefiable and easy to store and transport: on-board storage
  - Increase flexibility of feedstock choice

- Decomposition of methane
  - Abundant fuel
  - Connection to the existing gas pipelines

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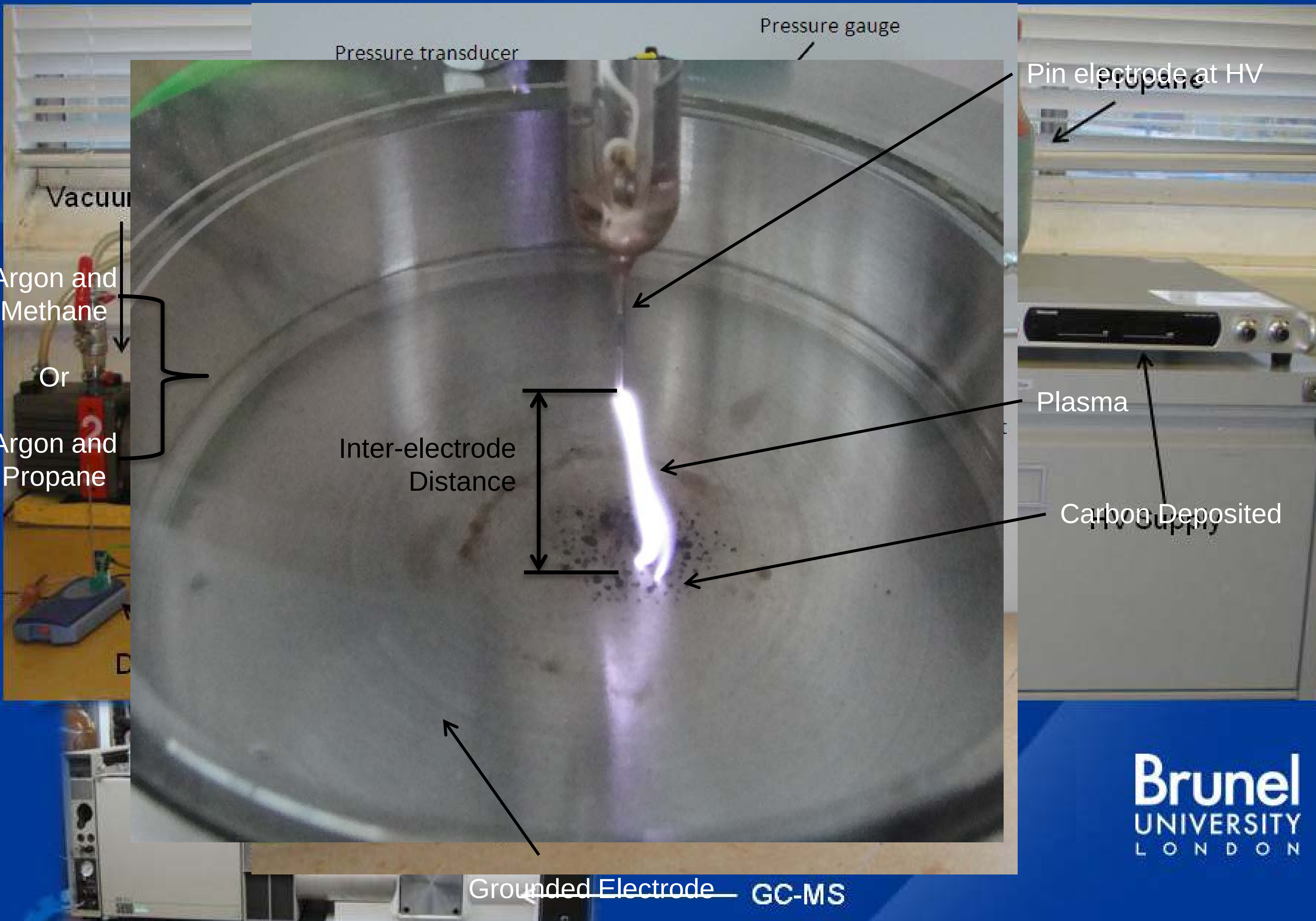
Experimental Rig

