Recent advances in plasma-assisted gasification for waste-to-fuel applications

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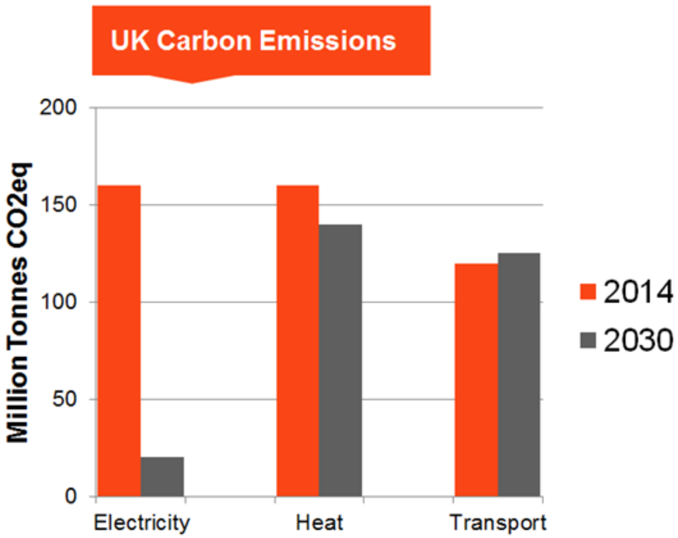
Waste gasification: Commercial application and R&D activities
Tuesday 26 November 2019, Burlington Hotel, Birmingham, UK

The UK Fuel Networks role in a 2050 whole energy system



'2050 Energy Scenarios The UK Gas Networks role in a 2050 whole energy system' KPMG (2016)
'Future of Gas' National Grid (2016)

- ✓ We need low carbon, secure and affordable solutions for heat and transport (HGV, Aviation, Shipping)
- ✓ In its recent report, the CCC acknowledged that the UK has made good progress decarbonising the power sector, but '*almost no progress in the rest of the economy*'
- ✓ Currently UK has 15m tpa sent to landfill and 3m tpa of RDF (Refuse Derived Fuel) exported.
- ✓ Sustainable drop-in fuels provide the lowest cost pathways to decarbonised heat and transport using existing infrastructure

The evolution towards waste…

Dakota

The largest SNG facility in the world, with 3GWth input capacity (producing ~200,000 Nm3/hr CH4), fuelled by lignite. Gasifiers: Lurgi Dry Ash with Rectisol gas cleaning. Has Carbon capture fitted.

GobiGas

Fuel: Wood pellets. Indirect gasifier. Phase 1: 32MWth input, Technology: Repotec

Edmonton

Fuel: MSW. Steam-Oxy gasifier. Scale: 100k tonns/year input, Technology: Enerkem

Waste-to-Alcohols

Biomass-to-Gas

Power to Gas

Coke oven gas (CO_2 meth.)

Coal-to-Gas

Methanation for gas cleaning (Ammonia synthesis, Hydrogen production, PEM fuel cells, etc.)

1902 Sabatier

1910 Haber-Bosch patent

1925 Fischer-Tropsche

1950

1973 Oil crises

2000

2014 Waste pilot

The evolution towards waste…

FEEDSTOCK

- The UK's dominant biomass resource is waste derived.
- Globally few to no WtF projects using waste feedstock

TECHNICAL CHALLENGES

- **Heterogeneous feedstock** (size and composition)
- **Sensitivity to ash content** (quantity and composition)
- **Tar yield**
- Provision of **clean, high quality synthesis gas**
- Gas cleaning and Catalytic transformation at **moderate scale**, implicit in renewable resources

DEVELOPMENT PATHWAY

- The technical approach needs piloting and sustained operation
- R&D efforts on new technologies

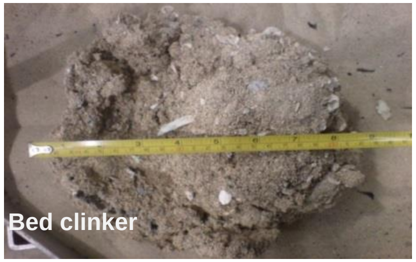
Fluidised bed gasification (FBG)

- Gasification by oxygen and steam (direct heated)
- Ideally suited to non-homogeneous feedstocks
- Readily scalable
- No need for fuel pellettization/torrefaction
- Typically operate at 700-850ºC

Ravenna (Italy) 200t/day RDF Fluidised Bed Plant

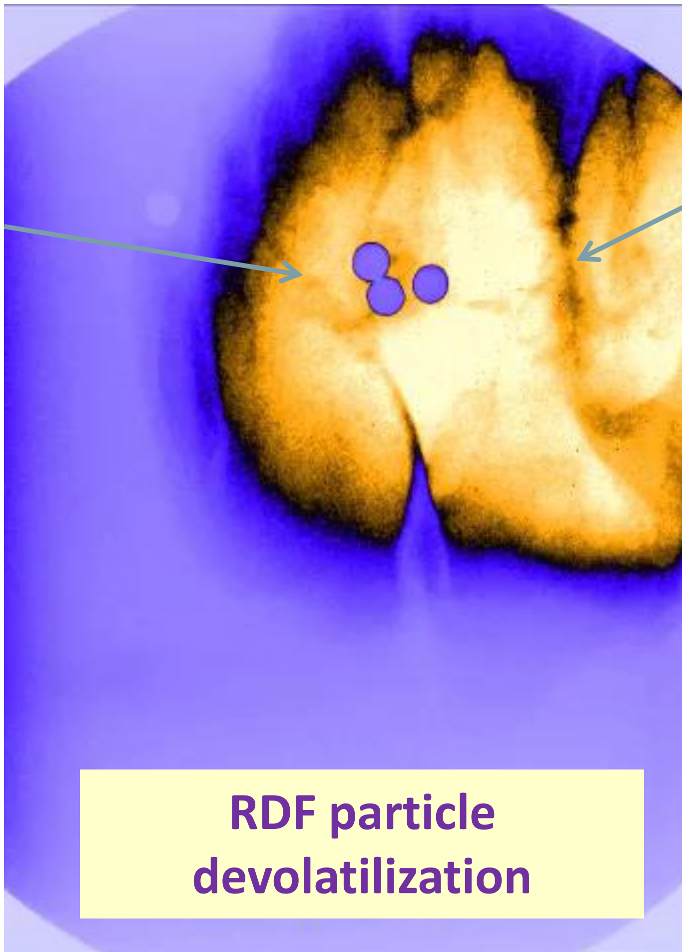
Challenges with operation on waste

- Agglomeration risk (defluidization)
- > 100-10,000 mg/Nm^3 tar content
- > 5-10 g/m^3 VOC, $C_{<6}H_x$
- > 5-10 ppmv organic sulphur (excluding COS and CS_2)
- Increase rates of ash deposition in the ducts and on heat transfer surfaces

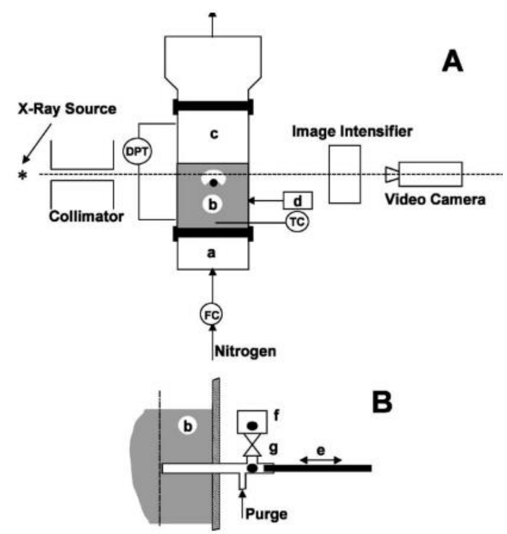


X-Ray analysis of devolatilising RDF

Waste particle



Endogenous bubble

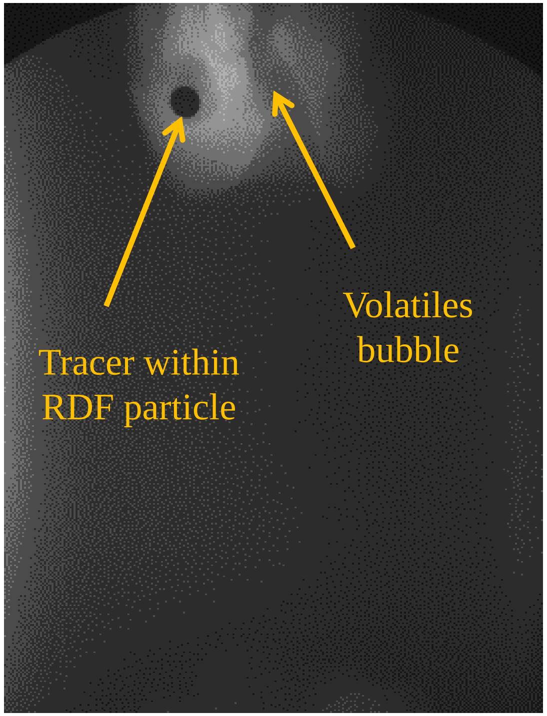


Materazzi, M. (2016). Conversion of biomass and waste fuels in fluidised bed reactors

