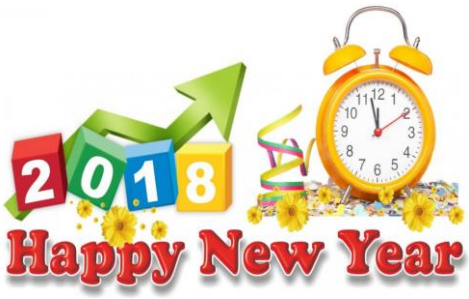
No. 4 **January 2018**

NEWSLETTER

of the
Fuel & Energy Research Forum



EDITOR'S NOTES:
A Happy New Year to all our readers, old and new from our committee. The new venture of the FERF is now beginning to find its feet and interest in what we are doing seems to justify our change of direction.

This newsletter contains a detailed report on the UKCCSRC Autumn Biennial conference held in Sheffield on 11th and 12th September. As the event ran parallel sessions even those who attended would not have been able to attend every session. Hopefully this report, with some project background, may be easier to follow for the 'lay' reader of this newsletter.

Preparations continue for the FERF biennial conference, still badged as ECCRIA now up to ECCRIA 12. Please watch out for further information and those wishing to submit abstracts have until 26th January 2018 to do so. For further information regarding the conference visit our website at http://www.eccria-conferences.org/

Contact Details:

Secretary
Dr David McCaffrey
The Fuel and Energy Research Forum
Tel: 01242-236973
E-mail: mail@tferf.org
Website: http://www.tferf.org

Newsletter Editor & Treasurer
Dr Alan Thompson
The Fuel and Energy Research Forum
Tel: 01332-514768
E-mail: alan.thompson5511@btinternet.com

Student Bursaries for 2017-2018

Travel and subsistence bursaries of up to £300 are on offer to bona-fide full-time students who wish to attend appropriate National and International fuel and energy related conferences, (for example, the 12th ECCRIA Conference, please see the Calendar of Fuel and Energy Research Events for details of future conferences), and whose supervisor is a member of the Fuel and Energy Research Forum. To apply, please send the abstract submitted to the conference with a brief supporting letter from your supervisor together with details of the expected expenditure and other sources of funding applied for, to:

Professor J.W. Patrick,
Dept. of Chemical and Environmental Engineering,
Faculty of Engineering,
The University of Nottingham,
Energy Technologies Building,
Innovation Park, Triumph Road,
Nottingham NG7 2TU

The requirements for eligibility for award of a bursary are that the recipient will submit a short report about his or her impressions of the conference to the Newsletter Editor for inclusion in the next edition. In addition, this report will provide some brief details of the beneficiary, their topic of study and the reasons for wishing to attend the conference. Potential applicants should see the template for these reports on the FERF website, http://www.tferf.org where such reports must comply with these requirements.

Please note that these bursaries are only for travel and subsistence to attend the conference, (i.e. not for conference or other fees). In addition, priority will be given to applicants who will be attending the whole of a conference rather than one day of a multi-day event and will be using the conference accommodation provided should this be required. It may not be possible to fund all applications for bursaries or meet the request in full as this will depend on the funds available at the time.

Notes of joint UKCCSRC Biannual meeting and the Inaugural Meeting of the FERF's Carbon Capture and Storage Interest Group
11th and 12th September 2017
University of Sheffield

This prestigious meeting was held at the University of Sheffield and attracted more than 100 attendees from all over the world. It was an ambitious programme with three streams each having three parallel sessions of oral presentations. A total of 30 presentations were given of which 26 have been made available and can be viewed on the FERF website.

The main themes were "Transport and Storage" and "Capture", each of which comprised three sessions. Other topics of which there were single sessions were on Biomass, Greenhouse Gas Removal (GGR), Crosscutting projects and a Plenary Session.

TRANSPORT AND STORAGE 1

This topic was opened by Anatoliy Vorobov of the University of Southampton whose paper was entitled **"Thermo- and Hydrodynamics of Slowly Miscible Interfaces".** Anatoliy described his work on the theoretical modelling of miscible interfaces both gas/liquid and

liquid/liquid. The model would take account of interfacial diffusion, variations in interface shape, dynamic surface tension, and hydrodynamic flows induced by concentration gradients. To illustrate the nature of his study he showed as an example the dissolution of a droplet of honey in a cup of tea or the absorption of a carbon dioxide bubble by crude oil. The derivation of a valid model would have applications in enhance oil recovery (EOR), CO_2 sequestration, enhanced aquifer remediation and the chemical extraction of vegetable and essential oils.

The second paper was entitled **"Migration of CO_2 through North Sea Geological Carbon Storage Sites: Impact of Faults, Geological Heterogeneities and Dissolution"** and was given by Jerome Neufeld. No slides were provided after the presentation.

Haroun Maghereftеh of University College London gave a presentation entitled **"The Development and Demonstration of Best Practice Guidelines for the Safe Start-up Injection of CO_2 into Depleted Gas Fields".** Highly-depleted gas fields such as Hamilton and Viking A represent prime potential targets for large-scale storage of CO_2. They have excellent storage efficiency (utilising between 70% to 80% of the available pore space), but do require careful operational management because of their very low pressure and relatively shallow depth. In the case of the Hamilton gas field, for instance, its shallow depth and low pressure means that the injected liquid or dense phase CO_2 during start up injection will expand into the vapour phase. This results in a reduction in the storage capacity and the accompanying expansion-induced cooling of the CO_2 also poses significant safety and operational risks. One potential solution is to pre-heat the CO_2 on the platform until the liquid CO_2 can be injected without crossing the liquid to vapour transition at any time during the injection process. However, this is expensive and is regarded as being 'hit and miss'.

The aim of this project was to develop a rigorous CO_2 Injection Model, accounting for all the important processes governing the fate of CO_2 in terms of its variation in pressure, temperature and hence the fluid phase along the well during the injection process. The objective was to demonstrate the efficacy of the model as a powerful optimal injection process control tool by simulating a real case study involving various ramp-up CO_2 injection rates and starting temperatures and pressures.

Results presented showed that using the model the simulated temperature and pressure profiles at any time and location along the may be used to determine optimum injection conditions for CO_2 including the maximum allowable injection rate, ramping up duration, feed temperature and pressure, and if required, any preheating. The injection simulation model developed in this work provides such capability. The results presented are site specific and must not be generalised. Shallower reservoirs might exhibit lower pressure, exaggerating the above risks.

TRANSPORT AND STRORAGE 2

This session was opened by Andy Chadwick from the UK GeoEnergy Observatories who talked about "**UK GEOS"**. As background Andy explained that the Natural Environment Research Council (NERC) and the British Geological Survey (BGS) are two of the UK's leading scientific organisations who have planned the creation of an 'underground observatory' in the Ince Marshes area of north Cheshire. It will be a world-class research site, bringing together leading scientists and engineers considering new energy technologies. The observatory will enable the project team to study how gases and fluids flow within different rock types and between different layers of rock over the next 15 years. Creating this site would involve the drilling of several observation boreholes. The data collected will be accessible to all. It will

deliver a long-term environmental evidence base to inform future decisions about the use of the subsurface in the UK and the rest of the world.

The Permo-Triassic Collyhurst Sandstone of the region was used in this study as it is analogous to that of the East Irish Sea. The aim of the work was to provide a better understanding of the key processes in the UK storage reservoirs. Work done to date includes a review and costing of well designs and the negotiation of land access. The next step is a critique by the project science advisory group and an external panel of CO_2/well bore technology experts. The site will be characterised by drilling and core sample analysis. The CCS injection well will be located within the groundwater monitoring and seismic arrays.

The risks are several and include the business risk of the cost and value for money obtained. The geological risks are that the fault geometry is uncertain and whether the Manchester marl would be able to act as an effective seal. Other engineering risks remain associated with the Extended Leak Off Test and there clearly needs to be access granted to the sites by the landowners.

The project raises questions for the CCS community; for example, what is the future research programme of this well for the next 10 to 20 years? It also highlights the need to focus future research on the geology and reservoir processes to ensure ultimately that the expected value is achieved.

Michael Kendell of the Bristol CO_2 Group then spoke of the groups work on **"The need for passive seismic monitoring on CO_2 storage sites"**. Geological issues with CO_2 storage can result in leakage. These can be from either abandoned or active wells and can take the form of a loss of caprock either by geo-chemical dissolution, geo-mechanical deformation or fault reactivation. Seismic monitoring is by controlled 4-D (four-dimensional) surveying. Also known as time lapse seismic, 4-D seismic incorporates numerous 3-D seismic surveys over the same reservoir at specified intervals of time. Studying multiple time-lapsed 3-D surveys, or three-dimensional subsurface images, portrays the changes in the reservoir over time. Four-D seismic can determine changes in flow, temperature, pressure and saturation. By scanning a reservoir over a given period, any changes, such as might induce leakage of CO_2 within, can be traced and better understood.