Experimental Chamber



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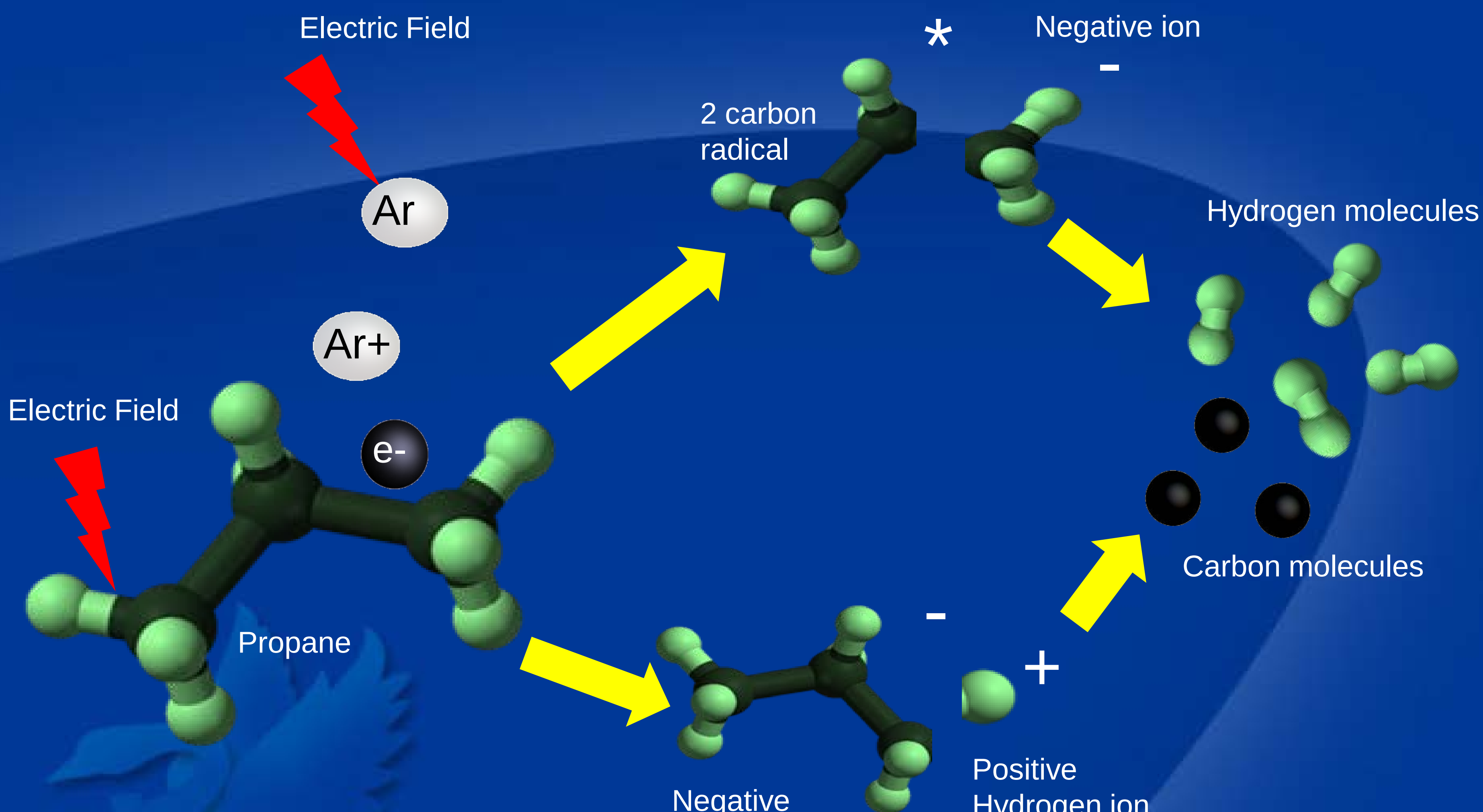
Plasma assisted decomposition of propane