Enhanced segregation from RDF

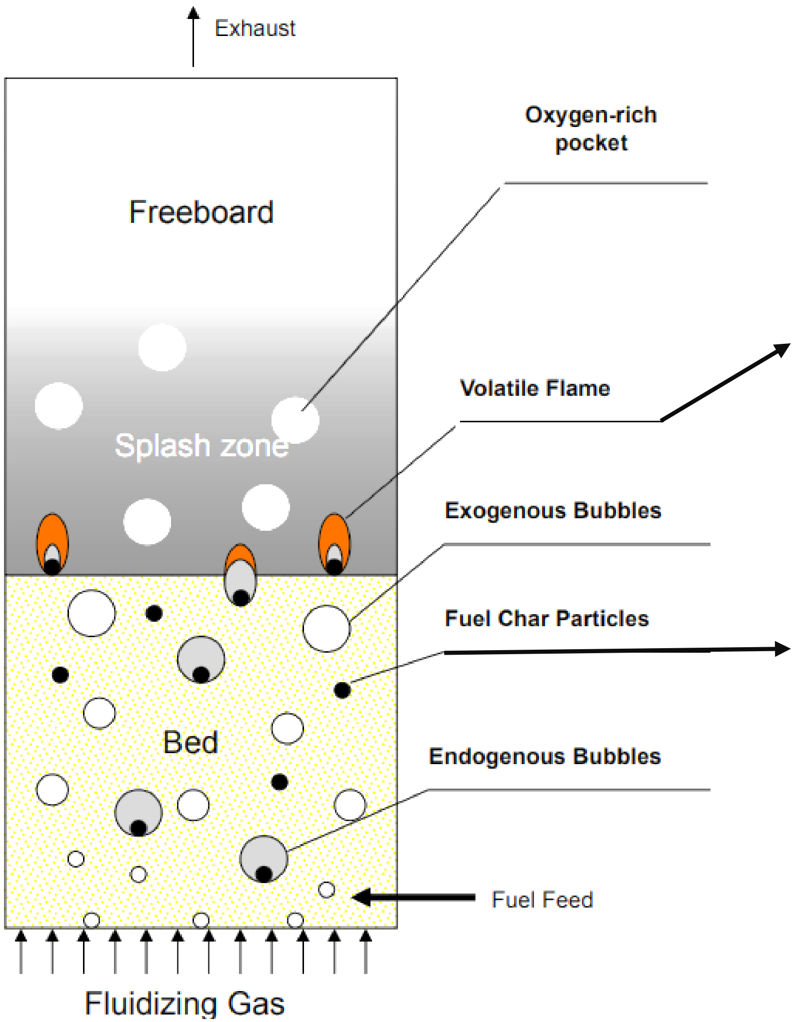
"**Stratified**" conversion: volatile matter mostly released above the bed and bypassing bed solids:

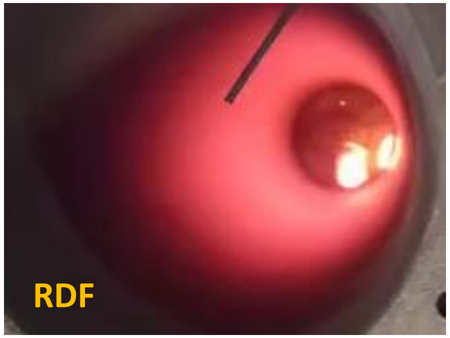
- loss of beneficial effects of bed solids as thermal flywheel,
- prevalence of "flaming" over "flameless"
- reaction loss of potential catalytic effects of bed solids (e.g. tar cracking).
- burn-out of fine particles in the freeboard/upper riser, higher conversion temperature

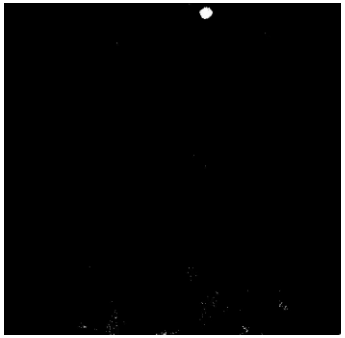


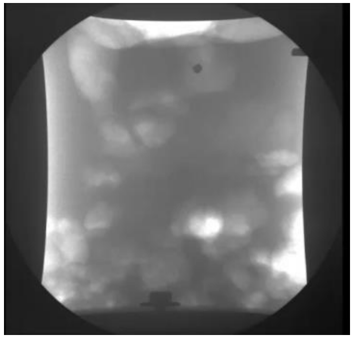
Materazzi et al. (2018), unpublished

Enhanced segregation from RDF









Materazzi, M. (2016). Conversion of biomass and waste fuels in fluidised bed reactors

… and solid drops

Plasma assisted gasification: a multi-disciplinary and multiphysics problem

- Formed by DC or AC electric arcs, radio-frequency or microwave electromagnetic fields
- Highly ionised (typically 100%, at least 5%)
- Strong radiative emission
- Local T_{gas} = 2,000-20,000K (close to equilibrium)
- Highly electron density (~10^{23} m^{-3})
- Very widely used in manufacturing and other industries (ash smelting, metal recovery, etc.)
- Quick start-up, possibility to couple with renewable electricity