Microseismic events are small usually unfelt earthquakes and fluids such as CO_2 when injected into rock will induce seismicity. They are caused by their location, the fault mechanism and the state of stress of the region. Methods available to monitor microseismicity may be borehole, surface monitoring or monitoring with sparse arrays. Borehole monitoring can detect a low-magnitude event but is of limited area, i.e. only near of the well. The cost of such monitoring increases with the number of wells and it is not always possible to locate sensors close to wells. An example of surface monitoring was mentioned where 10,000 sensors were placed on the sea bed at 2,500 locations. The method is computationally expensive but can locate microseismic events and gives good coverage. Monitoring with sparse arrays is better for long-term monitoring and is ideal to produce baseline surveys.

Some information on the monitoring of the world's largest CCS projects was described with Weyburn, an old oil reservoir, showing moderate amounts of seismicity when sparse arrays were used at the single well. Salah is a gas field which had CO_2 injected into the water leg of the reservoir. It was monitored with a single sensor and detected ~10,000 events per year. The Sleipner field was a saline aquifer which was not monitored for microseismicity. In the cases examined there was no evidence of leakage but the sites had poor passive seismic monitoring

in all cases. There is a need for thousands of reservoirs like Sleipner to accommodate the worlds current CO_2 emissions.

Conclusions from passive microseismic monitoring were that CCS projects will aim to minimise geo-mechanical deformation, so ideally become aseismic. Passive seismic monitoring serves as an 'early warning' for leakage and serves to calibrate geo-mechanical models. It is important for long-term predictions. For Weyburn, In Salah and Sleipner three very different geo-mechanical settings gave three very different responses. Seismicity can be used as an imaging tool having numerous seismic attributes (b-values, fracture induced anisotropy, plume migration, stress changes). There is a need for good baseline surveys and a need for fit-for-purpose seismic monitoring arrays. It is preferable to over-engineer early on – a felt seismic event is one of the single biggest threats to acceptance of CCS.

Ben Wetenhall from the School of Marine Science and Technology at Newcastle University gave a talk entitled **"S-CAPE Shelter and Escape in the Event of a Release of CO_2 from CCS infrastructure"**. The challenge is to move CO_2 from a variety of locations to several different storage sites in a safe, reliable and efficient manner. The consequences of a CO_2 pipeline failure are serious in that although not explosive or inflammable its properties make it dangerous. It is denser than air so may collect in depressions or valleys. It is also toxic and at concentrations greater than 10% it can have long term effects or prove to be fatal. To ensure safety around any pipeline failure it is necessary to be able to calculate the concentration of CO_2 at different locations around the failure. This is done using a Quantitative Risk Assessment approach. A pragmatic infiltration model is needed to predict the effect of CO_2 exposure on humans in buildings.

The outcome of this study was that two shelter models have been developed; an analytical and a CFD model. The models compare favourably with experimental test data and it has been demonstrated that the ability of buildings along a pipeline route to provide shelter can be determined using these models. The wind speed has been shown to have the greatest impact on concentration profiles within the building. In conducting a full QRA a failure frequency analysis would be incorporated with these results to calculate the risk at any particular location.

The next paper was from Zoe Shipton of the University of Strathclyde and was entitled **"Impacts of faults in migration pathways from CO_2 storage sites: field and modelling approaches"**. Faults zones are formed through a complex interaction of mechanical, hydraulic and chemical processes and their permeability varies considerably over both space and time. The permeability of faults is governed by complex fully-coupled relationships between seismic (or aseismic) slip events, the fluid pressure field, mechanical properties of the host rock, and the geochemical environment.

Several studies have suggested that faults act as pathways for fluids and formation waters to pollute surface aquifers. The motivation for this work was to test this assertion as relatively few data are available on the bulk properties of faults at scales relevant to CCS overburden in shale (>800m), and in host rocks relevant to CCS overburden (shale).

In terms of fault barrier protection, data from the oil industry indicates that hydrocarbon tools can more or less predict shale smearing, that is, the ability of a fault to be closed off. However, there appears to be no suitable industry tools for fault sealing and permeability reduction by other mechanisms e.g. structural diagenesis or deformation bands. Nor are there industry tools for along-fault flow prediction.

Existing tools for evaluating fault fluid migration potential include slip and dilation tendency and the limitation of seismic resolution. Proposed new methodology includes damage zone connectivity, lenses as flow-paths and fault-overburden fluid exchange. [NOTE: - In geology a **lens** is a body of ore or rock or a deposit that is thick in the middle and thin at the edges, resembling a convex **lens** in cross-section. A **lens** can also refer to an irregular shaped formation consisting of a porous, permeable sedimentary deposit surrounded by impermeable rock].

Faults can provide localised seal bypass systems through: localised sand lenses; high permeability damage zones and transient slip surface permeability. In light of this, consideration of leakage must include interaction between pathways in the fault and host rock. For example: - how to get fluids in to the fault? and how can fluids escape the fault?

Modelling was performed to test the sensitivity to fault permeability. Three models were described, the first had an above average permeability; the second had high permeability, fault and damage zone and the third with a heterogeneous fault permeability. The last model was viewed as the scenario most applicable to real-world fault zones.

Conclusions were that both along-fault and across-fault permeability will affect leakage through overburden. Modelling tools for evaluating fault permeability have been developed. Flow will be localised in damage zone fracture networks and permeable lenses and fluids travelling upwards-along will partially be trapped in saline aquifers.

TRANSPORT AND STORAGE 3

This topic comprised four papers the first of which was **"Modelling the Thermophysical Properties of Impure CO_2"** and was presented by Richard Graham of the University of Nottingham. The work involved the prediction of properties of CO_2 containing oxygen, hydrogen, neon and CO. Properties of interest included miscibility, compressibility, phase transmissions and the speed of sound. Three different modelling methods were studied, (i) empirical equations of state; (ii) molecular simulation (empirical force fields) and (iii) first principles calculation. Empirical equations of state use a direct expression for the pressure, involve many parameters and extensive fitting to data is required. Molecular simulation of physical properties requires a small number of empirical parameters and some fitting to limited data is required. First principle calculations use ab-initio computational chemistry. It begins with first principles i.e. no parameters and predicts data without fitting.

After showing the evaluation of the methods Richard concluded that empirical equations of state were cheap and accurate when close to existing data; needed refitting when new data became available and were only as good as the available data. Molecular simulation produces more robust predictions than equations of state and less fitting is required. First principles calculations require no experiments or fitting; they are limited to gases for now, but extensions will be available soon. The ab-initio calculations are expensive but are a one-off cost. The final take-away message was to use first principle calculations to fit to equations of state.

Dr Kumar Patchigolla of Cranfield University was next up with his paper **"CO_2 Shipping for Storage: CO2LIQUID project".** Kumar began by outlining the status of work on CO_2 shipping and transport and then explained the rationale behind the main theme of his talk. The project is of two years duration and will end in 2018. The project deals with liquefaction of CO_2 and its transportation by ship either for storage or enhanced oil recovery, and the impact of impurities on loading and unloading scenarios. There is little experience of handling liquid CO_2 under shipping conditions. The levels, for which impurities (including water) need to be removed

from CO_2 in order to mitigate handling issues, and the associated impact on energy efficiency of compression and liquefaction, are not understood, especially for CO_2 from fossil-fired power plants.

The objective of the study has been to evaluate the propensity for leakages, freezing, blockages, and safety issues for liquid CO_2 suitable for transportation by ship (near to the triple point). The project will modify the existing PACT facility at Cranfield to allow the multi operational facility to test CO_2 in either dense phase or semi refrigerated fluid state. Two key technology gaps will be addressed: How to prepare an energy efficient triple point CO_2 under controlled manner and what operational issues would encounter as a function of key impurities?

Conducting underpinning research will aid the development of low pressure, cost effective CO_2 shipping transportation in an energy efficient and controlled manner. It will address the effects of the relevant contaminants in loading and unloading scenarios, with experimental validation supported by thermodynamic calculations and flowsheet models

The specific measurable objectives are to investigate the impact of these new conditions on liquefaction performance and to establish a first assessment of safe operation limits by measuring all process parameters in real time; to develop guidelines for transporting CO_2 with trace contaminants for shipping and to further the understanding of the impact of these contaminants in the captured CO_2-rich stream under liquid conditions (i.e. impact of SOx, NOx & O_2 etc.) and to investigate and measure the CO_2 outflow in the immediate vicinity of leak from a shipping system and its impact on the local environment, and to deliver information on operation and maintenance strategies during loading and idle periods.