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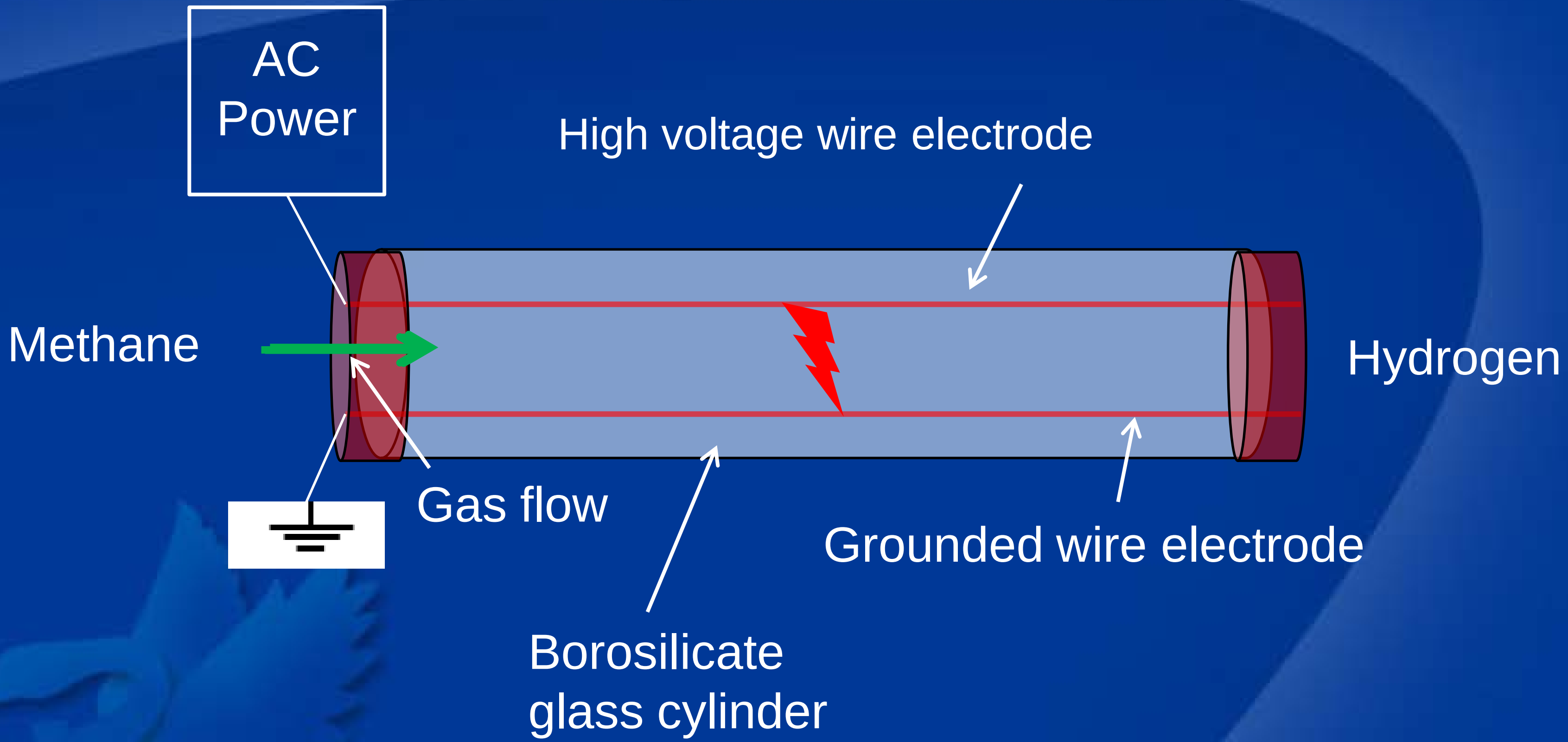