Plasma assisted gasification: a multi-disciplinary and multiphysics problem

$T_e \approx T_v \approx T_n$

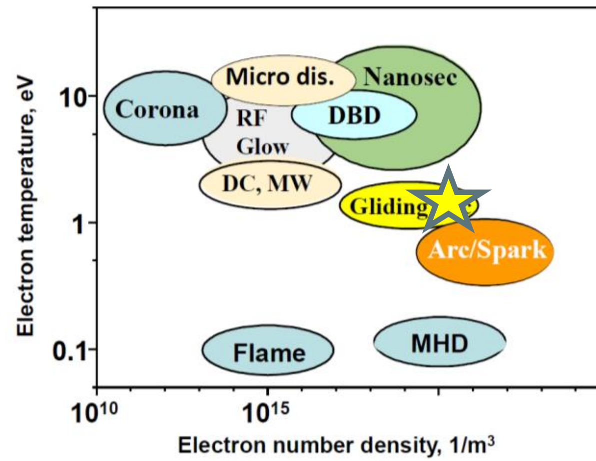
Near Equilibrium plasma

arc

T_n~n*10,

$T_e > T_v > T_n$

Electron temperature



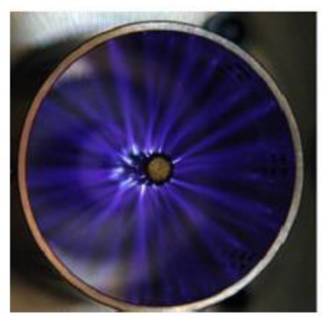
Gliding arc

T_n~n*1000 K

Electron number density

Non-Equilibrium plasma

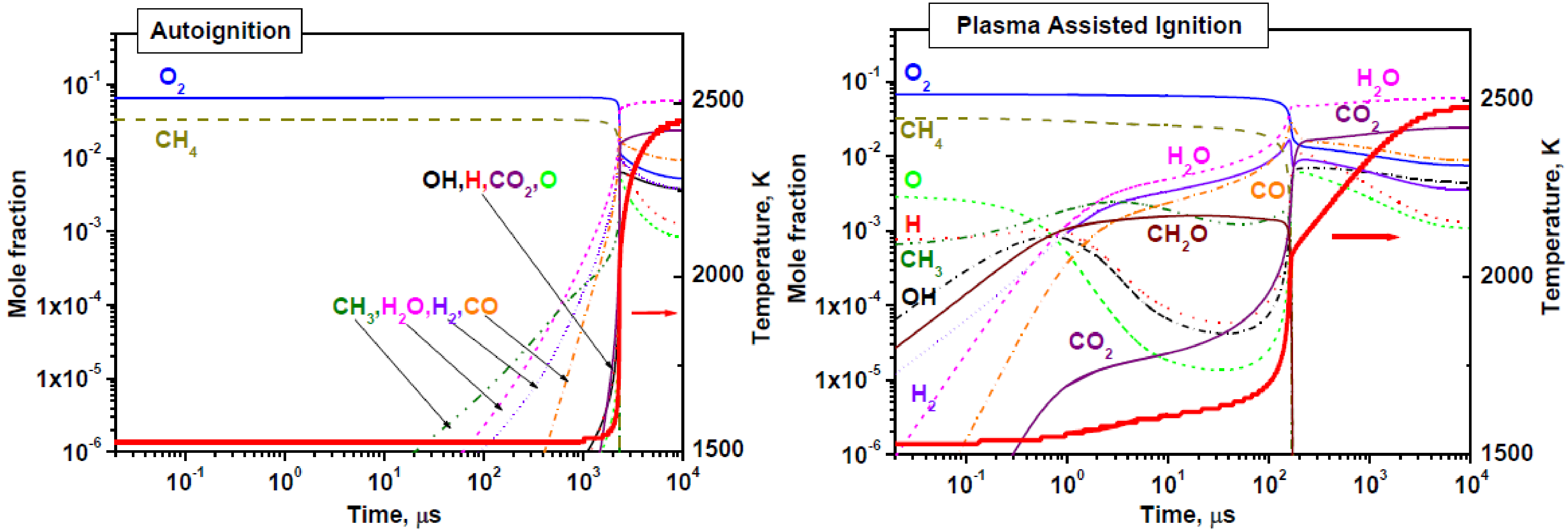
$T_e >> T_v >> T_n$



Corona

T_n~n*100 K

Plasma assisted gasification: a multi-disciplinary and multiphysics problem

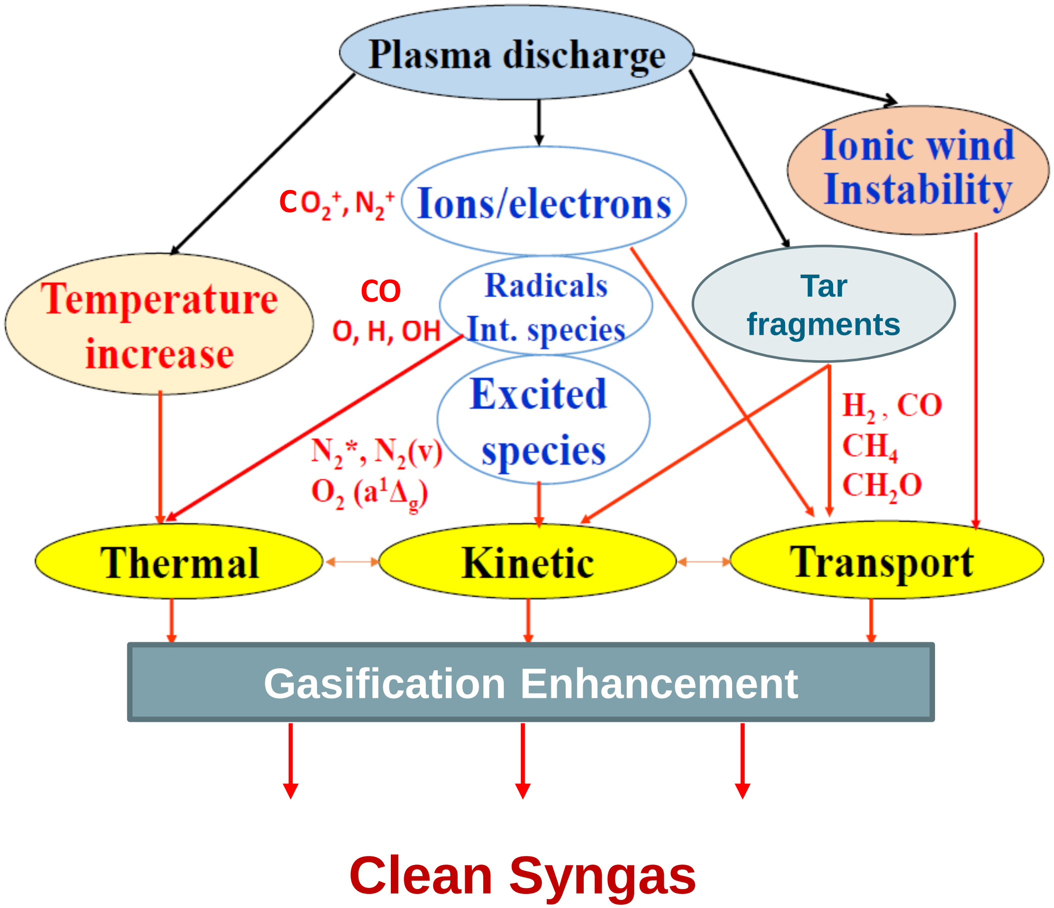


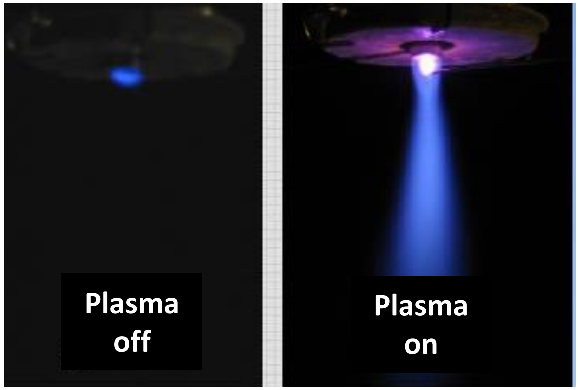
Plasma assisted ignition is characterized by:

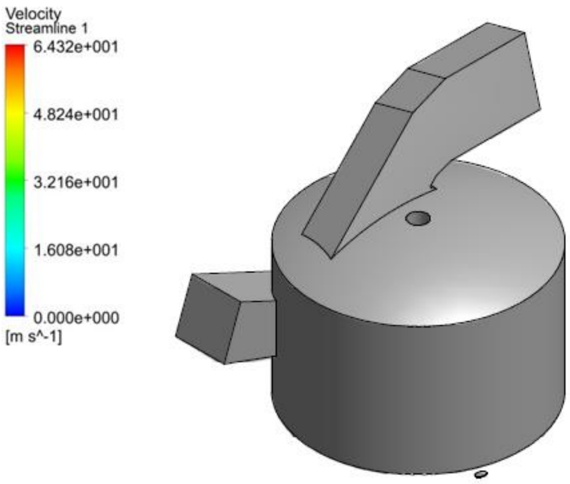
– slow increase of gas temperature
– developed kinetics of intermediates
– partial fuel conversion during induction time

I N Kosarev, N L Aleksandrov, S V Kindysheva, S M Starikovskaia, A Yu Starikovskii, Combustion and Flame, 154 (2008) 569-586

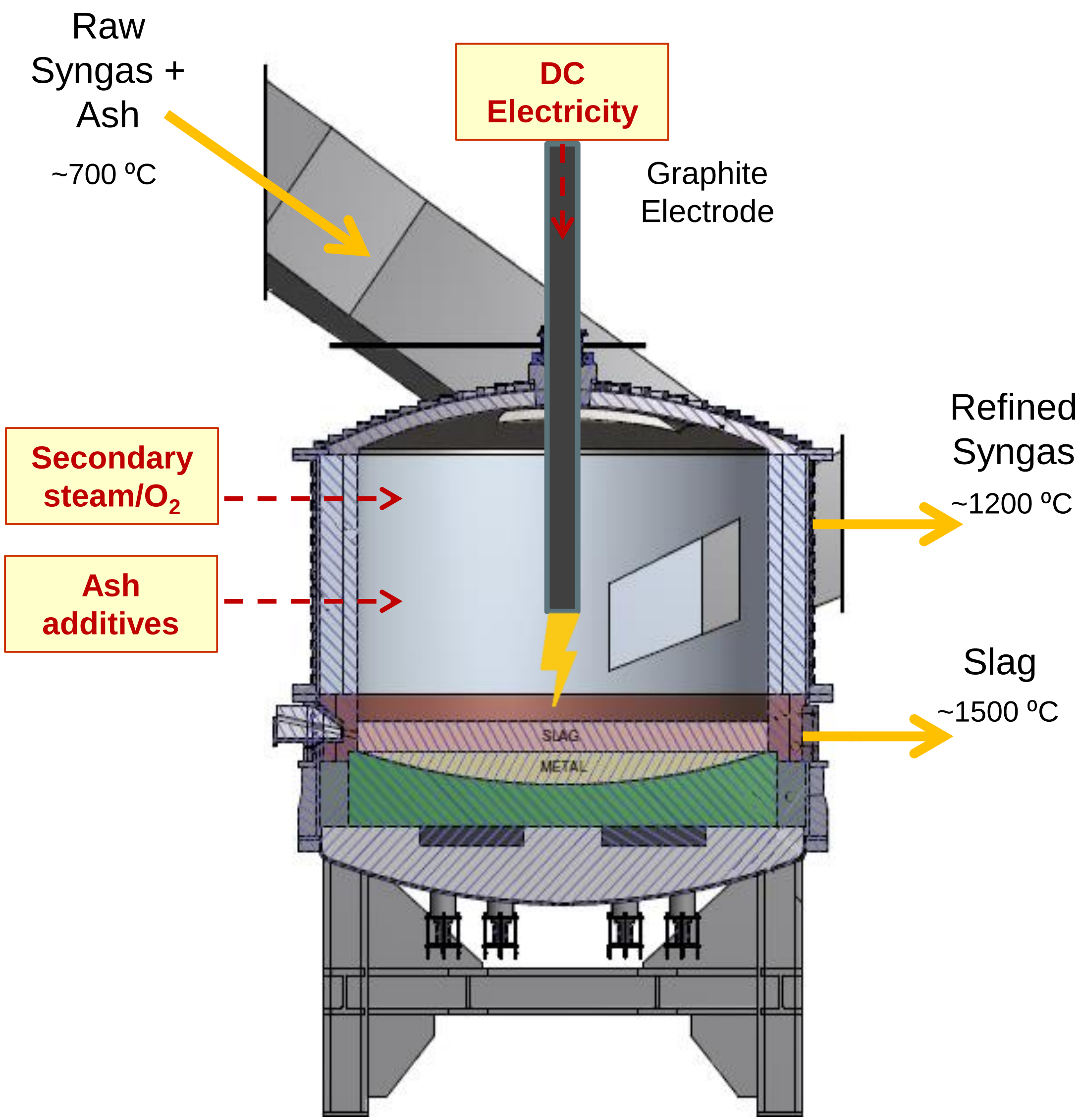
Plasma assisted gasification: a multi-disciplinary and multiphysics problem