The work has built on earlier work in the EPSRC-funded project MATTRAN where National Grid Corrosion studies took place in 2014-2015. So far a number of poster presentations have been made as follows:- "CO_2 shipping: development of more efficient and safer procedures as function of key impurities" by Hisham Al Baroudi; "CO_2/SO_2 gas emission treatment system and losses from CO_2 shipping infrastructure" by Adeola Awoyomi; "CO_2 shipping: development of more efficient, reliable operations and the impacts of impurities" by Hisham Al Baroudi and "Development of efficient and reliable large scale CO_2 shipment with related emissions management" by Hisham Al Baroudi and Adeola Awoyomi.

The following presentation was by James Verdon from the University of Bristol and was entitled **"CCS and Injection Induced Seismicity".** James presented a series of slides without much explanatory detail. Some slides were overlaid with other slides and hence were difficult to interpret. The work involved the modelling of injection-induced seismicity (IIS) using numerical and statistical methods and the implications that could be drawn therefrom.

In conclusion James stated that induced seismicity and geomechanics are crucial factors for any future CCS site which must be factored in to site selection together with monitoring systems. At some point, a CCS site will trigger induced seismicity. What protocols do we put in place for this? Would they be operational protocols such as traffic-light schemes? Seismicity forecasting? Or risk assessment? Public communication is likely to be very different in different countries/regions and social acceptance remains a barrier to CCS.

The final paper in this segment of the programme was given by Stuart Gilfillan and was entitled **"Using inherent fingerprints to monitor CO_2 storage".** Although CCS is a promising means of directly lowering CO_2 emissions from fossil-fuelled combustion, concerns about the possibility of CO_2 leakage are contributing to slow the widespread adoption of the technology.

Research to date has failed to identify a cheap and effective means of measuring how CO_2 injected underground is being stored. CO_2 can be stored in four different ways: physically, where gaseous or liquid CO_2 is trapped beneath an impermeable sealing cap rock; residually, where CO_2 is trapped within individual and dead-end spaces between rock grains (pores); where CO_2 is dissolved into the formation water, which fills the pores between rock grains and lastly where CO_2 reacts with the host rock forming new carbonate minerals within the pores.

Importantly, physically trapped CO_2 is mobile and able to leak should a break form in the overlying sealing rocks. CO_2 stored by the other three means is not mobile or buoyant, and hence will not migrate out of the CO_2 storage site should the seal fail. It is therefore critical for reassurance to the public and regulators of CO_2 storage that reliable ways to measure how much of the CO_2 injected into the subsurface for storage is locked away in these secure means. Few research studies to date have quantified exactly how much CO_2 is stored by residual and solubility trapping across an entire storage site. Estimations have been made from laboratory studies on rock core samples, but these only represent rocks from a small part of the CO_2 storage site. Extending these results to infer how CO_2 will be stored in the entire storage site is difficult as the rock cores do not represent the variation seen across the storage site. It is possible to use seismic waves to image the CO_2 injected. This has proved to be a reliable means of imaging large amounts of CO_2 but is unable to image thin layers of CO_2 or percentage of dissolved CO_2 which makes it very difficult to quantify exactly how CO_2 is being stored. Hence, there is a need to develop a reliable test which can be performed at a single CO_2 injection well during assessment of a potential site for CO_2 storage.

Results from the project and a review of studies from CO_2 storage projects around the world showed that the oxygen isotope composition of reservoir water changes due to oxygen isotope equilibrium exchange with CO_2 when large amounts of free-phase CO_2 are in contact with the water in the formation. Field experiments at EOR sites in Texas and Alberta show that oxygen isotope shifts in reservoir waters from baseline conditions due to CO_2-water oxygen isotope equilibrium exchange can be used to estimate CO_2 pore-space saturation using a multi-well field configuration

Oxygen isotope data from the Otway test facility in Australia were the first from a field project with a single-well configuration that have indicated the potential of using oxygen isotopes to quantify residual trapping levels of CO_2 in a reservoir over a time span of only a few days. Results from the field, laboratory and theoretical studies provide evidence for the viability of using oxygen isotopes and the developed model to quantify CO_2 pore-space saturation on a reservoir scale during field experiments with either a multi- or single-well configuration.

Although oxygen isotopes can provide a simple and inexpensive monitoring technique to quantify small and large-scale CO_2 pore-space or residual CO_2 saturation changes near and further away from a well, it has its known limitations and will not be applicable in all cases. Therefore, a combined geophysical and geochemical monitoring programme would be most effective in determining the fate of the injected CO_2 in a storage reservoir and would provide a commercial operator with greater reassurance of the viability of their proposed storage site in terms of structural and residual CO_2 trapping levels.

CAPTURE 1

This topic comprised three papers, the first of which was given by Mathieu Lucquiaud entitled **"Towards more Flexible Power Generation with CCS: Pilot Plant Test Campaigns for Best Practice Guidelines for Post-Combustion Capture".** The project is aimed at building on and strengthening joint industry research programmes with the objectives to move beyond current

concepts for designing CO_2 absorption columns for base-load operation, and towards new columns capable of meeting the requirements for flexible and highly dynamic operation of CCS power plants. It is important research for the UK to ensure that conventional power plants fitted with CCS can become a source of dispatchable and low carbon energy to complement non-dispatchable renewable technologies such as wind or solar power.

The project proposes to demonstrate the capabilities of novel ways to use solvent property instrumentation to significantly enhance the dynamic flexibility of the amine pilot plant at the UK CCS Research Centre Pilot Advanced Capture Testing facilities and to develop an underpinning understanding of the capabilities of state-of-the-art hardware, such as structured packing, liquid distributors used in and around packed columns.

The project objectives are to demonstrate at pilot scale, flexible operation of post-combustion CO_2 capture; to characterise ramp rates at pilot scale; to demonstrate at pilot scale, advanced operating strategies, e.g. to trade electricity vs CO_2 emissions and to develop fit-for-purpose process instrumentation to do so. More specifically with UKCCSRC support the project aims to plan, execute and analyse a 10-day pilot plant test campaign at UKCCRC PACT focused on dynamic operation of the amine plant. It will build and deploy new instrumentation at UKCCSRC PACT and demonstrate, at pilot-plant scale, real-time control of process during transient operation between set points.

Results obtained so far indicate that there were no significant barriers to flexible operation for PCC; solvent inventory and circulation times influence plant response. Capture rate response is delayed by solvent circulation times and possibly mixing effects. Understanding of solvent mixing in PCC plant is important but difficult to implement accurately in models. Real-time solvent measurement could become a control variable in advanced control systems for PCC. In addition, there were no significant barriers to advanced flexible operation for post-combustion capture, such as capture by-pass, frequency response.

Meihong Wang of the University of Sheffield then talked about the **"Study of Process Intensification for Solvent-based Carbon Capture using Systems Engineering Techniques".** Post-combustion CO_2 capture by chemical absorption using solvents (for example, monoethanolamine - MEA) is one of the most mature of technologies. The conventional technology uses large packed columns. The cost to build and run the capture plants for power plants is currently very high because: (1) the packed columns are very large in size; (2) the amount of steam consumed to regenerate solvents for recirculation is significant. If it is possible to reduce the size of packed columns and steam consumption, then the cost of carbon capture will be reduced correspondingly.

From previous studies, it was found that mass transfer in conventional packed columns used for carbon capture is very poor. This project expects to make very significant improvements in mass transfer. The key idea is to rotate the packed column so that it spins at hundreds of times per minute - a so-called rotating packed bed (RPB). Better mass transfer will be generated inside the RPB due to a higher contact area. With an intensified capture process, a higher concentration of solvent can be used (for example 70 wt.% MEA) and the quantity of recirculating solvent between intensified absorber and stripper will be reduced to around 40%.

This proposal will investigate how to design and operate the RPB to separate carbon dioxide most efficiently from flue gas. The work will include design of new experimental rigs, experimental study, process modelling and simulation, system integration, scale-up of intensified absorber and stripper, process optimisation, comparison between intensified

capture process and conventional capture process from technical, economic and environmental points of view.