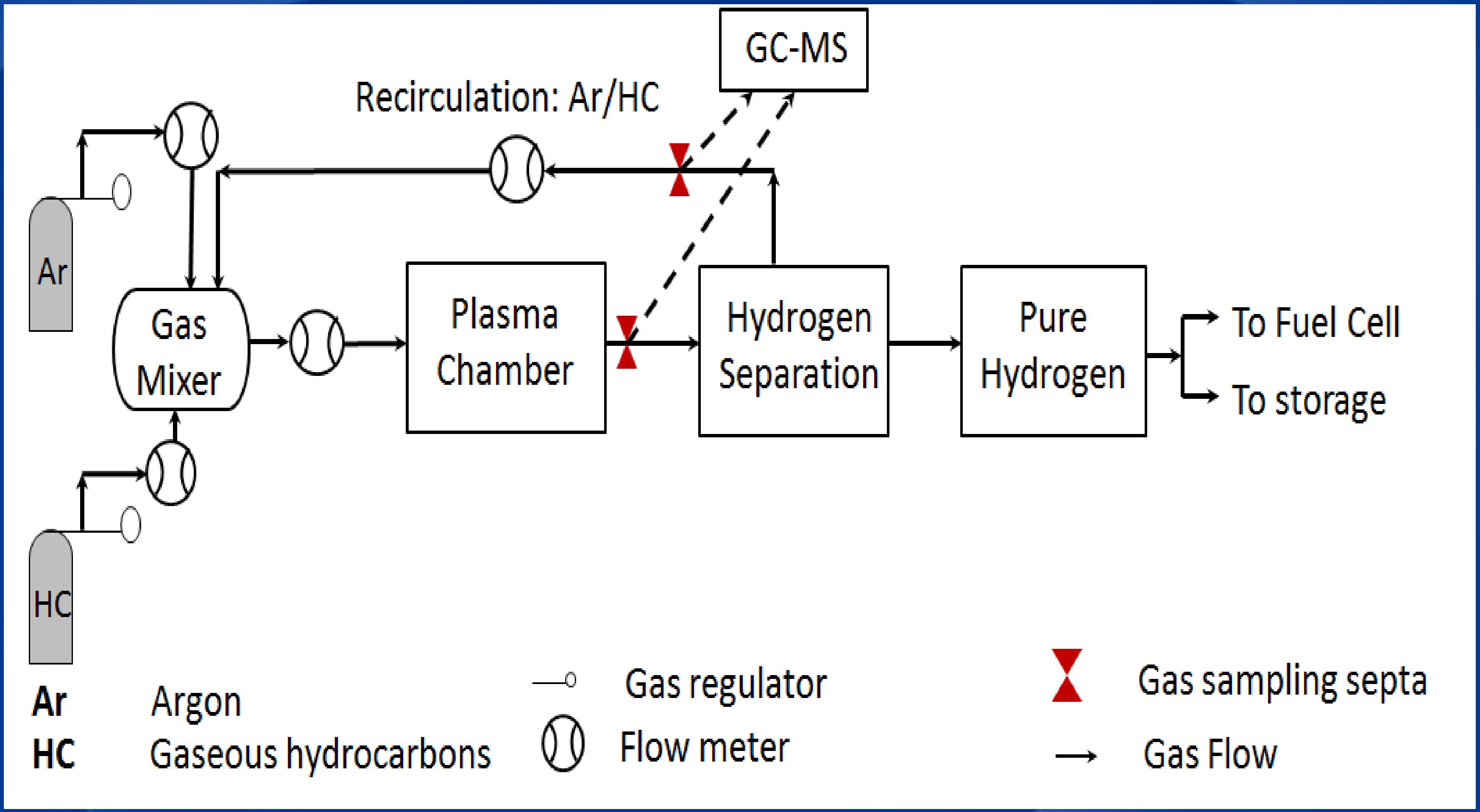