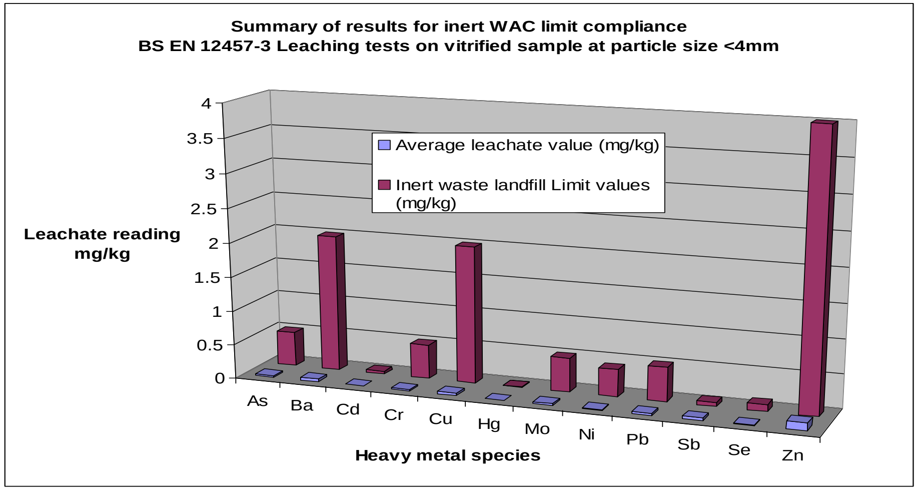
Thermal plasma reforming in DT furnaces



Thermal plasma reforming in DT furnaces

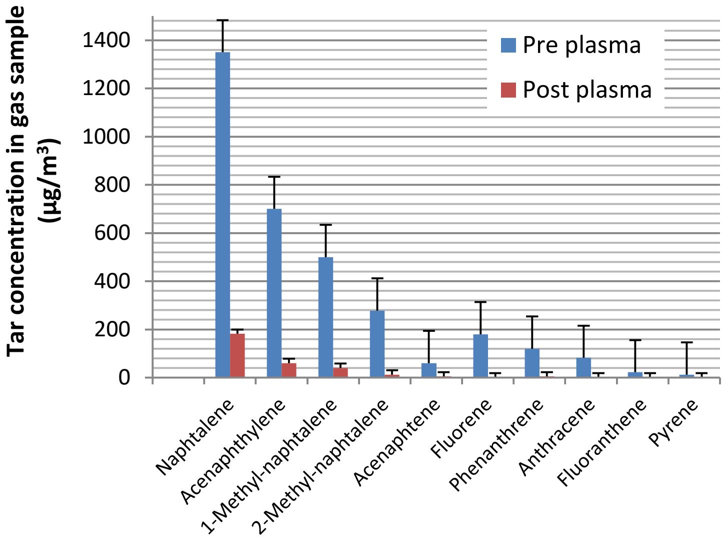
When used in combination with a FBG, plasma has several advantages:

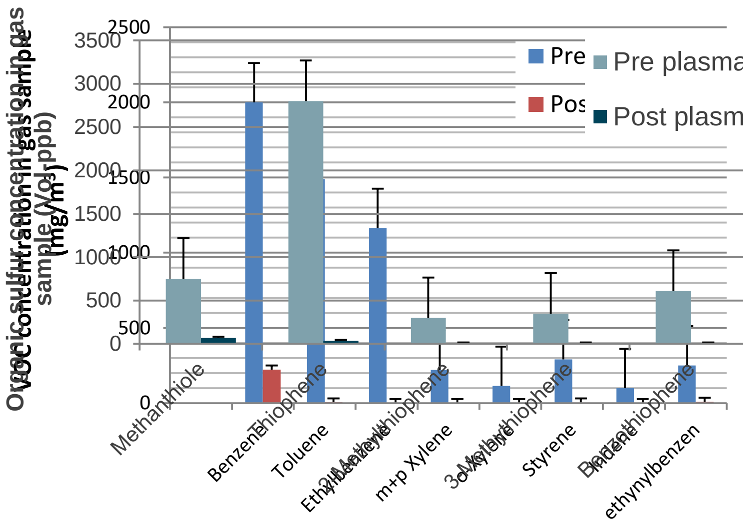
- **Applies plasma energy to transform traditional char and tars from FBGs** to clean, simple syngas components (H_2 + CO)
- **Possibility to operate at optimal Equivalence Ratio** (staging the oxidant stream)
- **Independent optimization** of each operation
- **Captures and vitrifies most of the ash generated from the FBG**, producing an non-leachable, mechanically strong product that can be used as an aggregate material
  (Main constituents: Silica 37%; Lime 31% ; Alumina 16%. Others include: Iron Oxide; Titania; Magnesia).

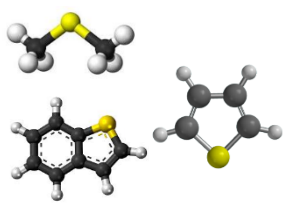


Thermal plasma reforming in DT furnaces

- Tars are converted overwhelmingly to CO and H_2
- Tars reduced to 300µg/m^3 (< 20 after gas cleaning)
- VOCs reduced to <250mg/m^3 (< 25 after gas cleaning)
- Organic-S is less than 500 ppbv, i.e. ~ 93% less than that of a conventional FBG gasifier
- **Carbon to carbon conversion efficiency >96%**