The research will include an investigation into the optimum flow directions for the solvent and flue gas stream (parallel flow or counter-current) for intensified absorber and the optimum design of packing inside the RPB. The proposal will also compare the whole system performance using process intensification versus conventional packed column for a CCGT power plant. Based on this, an economic analysis will be carried out to quantify the savings provided by this new process intensification technology. Meihong provided status reports on the key project activities. The initial analysis data has been published in an international leading journal and it indicates that the packing volume in an RPB will be less than 10% of an equivalent conventional packed column.

The final paper in this section on Capture was entitled **"Carbon Nanotube/PVA Composite Aerogels for CO_2 Capture"** and was given by Eleanor Campbell of the University of Edinburgh. The key challenge in PCC from gas-fired power plants is the low CO_2 concentration in the flue gas, approximately 4% by volume. This means that conventional amine processes will have a large energy penalty and the presence of high concentration of oxygen leads to high amine deactivation rates. Novel adsorbents and adsorption processes have the potential to improve the efficiency of the separation process. Given the very low CO_2 partial pressure in the flue gas, the selection of novel adsorbents is very different from the equivalent approach to coal-fired power plants. The adsorbents will need to have very high selectivity to achieve good capture capacity with dilute mixtures. As a result, these materials will have to demonstrate either very strong physisorption or chemisorption and the regeneration will have to involve thermal cycling. This poses the engineering challenge of developing a process that will achieve rapid thermal swings of the order of a few minutes. This is over an order of magnitude faster than traditional Thermal Swing Adsorption (TSA) fixed bed processes.

Several syntheses were described to produce activated mesoporous carbon with various pore sizes. The carbons were then impregnated with a number of amines and their CO_2 adsorption capacities were measured.

The project conclusions were that porous carbons impregnated with liquid amines have properties that make them favourable for capture processes from dilute gas streams but that large amines block small pores. Carbon Nanotube/PVA aerogels impregnated with polyethylene imine (PEI) show CO_2 uptake of around 4 mmol/g at 0.1 bar (comparable to best alternative materials). They are stable in water showing improved performance, have high selectivity, capable of being rapidly heated using electrical swing, mechanically stable and in monolithic form, however, diffusion by CO_2 through amine is slow.

CAPTURE 2 – SOLIDS

This topic also comprised three papers although only two were made available after the event. The first was given by Ben Anthony and was entitled **"UK demonstration of Enhanced Calcium Looping, and First Global Demonstration of Advanced Doping Techniques".** Calcium (carbonate) looping is a promising technology for carbon capture which has been demonstrated at the MWth scale for capture of CO_2 from the exhaust of a large-scale power plant. CO_2 is captured as $CaCO_3$ from the exhaust gas stream and then calcined to release pure CO_2. The exothermic CO_2 capture stage takes place around 650°C and the heat released in the carbonation process can be used in a standard steam cycle.

The aims of this project are to demonstrate the viability of enhanced calcium looping technologies for CCS with the use of a pelletised spent lime stream; to demonstrate the viability of calcium looping for the removal of CO_2 from industrial gases (steel, iron and cement industries) and to explore the use of techniques to improve sorbent performance.

Outputs from this research were that an experiment was carried out on the 50 kW_{th} dual-CFB facility at Cranfield where in total 12 kg of limestone was fed into the system during a 6-hour test period. Although the results were successful it was felt that the unit lacked flexibility, and it was decided to redesign a 25 kW_{th} unit which was also able to simulate, in pilot conditions, the CO_2 removal from various industrial gases.

An HBr-doping technique was modified in order to treat higher quantity of materials (of the order of 10 kg). This involved developing new techniques to treat the much larger amounts of materials. Several experimental campaigns were carried out with limestone and HBr-doped limestone which demonstrated the advantages of HBr doping when compared to untreated limestone. The results showed a higher capture efficiency and, more surprisingly, a lower attrition tendency of the sorbent. Different industrial gases have been tested proving the calcium looping concept in different industrial sectors using flue gases of up to 40% vol. CO_2 in different campaigns.

Seventeen scientific papers have been published based on this work which help broaden the general understanding of calcium looping and carbon-capture technologies. Calcium looping is shown not only to be more efficient than any other back-end capture technology, but able to decarbonise the cement industry. The viability of using a spent lime stream for cement manufacture was proven and cements produced from kilogramme quantities of bed material performed similarly to normal cement.

Ed Lester of the University of Nottingham presented his talk on **"Industrial Scale Manufacture of Sorbent Materials for Carbon Capture"** – no copy available.

The final paper in this section was entitled **"CO_2 Flow Metering through Multi-Modal Sensing and Statistical Data Fusion"** by Gang Lu of the University of Kent. Measurement of CO_2 flow across the CCS chain is essential to ensure accurate accounting of CO_2 flow and prevent leaking during transportation. Significant changes in physical properties of CO_2 (gas, liquid, two-phase or supercritical) mean that CO_2 flows in pipelines are complex in nature. The project aimed to develop a cutting-edge technology for CO_2 flow metering in CCS pipelines. The objectives are to establish a mass reference platform for CO_2 flowmeter calibration; to develop a prototype multi-modal sensing system and data fusion algorithms for mass flow metering of CO_2 and to evaluate the performance of the multi-modal sensing system under single phase and two-phase CO_2 flow conditions.

The main activities included the development of a dedicated flow test facility for CO_2 flowmeter calibration and evaluation under CCS conditions. The facility can provide single-phase (liquid or gas) or two phase (liquid/gas) CO_2 flows in one-inch bore, horizontal and vertical pipelines with pressures up to 72 bar. Two-phase flow regimes (stratified, bubbly, plug and slug flows) can be created. Impurity gases can also be injected into the test section to assess their impact on the performance of CO_2 flowmeters. The facility incorporates Krohne Coriolis flowmeters and intelligent data fusion algorithms and can measure the mass flow rate of CO_2 under single-phase (gas or liquid) and two-phase (gas/liquid) flow conditions. The gas volume

fraction of CO_2 under two-phase flow conditions can also be predicted. Gang then described experimental work carried out using the flow test facility.

The developed CO_2 flow facility has served its purpose as a reference platform for CCS applications and is probably one of the very few CO_2 flow facilities in the world. Coriolis flowmeters incorporating intelligent data models can provide mass flow measurements of CO_2 within ±1.5% under two-phase flow conditions. The flowmeters have achieved errors within ±0.15% and ±0.25%, respectively, for single-phase liquid and gaseous CO_2. The flowmeters incorporating intelligent data models can meet the ±1.5% uncertainty requirements set by the EU-ETS (Emissions Trading Scheme).

CAPTURE 3

The final section of Capture, 3 Solids again comprised three papers but only two were made available after the event. The first paper was from Professor Mohammed Pourakashian of the University of Sheffield and was entitled **"In-Depth Studies of OxyCoal Combustion Processes through Numerical Modelling and 3D Flame Imaging".** A copy of this paper was not made available.

The next paper was by Richard Marsh of Cardiff University with the snappy title of **"Oxyfuel and Exhaust Gas Recirculation Processes in Gas Turbine Combustion for Improved Carbon Capture Performance & Selective Exhaust Gas Recirculation for Carbon Capture with Gas Turbines: Integration, Intensification, Scale-up and Optimisation".** Richard began by outlining the background to the first of his projects.

Dry low emissions (DLE) gas turbine systems typically rely on lean burn processes to control NO_x. This results in low CO_2 exhaust concentrations, which require large and costly scrubbing plant. Moreover, the energy required per tonne of CO_2 is also increased as the CO_2 concentration is lowered. This is also affected by purity requirements. From a CCS perspective, the aim of Oxyfuel or Exhaust Gas Recycle (EGR) is to increase CO_2 exhaust concentration, without compromising operations.

Regarding Oxyfuel combustion research, energy sector decarbonisation efforts create the potential for future Oxyfuel CCS plants coupled with GT cycles. Oxyfuel CCS-GT could provide high CO_2 purity for post combustion processing and sequestration. Oxyfuel combustion environments result in increased burning velocities, increased flame temperatures, and augment lean and rich stability limits.

Research aims are to show how flame location changes in relation to O_2 mole fraction and equivalence ratio, in conjunction with the local flow field of the swirl zone and to demonstrate whether the flow field is affected by the different diluents capacity to absorb heat. Hence to determine if the shift in heat release position will affect fluid dynamics. Lastly, to measure exhaust gas concentrations with N_2 and CO_2 diluted O_2/CH_4 swirling flames.

Key findings from this work were that it is possible to operate a modern swirl burner with a variety of oxygen concentrations and that these flames will also operate with CO_2 / O_2 mixtures, but the operating points are different to that of air. The high heat capacity of CO_2 removes excessive amounts of heat from the flame, causing an increase in CO. Richard speculated that perhaps there is a compromise to increase CO_2 concentration without the need for pure O_2 as the comburant?