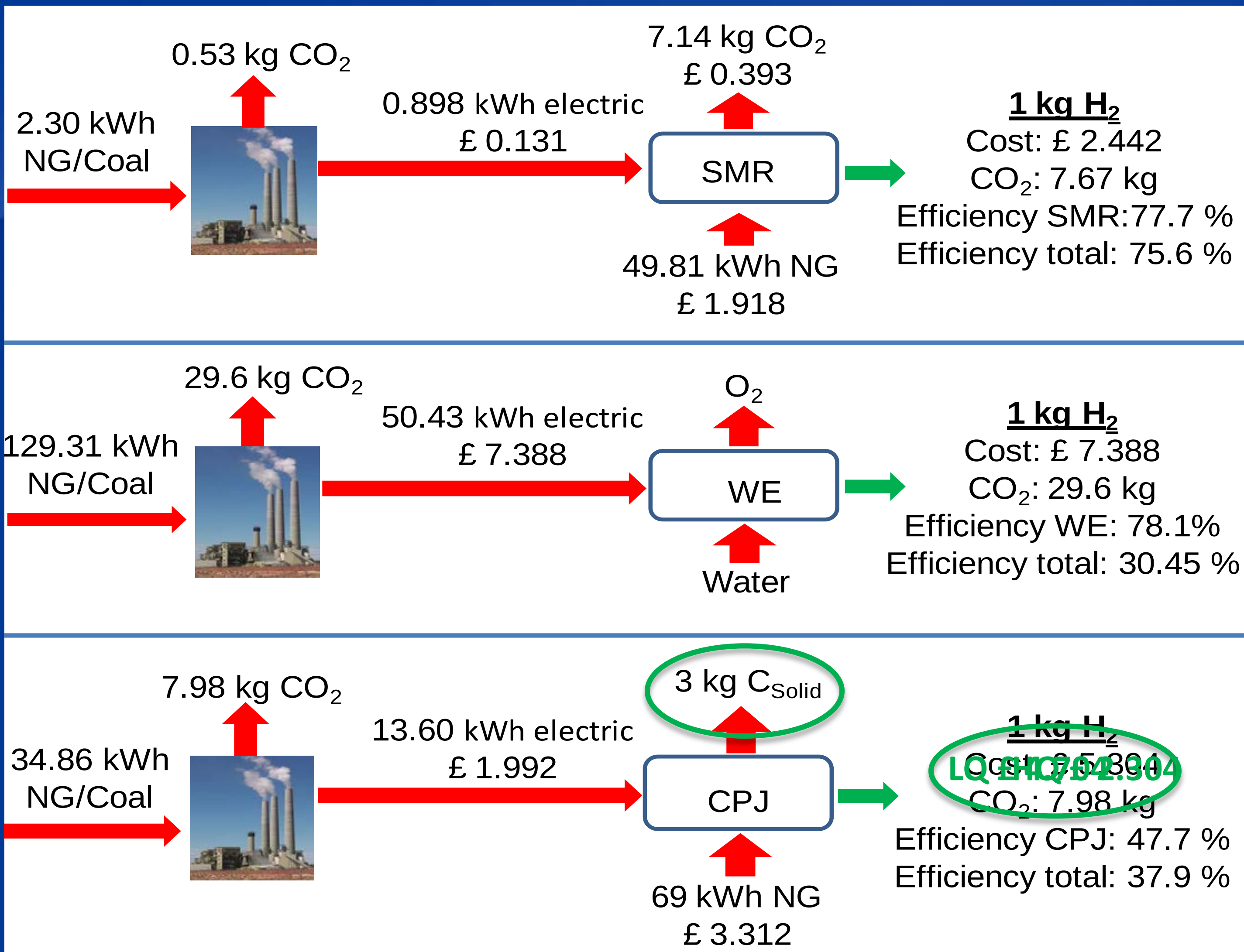
Future of Research at Brunel: design of a flow system