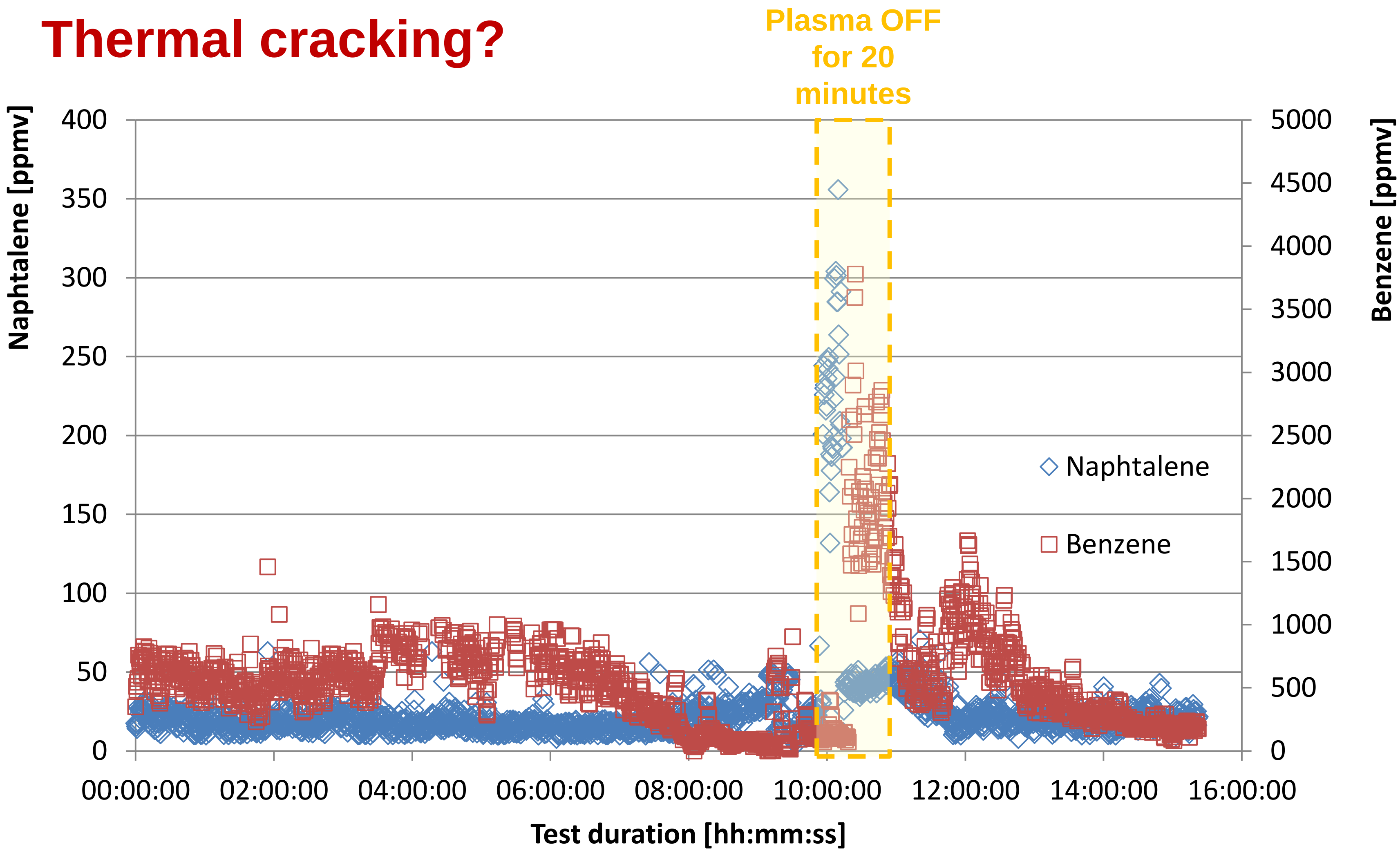






Materazzi, et al. *Fuel Process. Technol.*, 137 (**2015**), pp. 259-268

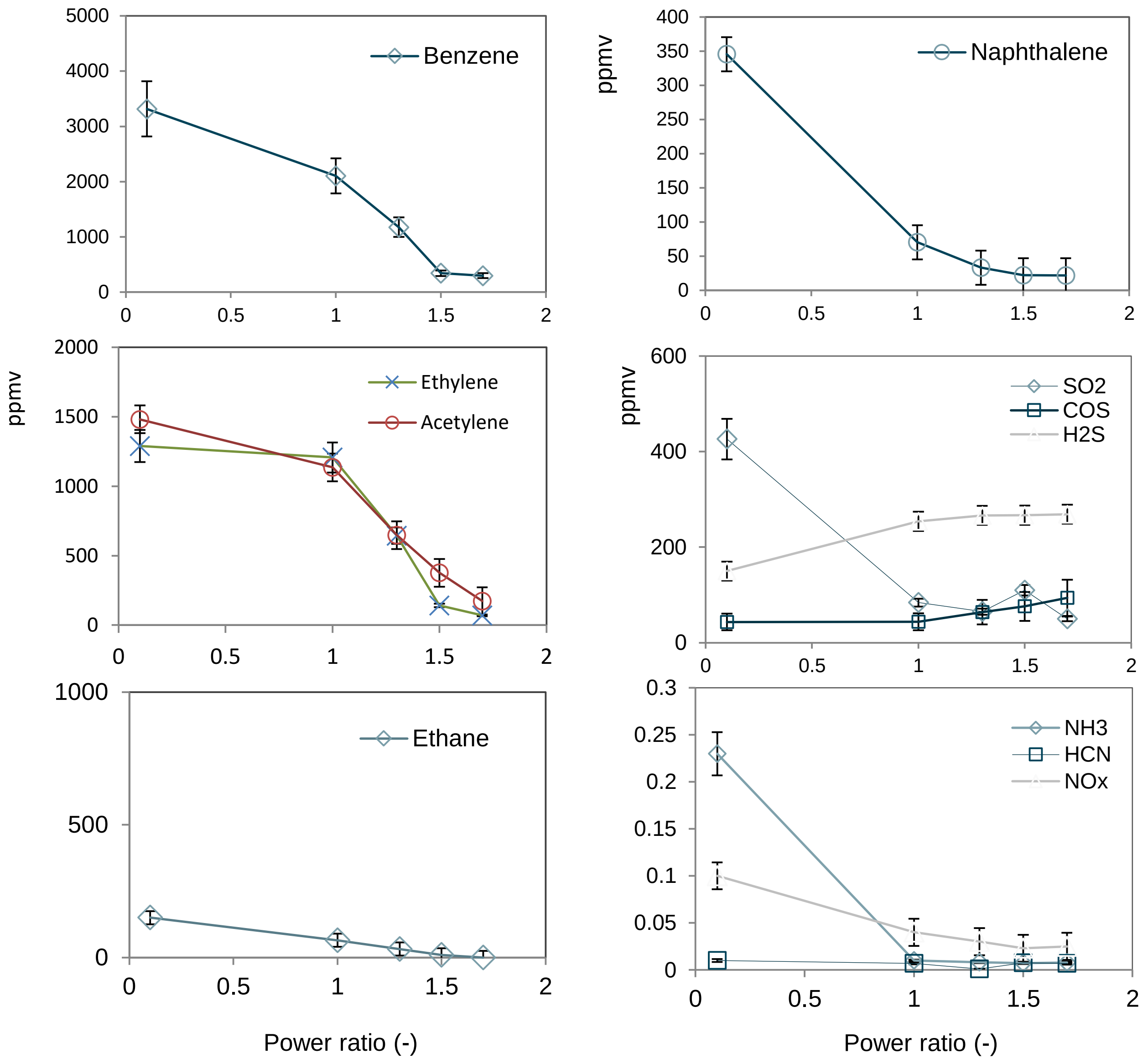
Thermal cracking?



– Effect of plasma on tar reforming is to '*some*' extent disconnected from temperature

– Research on effect of O and OH radicals in progress

Isothermal tests



BioSNG PILOT PLANT (50 kWth)

Project

- Three year programme to establish technical, environmental and commercial viability of BioSNG production from waste and residues.
- Successfully completed March 2017.
- Overall cost £5m (£4m EU and UK grants).

Cadent Your Gas Network

Advanced Plasma Power

Carbotech Viessmann Group

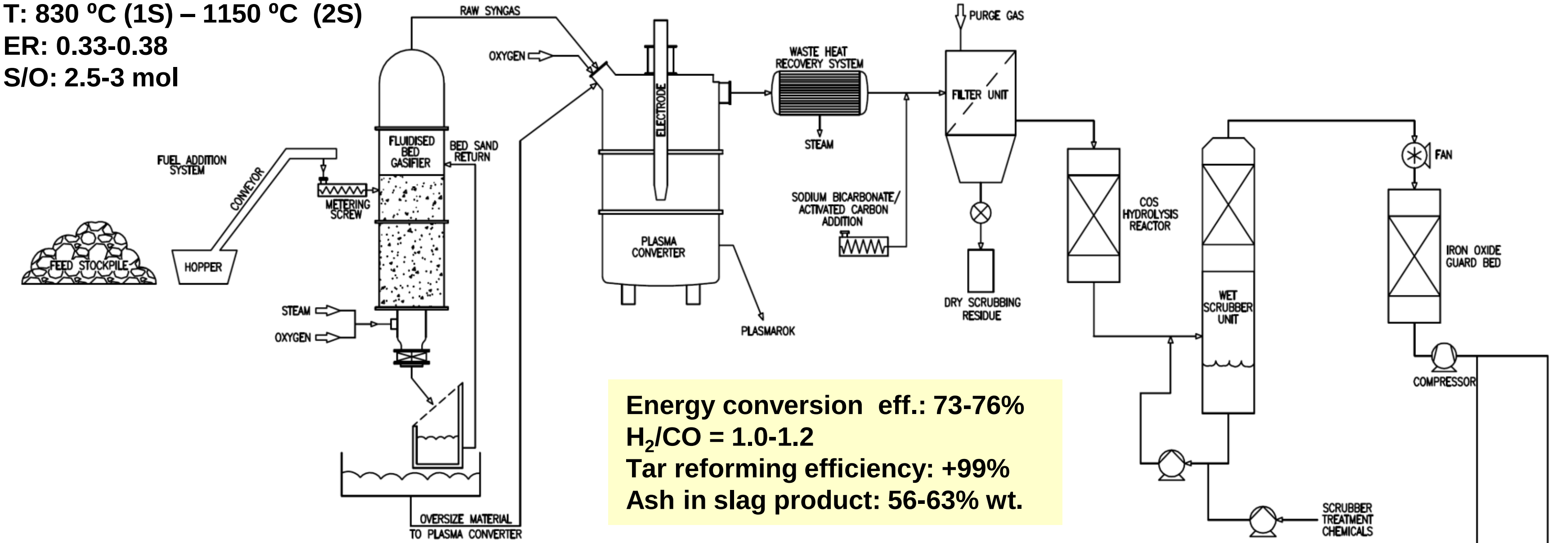
Progressive energy

UCL

Pilot plant configuration

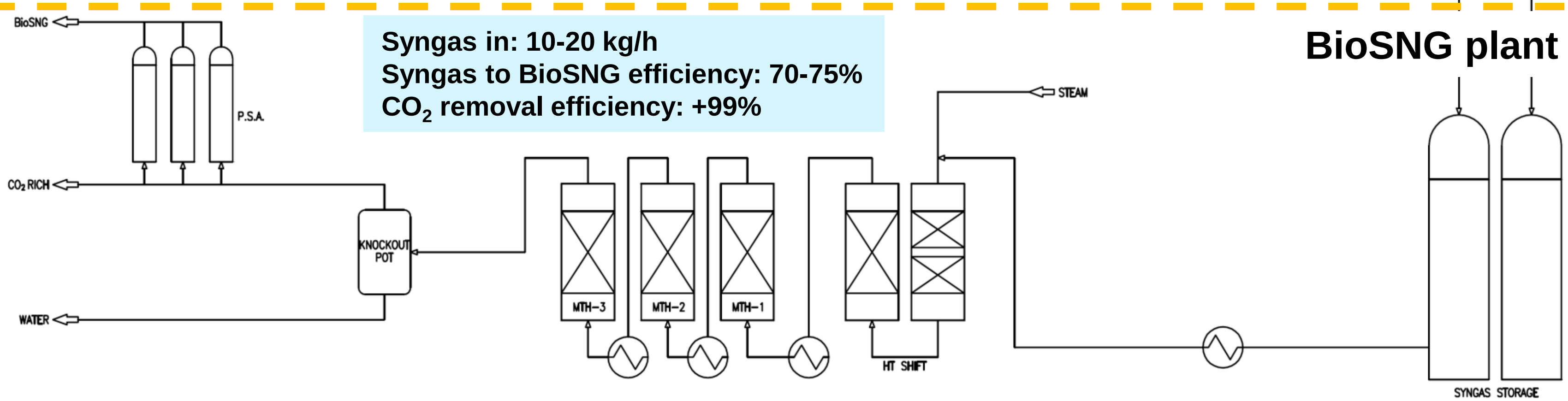
Gasification plant

~100 kg/h RDF (GCV:22.1 MJ/kg)
T: 830 ºC (1S) – 1150 ºC (2S)
ER: 0.33-0.38
S/O: 2.5-3 mol



Energy conversion eff.: 73-76%
H_2/CO = 1.0-1.2
Tar reforming efficiency: +99%
Ash in slag product: 56-63% wt.

BioSNG plant



Syngas in: 10-20 kg/h
Syngas to BioSNG efficiency: 70-75%
CO_2 removal efficiency: +99%