Moving on to the second of his projects Richard explained that Selective Exhaust Gas Recycling (S-EGR) has been suggested as a GT-CCS technique to improve CO_2 concentrations of the flue gas such that the cost and volume of the capture unit can be minimised. This can potentially deliver process intensification and enhanced net cycle efficiency. In essence, the S-EGR concept recycles CO_2-enriched exhaust rather than exhaust gas only, therefore minimising the recycling of nitrogen within the EGR loop.

Project aims included the first extensive test programme of combustion under S-EGR conditions at the Gas Turbine Research Centre at Cardiff University to generate fundamental data on flame temperature, stability etc. Other objectives were the first extensive test programme of gas turbine operation with S-EGR at the UKCCSRC PACT facilities, at low-turn down conditions and for transient behaviour and the first experimental programme at PACT assessing the energetics performance of post-combustion technologies at these flue gas concentration and flow rates. In addition, a process intensification and optimisation of innovative and modular CO_2 absorber configurations programme operated at lower flow rate, typical of S-EGR systems was undertaken together with the first application of Electrical Impedance Tomography to CO_2 absorption with amine solvents to characterise gas/liquid flows on structured packings for the characterisation of the above configurations.

Richard rounded off an impressive description of the work by outlining the overall projects status and take-home messages. Modelling has shown that modern gas turbine configurations can operate with S-EGR, which will both reduce cost and plant size. Experimental measurements have shown that the presence of CO_2 slows down flame chemistry, but this should keep within the capabilities of modern burners. Engine tests are showing that S-EGR can be tolerated, provided the engine is run under richer conditions. Modelling has shown that mass flow and capture efficiency could be competing factors in system development, so optimisation is necessary. A dissemination event is planned for 2018.

The final paper of this topic was given by Xianfeng Fan of the University of Edinburgh who presented his talk **"A compact CO_2 Capture Process to Combat Industrial Emissions"**. CO_2 capture by using amine solvents is the most mature technology employed in most carbon capture plants. Incremental improvements using alternative amines or amine mixtures with higher capacity and/or lower regeneration/degradation costs are potentially possible. However, major problems with this process remain without a fundamentally different design. They include (a) low mass transfer efficiency in the absorber and desorber, resulting in large equipment size and high capital and operating costs, (b) high energy consumption in solvent regeneration, causing a very high energy penalty and operating cost, (c) corrosion caused by concentrated amine solutions, which makes it necessary to use more expensive materials and (d) thermal and oxidative degradation of amines above 100°C. More solvent make-up means a high operating cost.

This project proposes to address this challenge by combining two technologies, rotating packed bed absorption and microwave-assisted regeneration, which will enable small and flexible capture devices to be installed at a wide range of industrial sites. A rotating packed bed column offers a dramatically reduced volume by 90% compared to a traditional absorption column, while microwave regeneration is a revolutionary method for regenerating amine solutions at 70°C (rather than 120°C) that can operate without a temperature swing and is very fast, leading to a further significant reduction in capital costs (by around 50%) in the sensible heat used for CO_2 desorption, and in corrosion and solvent degradation by over 90%. CO_2 desorption at 70°C also enables the regenerator to use low grade industrial waste heat.

This project which is scheduled to run from 2016 to 2019 has the objectives of developing a compact, efficient and flexible CO_2 capture process using solvents which combines a rotating packed bed absorber with microwave assisted regeneration.

Four work packages were described and the progress within each was illustrated. WP1-Rotating Packed Bed; using available data to estimate the size of full scale absorbers, the co-current absorber diameter would be 34% larger than the counter-current absorber. Increasing the diameter leads to an increase in the power required to accelerate the liquid to the tip speed of the rotating packed bed. This power increase outweighs the decrease in gas side pressure drop Currently data is being gathering for the cross-flow configuration

Progress on WP2, investigating microwave regeneration; WP3 modelling microwave regeneration and WP4 process modelling and performance assessment were also described.

GREENHOUSE GAS REMOVAL (GGR)

The topic of **Greenhouse Gas Removal (GGR)** was chaired by Phil Williamson who introduced the GGR Programme. Phil is with the UK Natural Environment Research Council which is based at the University of East Anglia. The rationale for the GGR programme is that it is near-impossible to meet the climate change commitments without negative emissions i.e. GGR. GGR needs to be at the Gt scale by about 2030 to achieve net zero emissions by about 2070. As well as carbon dioxide other gases such as methane, nitrous oxide, CRCs and other halogens also drive climate change. There are many sources of greenhouse gases (GHG) not just from fossil fuel power plant. These include gases arising from industrial and energy-related processes, forest loss, agriculture, transport, buildings and waste. However, it is worth noting that the UK contribution to world GHG emissions is only about 1.2% with China and the US being the largest emitters by country.

There are very many ways in which GHGs can be removed from the atmosphere with subsequent storage. Biological capture includes afforestation, soil carbon, coastal blue carbon viz. the process where salt marshes, mangroves, and seagrass beds absorb large quantities of the greenhouse gas carbon dioxide from the atmosphere and store it, ocean fertilisation, [A type of climate engineering based on the purposeful introduction of nutrients to the upper ocean to increase marine food production and to remove carbon dioxide from the atmosphere] and BECCS. This list is arranged in increasing order of storage security. Geochemical capture uses enhanced rock weathering [a process that that uses the dissolution of natural or artificially created minerals to remove carbon dioxide from the atmosphere], and enhanced ocean alkalinity whereby the acidification of the ocean by dissolved carbon dioxide is neutralised.

Phil went on to identify the research issues for GGR. Firstly, effectiveness – will a particular technique deliver intended climatic benefits? Secondly, scalability - can the technique be deployed at the scale envisaged? in which countries/regions? What of unintended impacts – for biodiversity/environment, also food and water security. What are the Socio-economic consequences - costs, acceptability and governance? Finally, full life cycle analyses – what are the weakest links?

Within the GGR research programme are four consortium awards. Pete Smith of the University of Aberdeen is leading "Soils research to deliver greenhouse gas removals and abatement technologies"; Nem Vaughan of the University of East Anglia heads up "Feasibility of afforestation and biomass energy with CCS for greenhouse gas removal". Gideon Henderson of Oxford University is leading "Releasing divalent cations to sequester carbon on land and

sea" and Niall Mac Dowell of Imperial College is leading "Comparative assessment and region-specific optimisation of greenhouse gas removal".

Seven topic-specific projects have been funded as follows:- "GGR projects in the land sector", Jo House (University of Bristol); "GGR in the iron and steel industry", Phil Renforth (Cardiff University); "Co-delivery of food and climate regulation by temperate agroforestry" Martin Lukac (Reading University); "New methodologies for removal of methane from the atmosphere" Euan Nisbet (University of London, Royal Holloway); "Metrics for emission removal limits for nature" Simon Tett (University of Edinburgh); "Harmonising and upgrading GGR consequential life cycle assessment" Pietro Goglio (Cranfield University) and "Assessing the mitigation deterrence effects of GGR" Nils Markusson (Lancaster University).

Phil then handed over to three of the team leaders to describe their specific projects. The first of the papers on GGR was given by Niall Mac Dowell of Imperial College who spoke on **"Comparative Assessment and Region-Specific Optimisation of GGR".** Niall explained that the project began in 2017 and is of three years duration. The project consortium is made up of IC London, UCL, MCC, University of Oxford, University of Cambridge, UEA, IIASA and MCC.

The questions being asked by the consortium are: -
1. How will GGR technologies (e.g., BECCS) "fit in" with the rest of the low carbon energy system? How do they provide value?
2. What is a feasible, region-specific portfolio of GGR technologies, explicitly accounting for local bio-geophysical and wider political economy constraints?
3. What are plausible and efficient region-specific GGR deployment pathways?
4. What are the likely rate-limiting steps in GGR deployment, e.g., in BECCS
5. GGR deployment pathways – what needs to be done where, when and by whom?
6. How should GGR "credit" be shared?
7. From a global perspective, what key parameters make a difference (social, technical or economic) and what potential is there for the risks to be "engineered out"?
8. Given global GGR efforts, how should this burden be allocated?
9. What role will inter-regional cooperation need to play in delivering a least cost system?
10. How does social licence to operate and political economy vary between different GGR technologies and across different regions? What are the main emergent social concerns?

The project contains five work packages with different partners undertaking specific packages. The approach is by modelling and this will be carried out using intra-nation and device scale modelling (WP1); nation scale modelling (WP 2 to 4) and multi-region global scale modelling (all WPs).