Future of Research at Brunel: plasma integration for domestic applications



Hydrogen generation: reformer performance



SMR
Steam Methane Reformer

WE
Water Electrolyser

CPJ
Cold Plasma Jet

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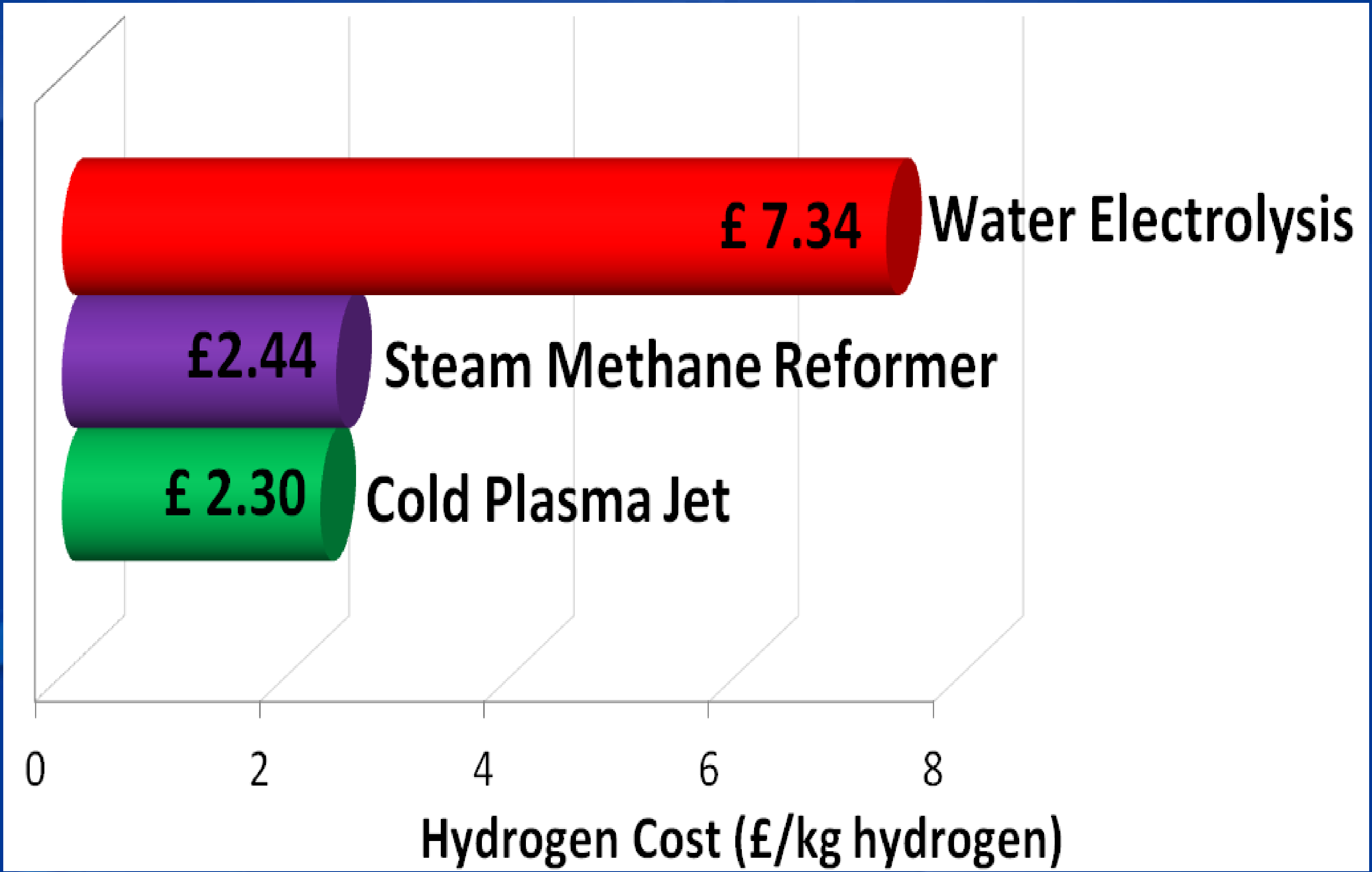
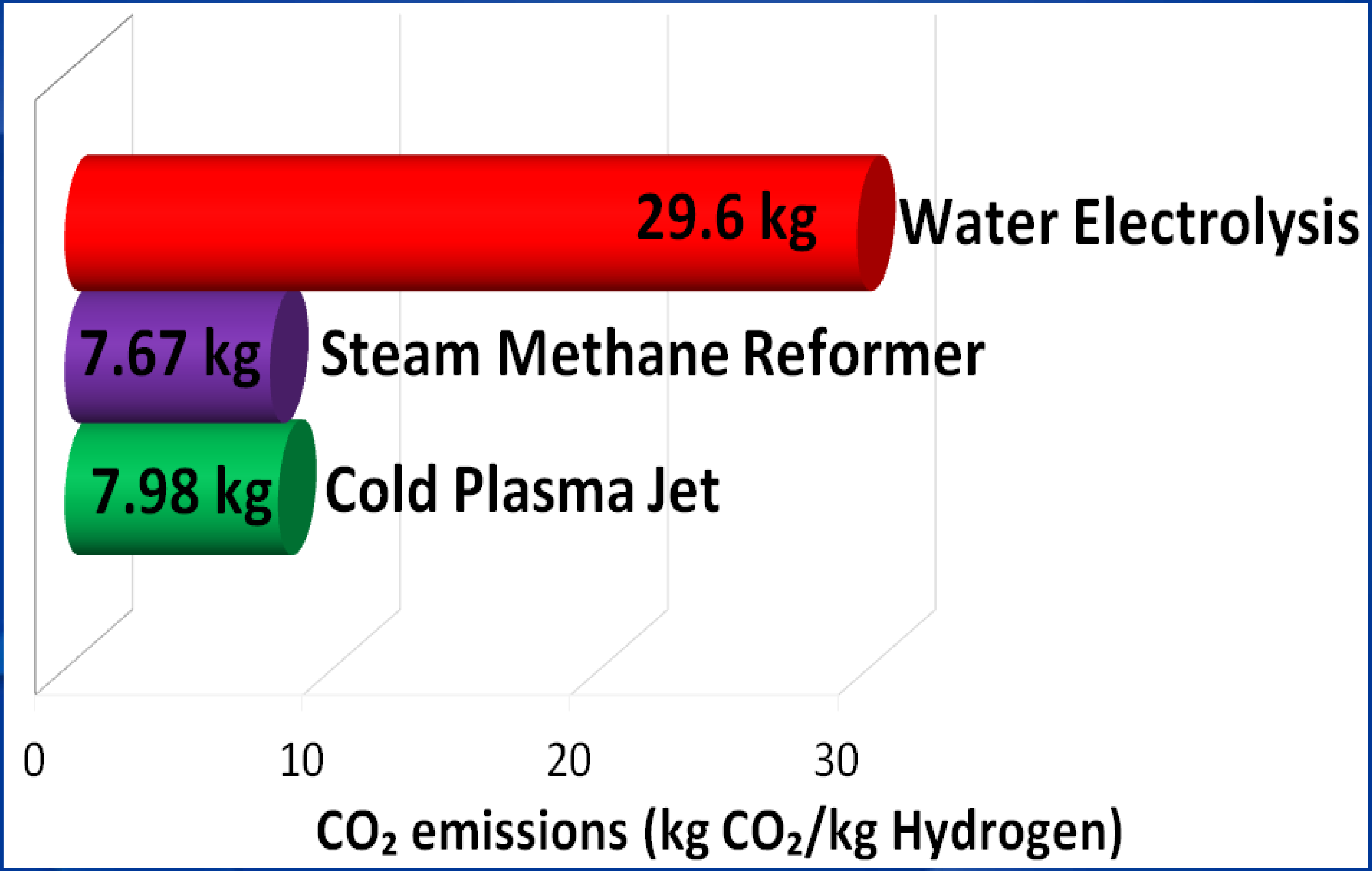
Reformer Performance: The cost of hydrogen