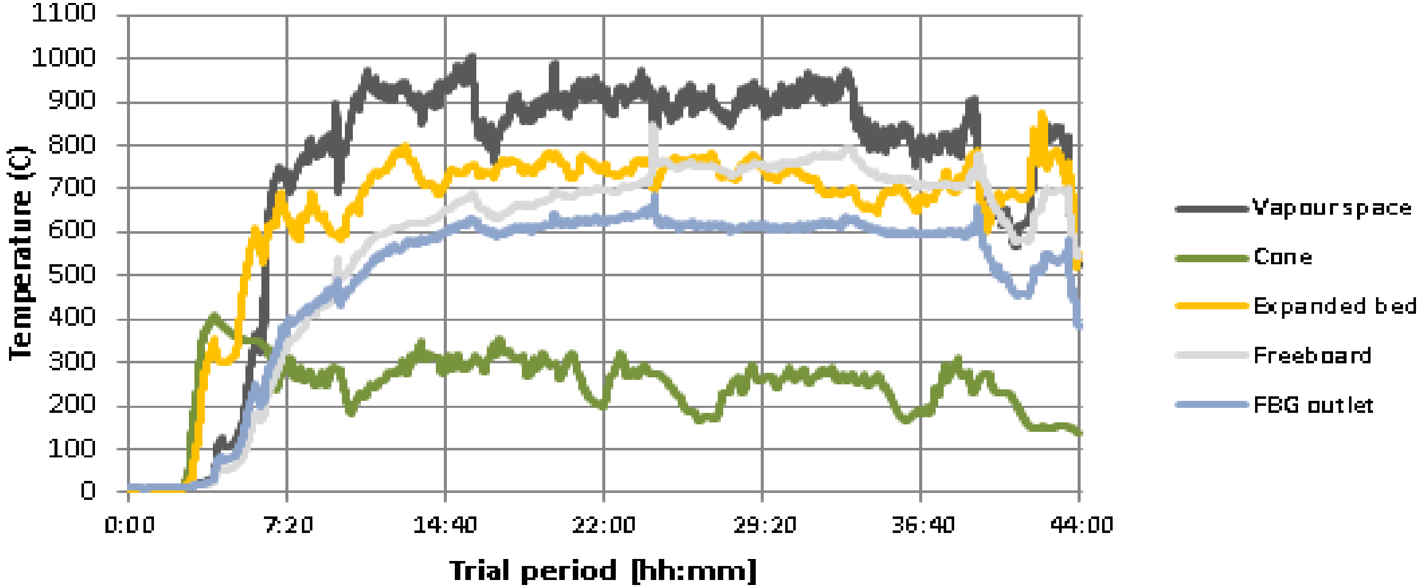
Feedstock

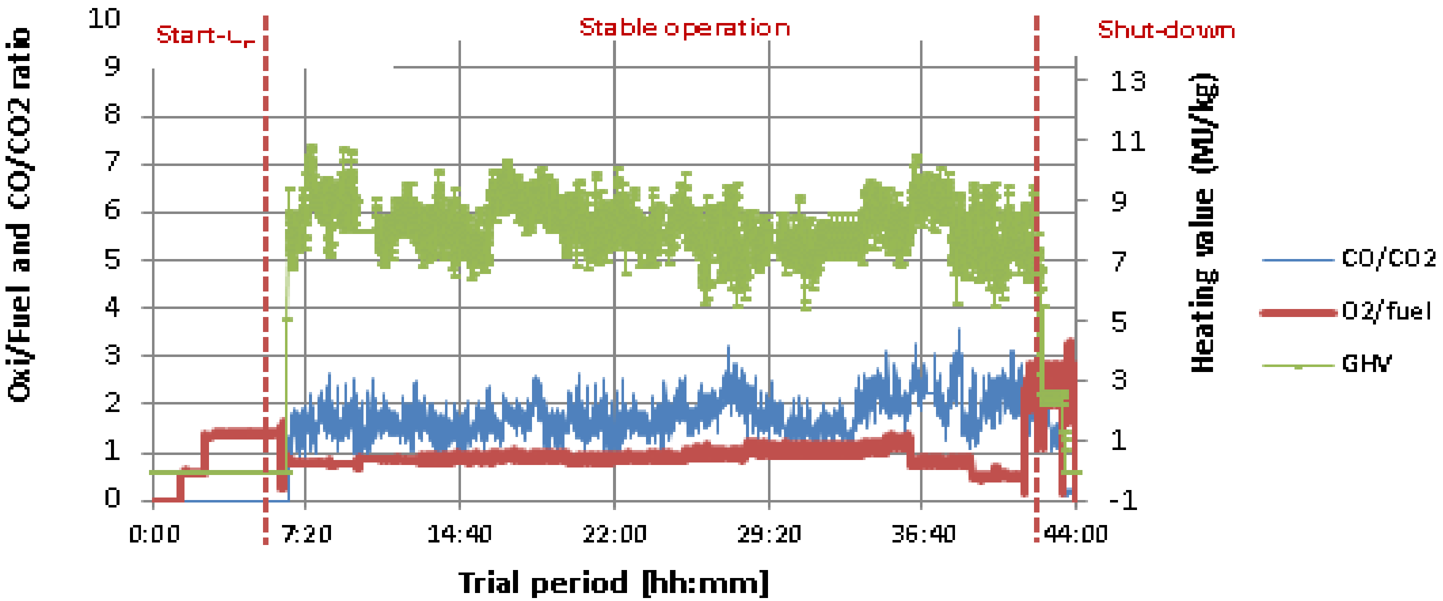
RDF (Refuse Derived Fuel)

	RDF (as received)
Description:	
Proximate analysis, % (w/w)	
Fixed carbon	6.4
Volatile matter	59.6
Ash	19.1
Moisture	14.9
Ultimate analysis, % (w/w)	
C	41.0
H	5.7
O	17.5
N	1.2
S	0.2
Cl	0.4
GCV, MJ/kg (dry basis)	22.1

ROC: > **60% wt. biomass content** in the feedstock

Category	Design Point	Lower limit	Upper limit
Paper (wt%)	30.36	19.47	64.00
Plastic Film (wt%)	5.72	3.55	17.80
Dense Plastics (wt%)	8.38	5.50	16.20
Textiles (wt%)	3.64	0.20	8.17
Disposable Nappies (wt%)	4.91	0.00	8.00
Misc Combustible (wt%)	6.40	2.29	10.92
Misc Non-Combustible (wt%)	6.08	0.00	8.93
Glass (wt%)	7.01	0.60	11.00
Putrescible (wt%)	16.82	3.00	27.00
Ferrous (wt%)	6.61	1.10	11.69
Non-ferrous (wt%)	1.96	0.60	2.90
Fines (wt%)	2.13	1.00	5.50
Total	100.00		
CV (MJ/kg)	10.05	9.08	13.62
RDF biomass content (wt%)	67.7	49.1	80.1
RDF biomass content (energy%)	64.1	39.9	79.8


Temperature (C)
1100
1000
900
800
700
600
500
400
300
200
100
0
0:00
7:20
14:40
22:00
29:20
36:40
44:00
Trial period [hh:mm]
Vapourspace
Cone
Expanded bed
Freeboard
FBG outlet


Oxi/Fuel and CO/CO2 ratio
10
9
8
7
6
5
4
3
2
1
0
Stable operation
Shut-down
13
11
9
7
5
3
1
-1
Heating value (MJ/kg)
0:00
7:20
14:40
22:00
29:20
36:40
44:00
Trial period [hh:mm]
CO/CO2
O2/fuel
GHV

Syngas quality

Quality Parameter:		Stored syngas
Composition:		
H_2	vol.%	35.77
CO	vol.%	33.20
CO_2	vol.%	23.54
CH_4	vol.%	1.67
H_2O	vol.%	0.89
Other	vol.%	4.90
Energy Analysis		
NCV	MJ/kg	8.75

Further conditioning:

HT- Water Gas Shift

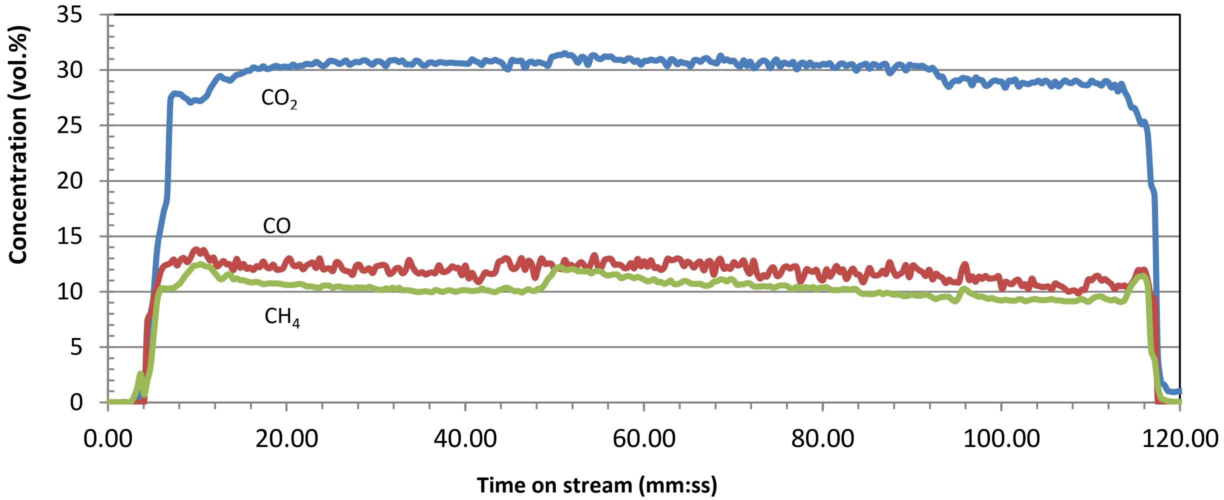
- **Fe_2O_3 78-80 wt.%, Cr_2O_3 > 7 wt.%**
- Operating temperature: 350 ^oC
- H_2: $(3CO+4CO_2)$ = 0.25 - 0.5
- Residual COS hydrolysis