There are 16 different companies and research association with whom the project will be working, namely MIT, University of Twente, CCSA, The Center for Carbon Removal, Baringa, ETI, Global CCS Institute, School of Mines Colorado, UK Department for Business, Energy and Industrial Strategy, I.Chem.E. Energy Centre, Shell, MCC, CICERO, IIASA, Bellona and IPCC.

This was followed by Nils Markusson with his paper **"AMDEG: Assessing the Mitigation Deterrence Effects of GGRs"** The AMDEG project began in August 2017 and will run for two years. Although GGR technologies have the potential to lower the concentration of greenhouse gases in the atmosphere they might be needed alongside mitigation technologies (e.g. solar panels). However, there is reason to think that the two kinds of technologies interact, and that GGRs might delay or deter the use of mitigation technologies in various ways. It is possible

that even doing research about GGRs could have a deterrent effect and combining GGRs and mitigation technologies may be more difficult than often assumed.

This is important because current climate policy targets are based on scenarios that rely on the promise of GGR technologies becoming available and being deployed at large scale. They also rely on the (implicit) assumption that there will not be a substantive mitigation deterrence effect. This project sets out to study the likelihood and significance of any such effects, to learn more about how they might work, how serious they might become, and what could be done to counter them.

More specifically, the project aims to explore how GGR promises shape economic, political and cultural processes in society, and so - indirectly, potentially impact on mitigation technologies and practices. In addition, the project team will study the evolution to date of promises of GGR technologies, and develop scenarios for how they might evolve in the future and impact on (deter) mitigation technologies. It will test these scenarios, by deliberating on them with existing and potential GGR stakeholders. The team will engage with GGR researchers and developers, and with others with reasons to be interested in the future of GGRs - such as other climate researchers, financiers, policy makers and environmental NGOs.

This approach will provide information about some aspects of mitigation deterrence, but may also prompt key GGR stakeholders to be more alert to mitigation deterrence risks and their potential roles in causing and/or countering them. It is expected that knowledge about mitigation deterrence mechanisms and impacts will be developed. It should help stimulate awareness about mitigation deterrence risks, and help develop strategies to counter them.

The session was rounded of by Phil Renforth who spoke on **"Greenhouse Gas Removal in the Iron and Steel Industry".** The project will investigate the techno-economic impact and environmental feasibility of using iron and steel slag deposits to remove carbon dioxide from the atmosphere based on fieldwork at Consett and Port Talbot. Systems will then be designed to scale up to climate-relevant greenhouse gas removal.

Up to 200 billion tonnes of slag may be produced over the next century as a by-product of the iron and steel industry, which could theoretically sequester up to 90 to 155 billion tonnes of CO_2 through enhanced weathering. This project explores the possibility of realising an economic GHG removal technology within an existing industry through the novel management of waste material. This will be done by exploring the internal chemistry of historic slag deposits to understand the long-term constraints on CO_2 sequestration, and undertake field trials of CO_2 injection into large controlled reactors. Three work packages comprise the project, the first (WP1) will carry out drilling and mineral characterisation of existing slag, WP2 will explore batch heap weathering experiments and WP3 examines feasibility analysis which includes a technoeconomic assessment and an environmental impact statement.

Iron and steel slags are a glass/semi-crystalline material rich in silicate and oxide minerals, which dissolve 4-5 orders of magnitude more rapidly compared to their naturally occurring counterparts. These wastes are found as large deposits at current and former steelworks, and represent a considerable environmental liability for producers. By accelerating the weathering of slag, it may be possible to reduce this environmental burden. It also offers a mechanism by which the CO_2 intensive steel industry could begin to decarbonise, and ultimately become net negative, if combined with extensive emissions reduction at source.

Previous research has demonstrated unintentional atmospheric CO_2 sequestration over multiple decades in the drainage waters emerging from slag heaps, and small-scale engineered systems have been proposed to carbonate slag under elevated temperatures and pressures. What remains unclear is the feasibility and efficacy of engineering approaches to accelerate ambient weathering to occur in a policy-relevant time period at a relevant scale. This research aims to bridge this gap by demonstrating how such engineering interventions can accelerate the natural weathering processes and provide a means for these industrial residues to act as a major atmospheric CO_2 sink.

The economic impact of climate change mitigation technologies is the relative contribution of preventing the potential 5% to 20% economic reduction in the economy due to climate change. Even if a technology were only able to contribute to mitigating a small fraction of this cost, the value could still be in multi-billions per year. To realise these big-picture economic impacts, the project will 1) demonstrate the technology at a pilot scale and create a robust assessment of larger operation, 2) address key uncertainties about environmental impact, 3) identify a road map for future research, and 4) work with industrial partners to identify intellectual property and market value specific to slag weathering.

Progress in shifting to a low carbon economy has important impacts on society. Storage of carbon as alkalinity raises issues of environmental impact, global governance, and public perception. The project team will work closely with the Understanding Risk Group at Cardiff University to evolve projects that question public perception of this technology, the necessary conditions for a social license to operate. Questions of governance and policy will be explored further with collaborators (e.g. through existing collaborations with Oxford University).

BIOMASS

The topic of Biomass comprised three papers of which only two were available.

Professor Patricia Thornley, the Director of the Supergen Bioenergy Hub at the University of Manchester Tyndall Centre for Climate Change opened the session on Biomass by posing the question **"Bio-CCS: Can it deliver?"** or to put it another way "How certain are greenhouse gas reductions from bioenergy?"

The Supergen Bioenergy Hub aims to bring together industry, academia and other stakeholders to focus on the research and knowledge challenges associated with increasing the contribution of UK bioenergy to meet strategic environmental targets in a coherent, sustainable and cost-effective manner. The structure of the hub was illustrated, with a Core Management Group overseeing several work packages, such as Biomass & Waste, Pre-processing Technologies, Conversion Engineering, Energy Vectors and Systems Modelling. There are impacts on and outside of the hub and on complementary bodies.

The overall aim of the present study is to estimate the carbon reduction potential of BECCS (Bio energy with carbon capture and storage). Its objectives are to define a feasible biomass oxyfuel combustion system; to develop a life cycle inventory of energy, material and fuel and chemical input and outputs including waste and emissions for different co-firing ratios; to complete a life cycle impact assessment (LCA) to assess potential environmental impacts and to assess the implications of using different biomass co-firing ratios.

Patricia then presented a comparison of the GWP (Global Warming Potential) of 100% coal firing to 60% replacement with a biomass-based alternative. GWP is an index used to calculate equivalent warming effect of a unit mass of a given greenhouse gas integrated over a specified

time period, usually 100 years, relative to CO_2. Clear benefits in net CO_2 emissions ($kgCO_2/kWh$) emissions were shown for all replacement scenarios with the best results from the highest replacement of coal (60%).

For BECCS to be successfully delivered Patricia identified several key issues which must be addressed, the first of which was supply. Biomass needs to be sustainably and reliably sourced to avoid the negative effects outweighing the positive climate change benefits. This includes ensuring land use is not diverted away from forest and food production and into bio-energy crops. Policy objectives needs to be further clarified and developed at a global, national and UK level. In terms of greenhouse gas reductions, a consideration of the absolute emission reductions actually achieved by different technologies favours electricity deployment rather than heat; while appreciation of the cumulative impacts of greenhouse gas emissions suggests that annual greenhouse gas "budgets" are a more appropriate approach, placing more focus on the actual emissions than the savings. Other issues were understanding the engineering costs involved. Risk mitigation and public acceptability also need to be better understood.

The second (unavailable paper) was by Ed Lester of the University of Nottingham and was entitled **"Optimisation of Biomass/Coal Co-Firing Processes through Integrated Measurement and Computational Modelling".**

The final paper in this section was entitled **"Bio-CAP-UK and Beyond"** and was presented by Karen Finney of the University of Sheffield. Karen explained the importance of BECCS in that it has the potential for net negative emissions and is the only large-scale technology to remove CO_2 from the atmosphere. Evidence for the value of BECCS has been shown and it is claimed that it could deliver ~55m t/a of net negative emissions by 2050. Knowledge gaps have been filled during the last ten years and all major components have been demonstrated individually thereby minimising the risk with full-scale deployment. The most recent report from the IPCC – the Intergovernmental Panel on Climate Change – highlights BECCS as one of the key CO_2 mitigation strategies ('Fifth Assessment Report', Climate Change 2014: Mitigation of Climate Change); they advocate that in the absence, or with only limited availability, of such mitigation technologies, costs can increase substantially in the medium to long term. Furthermore, this is reinforced by the Committee on Climate Change (CCC, 2011) and the EU Energy Roadmap 2050, which both show that bio-CCS needs vital demonstration projects. At an international level, a key conclusion from a recent report published by the European Biofuels Technology Platform and the Zero Emission Platform (ZEP) also states that there is a clear "need for carbon-negative solutions such as bio-CCS – the only large-scale technology that can remove CO_2 from the atmosphere".