Reformer Performance: CO_2 emissions

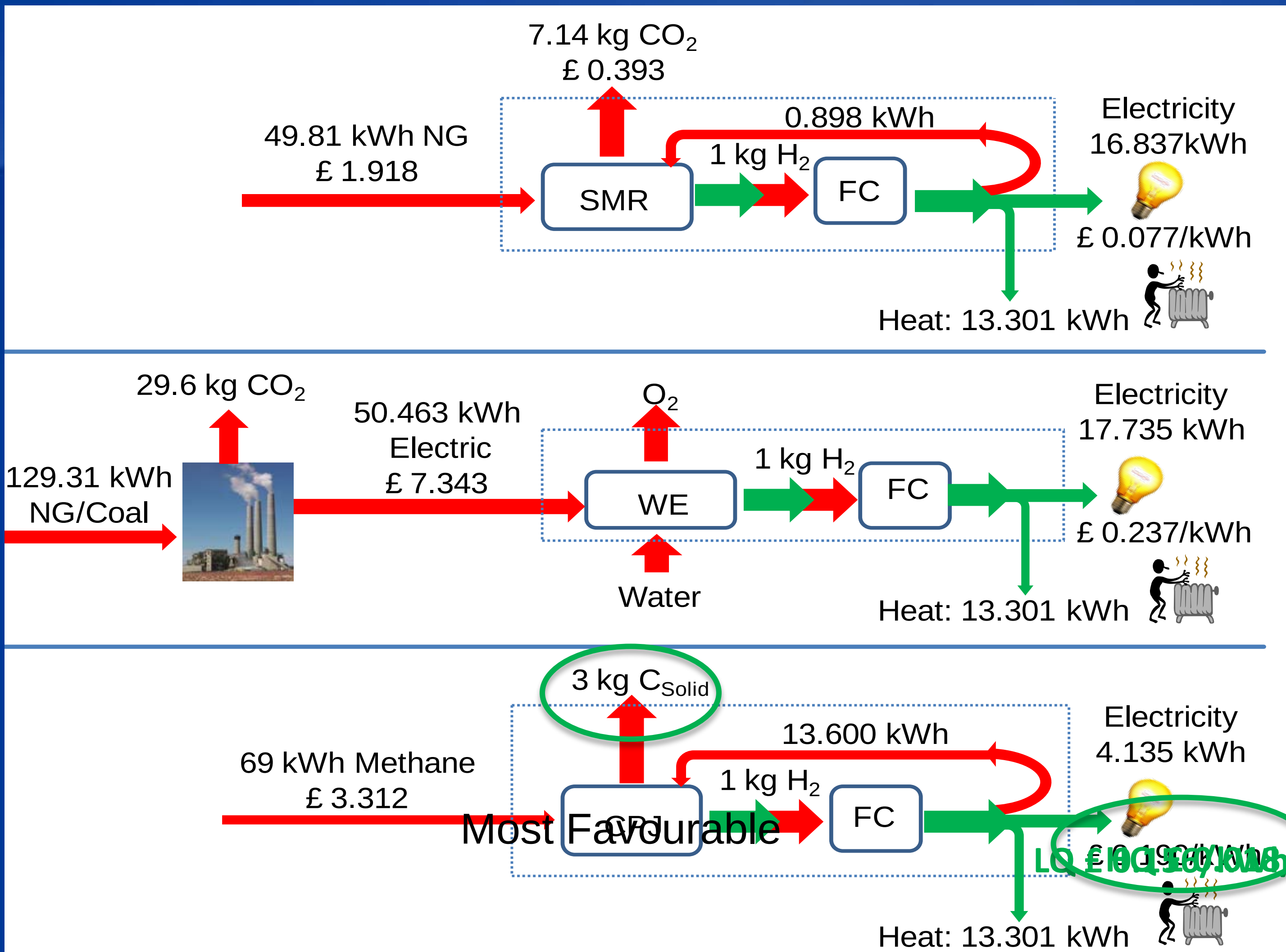


Towards clean and sustainable domestic energy: the potential of integrated PEMFC-CHP

- Proton Exchange Membrane Fuel Cell
  - Reliable and robust
  - Low operational temperature
  - Respond to load at the same efficiency

- Ballard MK5-E PEMFC - CHP stack
  - Temperature: 70 ^{o}C
  - Max output electric: 4 kW
  - Max thermal recovered: 3 kW
  - Power to heat ratio: 1.33
  - Electrical efficiency: 45 %
  - Thermal efficiency: 35 %
  - CHP efficiency: 80 %

THE FUTURE:
Combination of an integrated FC-CHP system



SMR

Steam Methane Reformer

WE

Water Electrolyser

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Cold Plasma Jet

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Conclusions

- Hydrogen economy is highly dependent on the availability of low cost and environmentally friendly sources of hydrogen

- Steam methane reforming
  - ✓ Currently a key technology for hydrogen production
  - ✓ Key drawback: high carbon dioxide emissions from the process

- Water electrolysis and biomass
  - ✓ Key advantage: hydrogen production from renewable sources
  - ✓ Key issues: high energy consumption and carbon dioxide emissions

- Research at Brunel University: Plasma assisted hydrocarbon decomposition
  - ✓ No catalyst: eliminate cost of catalyst regeneration /replacement
  - ✓ No carbon dioxide emissions
  - ✓ Generates two valuable products: hydrogen and solid carbon
  - ✓ Cost of hydrogen production is lower than with water electrolysis and competitive with steam methane reforming

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