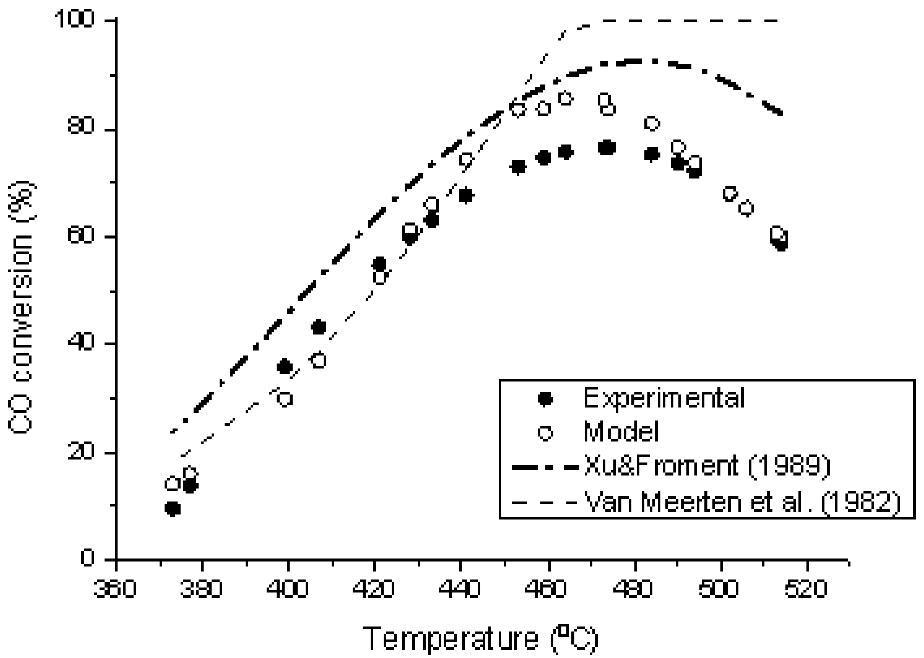
Trace S mop-up guard bed

- ZnO T=300 ^oC

$ZnO\ (s) + H_2S\ (g) \rightarrow ZnS\ (s) + H_2O\ (g)$

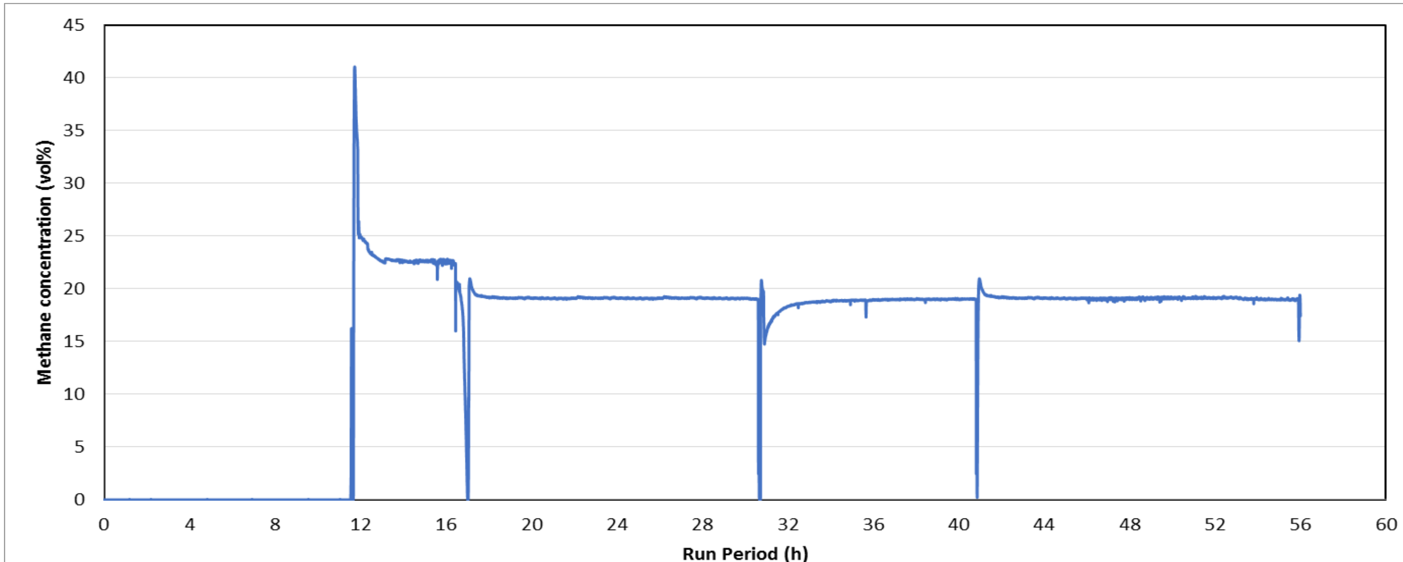
Methanation trials

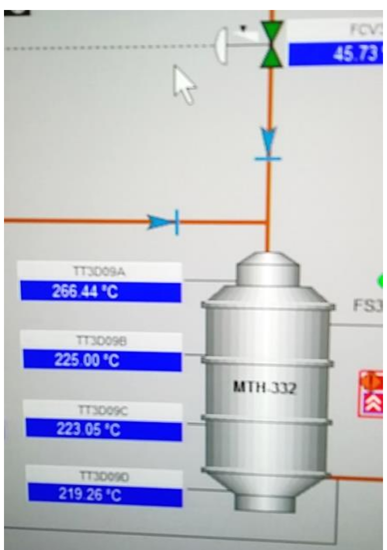


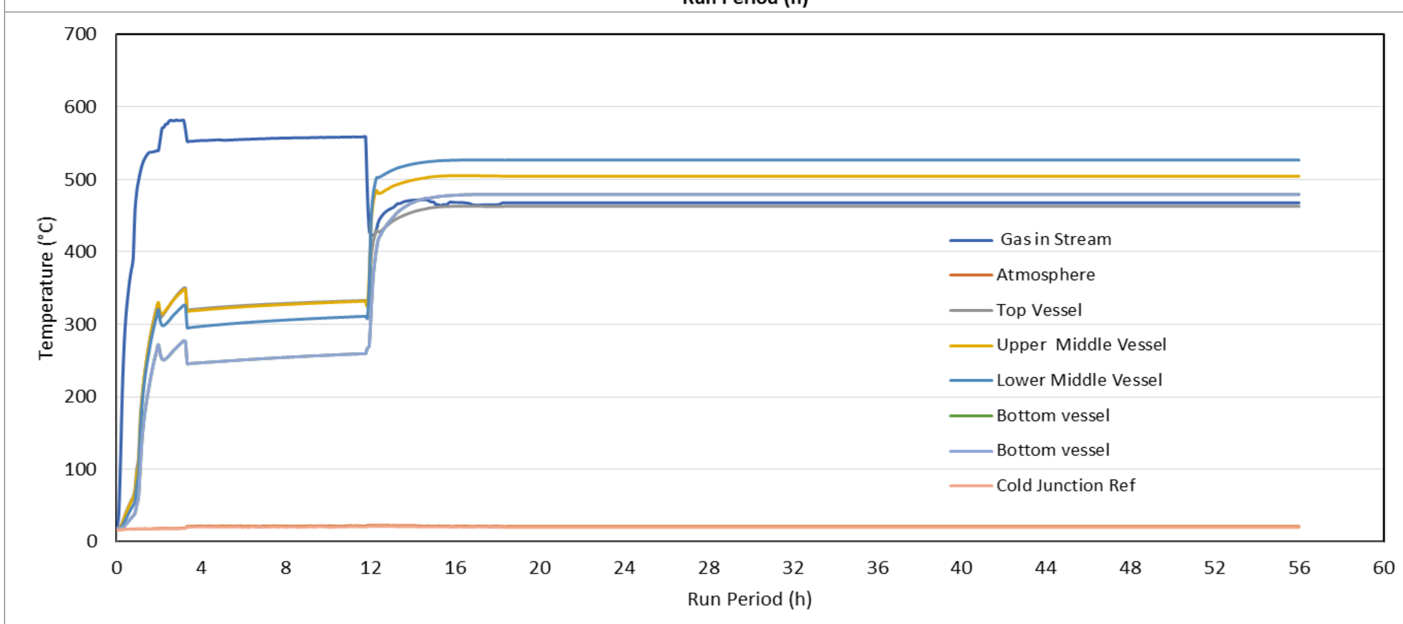


- **1th methanation reactor (MTH-1)**
- **Ni/Al_2O_3 (10% wt. Ni)**
- **GHSV: 5,000 - 10,000 h^{-1}**

4-day methanation with waste-derived syngas …

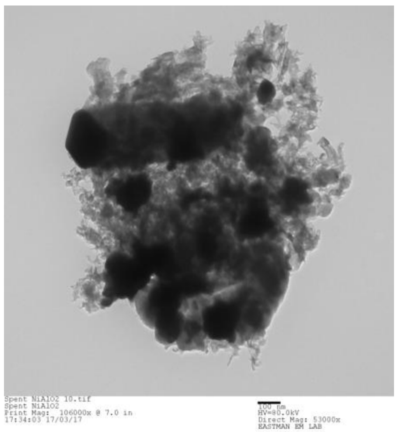




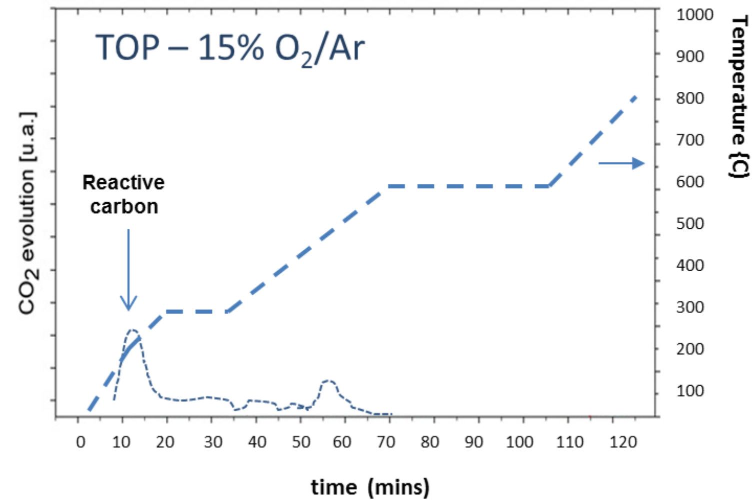


Spent catalysts analysis

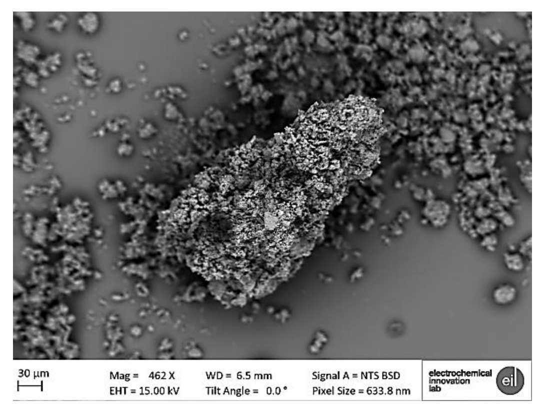
Temperature Programmed Oxidation (TPO) analysis of the catalyst samples from the first methanation reactor clearly showed that during trials almost no polymeric carbon was formed nor detectable sulphur was deposited.