Technical challenges remain, however, as biomass is known to be difficult to handle, mill, transport and feed into power plant. Inorganic constituents such as potassium can cause downstream plant problems which may affect the carbon capture process.

The Bio-CAP-UK project was jointly funded between the UK Carbon Capture and Storage Research Centre (UKCCSRC) and the Supergen Bioenergy Hub. It involved air/oxy biomass combustion with CO_2 capture technology. The project aim: — to address specific issues to deployment, remove some of the significant technical barriers to development and progress current understanding of its potential in the UK energy system, so that realistic projections of deployment, costs and achievable GHG reductions can be incorporated in policy development.

The project Industrial Advisory Panel's comments were that the results generated by Bio-CAP-UK project are novel for this industry, the project produced good data and outputs for

underpinning the science. It assessed critical, industrially-relevant issues such as plant performance, metal aerosol composition and particle size. Overall, it was a successful programme that has opened new research avenues.

Karen described new BECCS funding which enabled extensive additional work to be planned. For looking into fuel flexibility, a fully instrumented 250 kW grate-fired boiler burning solid recovered fuel (SRF) with a 150-kW solvent-based post-combustion capture will be available. The Supergen Bioenergy Hub extension has been granted where BECCS is a key theme in the submission. A range of biomass/recycled/waste fuels for testing impacts of bioenergy emissions on CCS will be provided. Subject to ETI approval, the BIO-FIB project will be extended to cover CO_2 Capture.

The new UKCCSRC 2017 grant has four BECCS research themes in its core research programme; BECCS under 'Combined Systems and Capture' and BECCS within the energy system under the 'Systems and Policy' theme. This will provide underpinning research on future deployment for all aspects of BECCS such as the next generation of CO_2 capture technologies and processes; detailed modelling coupled with experimental data using the PACT facilities and the ability to examine 'social license to operate'.

Combined systems and capture: BECCS will involve testing at PACT to demonstrate process integration at pilot scale (for retrofits) and the potential of oxyfuel capture for increased waste fuel flexibility (greenfield applications); combustion gases, metal aerosols and particulate formation will identify key species/pollutants from the combustion process and their impact on the capture plant and solvents. This will enable a better understanding of element partitioning from the combustion of recycled/waste fuels under a range of realistic pilot scale conditions, leading to the formation of comprehensive and novel datasets on the fates of specific elements.

Combined systems and capture: BECCS will use data/samples from previous projects by the applicants (e.g. Supergen Bioenergy Hub, UKCCSRC/Supergen Bio-CAP- UK) will inform the tests under a range of real operating conditions (air/oxy-firing) to evaluate the impact of alkali/transition/heavy metals and other species on: (i) the oxidative degradation and corrosion of CO_2 capture solvents, initiated and aggravated by transition metal carryover (ii) possible contamination of the high-purity captured CO_2 stream with a range of inorganic elements.

Systems and Policy: BECCS within the Energy System. This work will seek to address some critical questions: (i) what is the best (e.g. least cost per tonne of CO_2 removed, most removed from the atmosphere) way to achieve BECCS? (ii) is the best option pulverised fuel thermal plant co-located and integrated with electrolysis (e.g. an oxy-CCS plant could use the H_2), or a BIGCC-CCS plant? (iii) what is the best use of carbon-negative H_2 (heating, transport, chemicals)? (iv) what are the technical constraints of injection into the gas network? (v) how can BECCS be integrated into a renewable energy system and how can plants best operate within a system that minimises time that they are idle? Finally, Karen mentioned the PACT Expansion Activities where a new multi-fuel, grate-fired combustor of rating 200 kW model is to be installed at PACT which can burn a range of chipped or pelleted wood-based fuels

CROSS CUTTING

One of the last sessions of the day was on Cross Cutting technologies and was made up of three papers. The first by Jie Ke was entitled **"Measurement of Water Solubility Limits of CO_2 Mixtures to Underpin the Safe Pipeline Transportation of CO_2".** This research focuses on studying the impact of impurities in CO_2 streams such as N_2, H_2, Ar and H_2O on

thermodynamic properties of the mixtures. The experimental work on binary and ternary mixtures is performed using a variety of high-pressure facilities that have been developed at the University of Nottingham. The experimental data is validated using several types of equations of state (EoS) (Peng-Robinson with linear fit, Peng-Robinson with Boltzmann fit and GERG 2004/GERG 2008).

These high-pressure facilities were used for measuring the phase equilibrium and density of multi-component CO_2 mixtures and the solubility of water in impure CO_2. New vapour liquid equilibria (VLE) and density data of the binary/ternary mixtures of CO_2, N_2, H_2 and Ar were derived as was validation of the equations of state using the new data.

Conclusions to this work were that H_2 and H_2O are the key components in terms of understanding the thermodynamic properties of CO_2 mixtures relevant to CO_2 compression and transport. The presence of H_2 significantly increases the pressures required to form a homogeneous phase of impure CO_2. Permeant gases (e.g. N_2 and H_2) decrease the solubility of H_2O in CO_2 under liquid or supercritical conditions. Currently, no single equation of state (EoS) is better than any other for both VLE and density predictions. It is recommended that GERG-2008/EOS-CG is used for density calculation and the cubic EoS for VLE calculations of the mixtures with H_2.

The second presentation by David Newbery was entitled **"Evaluating Spill-Over Benefits from Low-Carbon Energy Investments".** David explained that the theme of his talk was about a project which was curiosity-driven, that is, no funding support. His chosen topic was "What is the case for subsidising renewables and how much subsidy is justified". David chose to consider solar PV vs CCS. Others points for consideration were the clear need which exists for collective action (as shown by the Global Apollo Programme 2015*) and factors influencing benefits and subsidy rates.

The **Global Apollo Programme** is a call for a major global science and economics research programme to make carbon-free baseload electricity less costly than electricity from coal by the year 2025. Launched in June 2015, the project - named for the Apollo Program, which brought together thousands of scientists and engineers to put mankind on the moon - calls for developed nations to commit to spending 0.02% of their GDP, for 10 years, to fund co-ordinated research to solve the challenge. This equates to $150 billion over a decade, roughly the same cost committed to the Apollo Program in 2015 money. Some developed nations, including the UK, already meet the GDP percentage target spend, but many do not and there is little international coordination to maximise the results. It has been modelled on the more recent International Technology Roadmap for Semiconductors, an international research collaborative that is credited with greatly and swiftly improving the quality and economics of semiconductor manufacture.

David illustrated the cases for subsidy by using what appeared to be rather complex equations to quantify the cases for subsidy. In conclusion David said that solar PV varies with location, has limited penetration that affects justified subsidy. Any benefits are maximised by choosing the correct locations. CCS is regarded as 'footloose' and its growth is constrained by the market. Global benefits need global support i.e. Apollo project as regional benefits capture only part of cost fall. Results are sensitive to fossil and carbon prices, PV learning and growth rates, discount rate, resource. CCS justifies subsidy much less than solar PV.

The final paper in this session was given by Ben Wettenhall and was entitled **"Flexible CCS Network Development (FleCCSnet)".** The FleCCSnet project is of 1.5 years duration and is

funded by UKCCSRC. Its scope is to consider the impact of flexibility across the whole CCS chain. It involves studies into the interfaces between each element of the system; e.g. at the entry to the pipeline system from the capture plant and at the exit from the pipeline to the storage site. Factors identified are intended to allow CCS network designers to determine the degree of flexibility in the system. It will allow effective reactions to short, medium and long-term variations in the flow of CO_2 from capture plants and the constraints imposed on the system by CO_2 injection and storage.

The work on operational flexibility in power plants with post combustion capture used a rigorous, fully-integrated model along with accurate assumptions about the capabilities of power plants to operate at part load and to regenerate additional solvent. It has characterised the operating envelope, performance and the corresponding compressed CO_2 flow of coal power plants for a range of loads and rigorously validated guidelines have been published including part-load operating strategies.