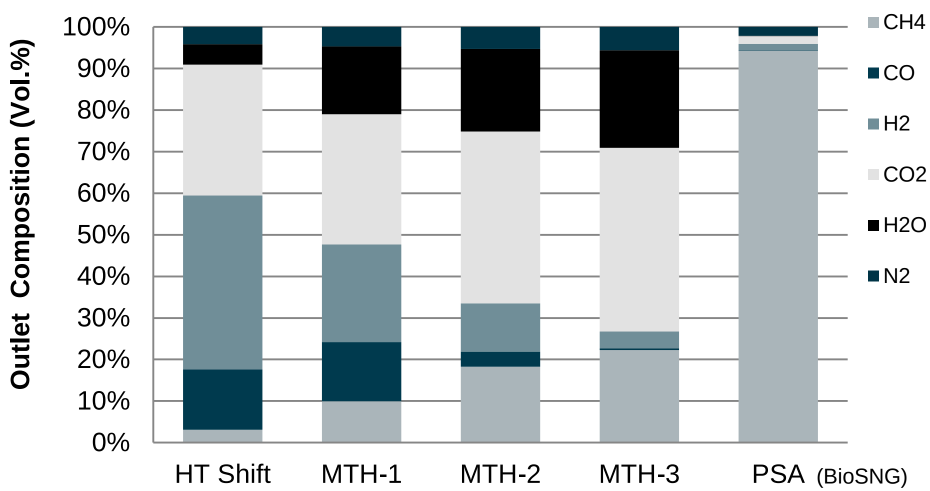
Transmission electron microscopy (TEM) showing Ni particles (black) and surface carbon



SEM image (X470) with Back-scattered electrons (BSE)



Final BioSNG product



	GS(M)R	Pilot
Sulphur	< 50 mg/m^3	None
H_2	< 0.1 % (molar)	0.1 – 1.5%
O_2	< 0.2 % (molar)	None
Wobbe	> 47,2 MJ/m^3 < 51,4 MJ/m^3	35.0-41.6 MJ/m^3 (pre-enrichment)
Other impurities	No liquid below HC dewpoint	None

- ✓ If additional hydrogen is added from external electrolyser, BioSNG output can almost be tripled compared to conventional Waste-to-Gas processes.
- ✓ Up to 60% of residual N2 and H2 remains in the product stream, demonstrating that to meet gas grid quality requires upstream control of these components.
- ✓ Also by reducing inerts to below 3% it is impossible to meet GSMR Wobbe index with methane gas alone. Additional HC synthesis or enrichment is required.

FULL CHAIN 5MW$_{TH}$ SMALL COMMERCIAL FACILITY

absl

wood.

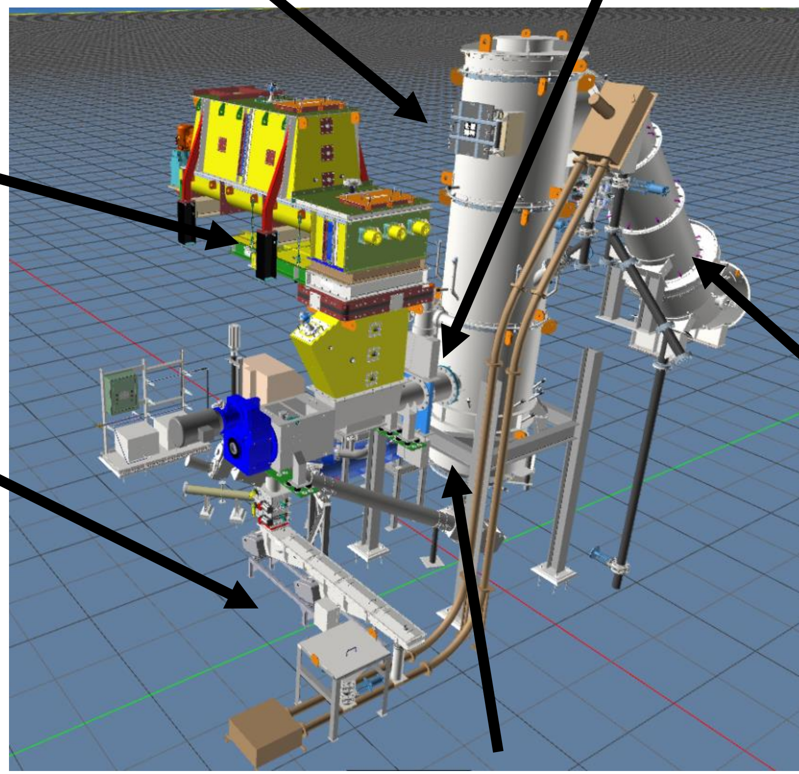
THE WORLD'S FIRST GRID CONNECTED, FULL CHAIN, WASTE TO SNG FACILITY OPERATING UNDER COMMERCIAL CONDITIONS

Gasifier

Gasifier shell.
Refractory lined steel tube.

Screw feed.
Screw system to inject feedstock above gasifier bed.

Feed hopper.
Carbon dioxide purged system to meter feedstock into gasifier.



Bed recycle
Bed continuously filtered to remove large non-combustible material. Fines fed back into gasifier.

Oxygen injection.
Oxygen injected into gasifier outlet duct to raise temperature to 1,200°C.

Gasifier bed.
Bed of sand fluidised using oxy-steam to provide reaction space for gasification reactions to occur at around 800°C.

Demonstration plant gasifier

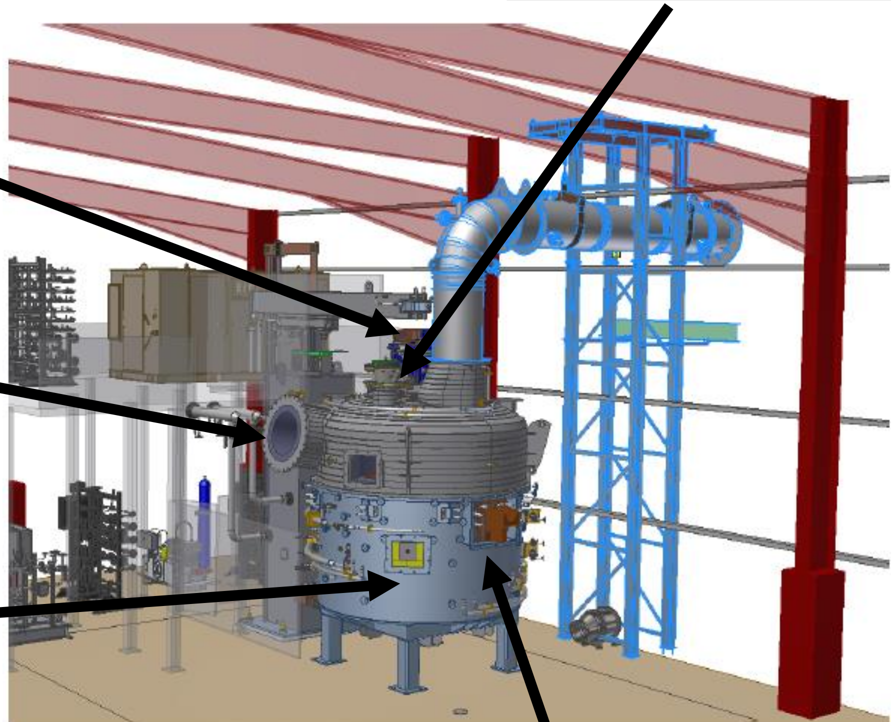
Plasma Arc Furnace

Flux port
Flux added to slag to control chemistry and viscosity.

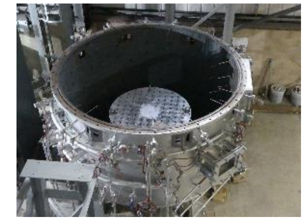
Carbon electrode.
Transfers electric energy into furnace to create plasma arc. Arc creates oxygen free radicals that catalyse break down of tars.

Syngas inlet duct.
Syngas enters the furnace at 1,200°C. Furnace designed to give residence time of more than 5s.

Melted slag
Fly ash in syngas is captured in converter and forms a melt pool at the base.



Tap hole
Slag is periodically tapped into slag pots to form inert vitrified material.



Demonstration plant furnace base - awaiting refractory lining.

Demonstration plant furnace assembled for alignment.

Project progress

- Construction and mechanical integration almost completed
- Single units commissioning undergoing
- Team of 20 to operate plant following completion of commissioning.
- Operating manuals currently being produced based on experience from pilot plant, supplier information and experience in other waste to energy plants.
- Delivery of 1 million kilogrammes of BioSNG in 2020

Conclusions

- Waste derived fuels are very complex materials that need extensive understanding of the physical, chemical, and thermochemical behaviour.
- FBG(indirect or directly heated) can accommodate a wide range of feedstock but need adequate control and ad hoc design requirements for specific applications.
- Plasma in multiple stage processes is proven efficient for tar reforming and ash inertization, with relatively limited parasitic load (when compared to single stage plasma)
- Successful demonstration of methane production from waste, at the design output of 50KW. This endorses several key strategic technical approaches:

- **The importance of producing a high-quality true 'synthesis' gas from the onset**
- **Simplified catalytic processes.**

Next Steps

- Longer term operation for testing catalyst longevity.
- Hundredfold scale-up from the pilot plant to operate under fully commercial conditions.

Thank you

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