Work on the impact of storage uncertainty looked at the link between offshore storage and transportation infrastructure. FleCCSnet looked at how uncertainty in CCS store properties lead to variations in CO_2 flow that can impact transportation infrastructure. This included the proximity of wellhead conditions to the CO_2 equilibrium line and a maximum limit on velocities constrains the operational envelope. These factors can limit the ability of the storage site infrastructure to handle variations in CO_2 flow coming into the store and impact on the design of the pipeline infrastructure.

One aspect of this project concerned the short-term storage potential of dense phase CO_2 in pipelines. It involved studying the available line packing time of CO_2 pipelines in terms of pipeline geometry, mass flow rate and line pressure and will ultimately publish relationships between these variables. These relationships allow an estimation of the line packing capability of a CCS pipeline network in terms of pipeline design and operation. They indicate that a pipeline, with dimensions typical of those considered for CCS schemes, can provide short term storage of CO_2 for around 10 hours. The level of flexibility for the pipeline to act as short-term storage could be key in the design of a CCS network system.

Results from the project into the effect of varying flow patterns on transportation networks indicate that a pipeline will follow the flow of the capture plant with a slight delay and single-phase operation can be maintained if adequate pressure management options exist in the system. With more active sources connected into a CCS network, network management in terms of maintaining flow into the storage site is made easier. As would be expected, the flow is dominated by the emitter with the highest flow rate and flow can be easily maintained if both emitters are not shut off at the same time. With more complex networks, the number of sources connected to a single pipeline can grow organically if the pipeline is designed to accommodate the peak volume.

Conclusions from FleCCSnet Project are that post combustion capture plant flexibility is often understated. Variations in key geological store properties and the required level of injection flow flexibility must be considered so that the transportation system can deliver the required CO_2 flow at the required conditions. The capability of the pipeline system to act as short-term storage in the network is very important and should be considered in the design of system (including reuse of infrastructure). If designed to accommodate peak flow, the transportation system can cope with fluctuating levels of CO_2 given adequate pressure management exists. Fluctuations in flow can still impact on storage side operation; this needs to be considered in

more detail in future work. Further work should also focus on different power plant and/or CO_2 capture options including capture from large industrial sources.

PLENARY SESSION

The event was concluded by the plenary session given by Mike Hemsley from the Committee on Climate Change and was entitled **"The role of CCS in reaching UK emission targets up to 2050, and also beyond to net zero".** Mike began by describing the Climate Change Act and the Committee on Climate Change (CCC). The CCC is an independent, statutory body established under the Climate Change Act 2008. Its purpose is to advise the UK Government and Devolved Administrations on emissions targets and report to Parliament on progress made in reducing greenhouse gas emissions and preparing for climate change.

In fulfilling this role its focus is to provide independent advice on setting and meeting carbon budgets and preparing for climate change, monitor progress in reducing emissions and achieving carbon budgets and targets, conduct independent analysis into climate change science, economics and policy and engage with a wide range of organisations and individuals to share evidence and analysis. The CCC draws on a wide range of evidence to provide its independent view of the best path to 2050.

Building a low-carbon economy (role of CCS) aimed at meeting the UK 2050 target is a tough but achievable challenge. The carbon budgets provide stepping stones to the long-term target. Carbon removals is already expected to play a role to 2050 vital for net zero.

Given various risks and uncertainties a portfolio approach, (i.e. firm minimum commitments on less mature technologies are required (e.g. 20-25GW offshore, 4-7 GW CCS by 2030), alongside competitive investment in mature technologies), is appropriate for power sector decarbonisation.

CCS is important in power for flexible low-carbon generator i.e. decarbonised mid-merit plant to complement the variable output of renewables. It will anchor load to support CCS infrastructure, sharing the costs and will provide a pathway to bioenergy for electricity generation, with CCS (BECCS).

CCC has done some work on hydrogen and found that there is a need to decarbonise heat. Previously electrification was considered the best option, but is costly, disruptive, and the consumers do not want it. There is a possibility of using the existing gas grid with a decarbonised gas (e.g. H_2) however, the best method of large-scale H_2 production is via steam methane reforming, but will still need to capture the carbon.

Not having CCS is likely to require almost full decarbonisation of buildings and surface transport and possibly further action (e.g. constraints on aviation). The CCC and ETI estimate not having CCS would double the cost of meeting the 2050 target. It could rule out large-scale production of hydrogen for low-carbon heating in the UK. Barriers to CCS mean this needs to be demonstrated in advance of major decisions on decarbonisation pathways and implies that CCS needs to exist as an option by 2030.

Previous CCC recommendations on CCS were that it is important for multiple sectors and that the cost of meeting 2050 target doubles without CCS. UK deployment is needed to drive cost reductions and the failure of commercialisation competitions indicates that new business models are needed.

Barriers to delivering CCS are that costs are currently high, the supply chain is limited and lacking in market signals. A lack of familiarity with CCS due to the immaturity of sector, raises the risk profile. CCS-specific risks include the volume risk, the cross-chain risk and the storage liability risk.

The CCC has offered a strategic approach to delivering CCS. There needs to be a clear policy signal, the development of strategic clusters (which prepare for industry CCS and share infrastructure). These can be power-led or use a power-and-industry-led approach. The strategy might include a "Part-chain" approach with separate contractual arrangements for capture, transport and storage. There should be a phased deployment programme to minimise initial cost burden. This approach will benefit later from technology, project learning and economies of scale. A supply chain should be developed and engagement with the financial community. Index capture CfDs linked to fuel prices are suggested as is the provision of a funding mechanism for industry capture.

Report of the BF2RA Energy Science Lecture 2017

2nd October 2017

The Energy Science Lecture, of which the FERF was a sponsor, was held on 2nd October 2017 at Prince Philip House, 3 Carlton House Terrace, London. It was presented by Dr Arshad Mansoor, Senior Vice President of R&D at the Electric Power Research Institute (EPRI) and was entitled "The Integrated Energy Network – A Pathway for Action".

Dr Mansoor is responsible for EPRI's portfolio of R&D and Demonstration Programmes spanning all sources of generation, power delivery and utilisation and the environment. Arshad has a Bachelor of Science in electrical engineering from the Bangladesh University of Engineering and Technology. He earned his Master of Science and PhD in electrical engineering focusing on power systems engineering from the University of Texas in Austin and completed the MiT Reactor Technology Course. Over recent years EPRI has examined the forces changing the world's energy systems culminating in the EPRI report "The Integrated Energy Network; Connecting Customers with Reliable, Affordable and Clearer Energy".

Arshad's lecture described the Integrated Energy Network (IEN) that envisions a future in which customers have flexibility to use, produce and manage energy as they choose, while improving access to reliable, safe, affordable and cleaner energy. Arshad focused on three areas: Using Cleaner Energy through Efficiency and Electrification, Producing Cleaner Energy and Integrating Energy Resources. The talk highlighted insights from his work with implications for research and infrastructure development.

The talk was interspersed with five video clips each highlighting areas of EPRI's activities in this field. IENs will provide a pathway for action designed to ensure safe reliable affordable and cleaner energy resources. The videos described how the integration of all types of energy generation was essential and showed the life of a typical family living in a "connected electrified environment". The replacement of fossil generated energy, termed electrification, was described as was the integration of the distribution networks via flexible "smart demand".

The talk was concluded by the presentation of a series of discussion topics, as follows:-
What do customer's expect from their energy system today, tomorrow?
How do we accelerate development of economic and efficient electric technologies?
How important is a diverse generation portfolio? How do we value?

How do we fund, plan, and operate a grid with more diverse options?
Are digital technologies the "glue" that integrates the pieces?
What R&D initiatives are required for an Integrated Energy Network?

Reports from the Technical Press

BIOMASS

Solar and Wind Cheaper Than **Biomass** to Reliably Power the UK
Natural Resources Defense Council
A new study concludes that there is no economic or strategic case for coal-to-**biomass** conversion in the United Kingdom. While the **biomass** industry ...

Drax eyes battery storage to accompany gas and **biomass** conversions
edie.net
UK power station operator Drax plans to complement its ongoing **biomass** conversions with gas and battery storage options at two coal power units, ...

Britain seeks to limit **biomass** power costs
Reuters UK
Britain's government has launched a consultation into cutting the cost of support it provides for **biomass** power units, it said on ...

EIA: Densified biomass production reaches 570000 tons in June
Biomass Magazine
The U.S. Energy Information Administration has released the September edition of its Monthly Densified **Biomass** Fuel Report, reporting that data ...

Recent progress in torrefaction for upgrading solid biomass fuels
Biofuels conferences - Conference Series
Biomass can be transformed into gas or liquid fuels via a variety of methods such as gasification, pyrolysis, anaerobic digestion, fermentation and ...

Drax powers ahead with plan to cut down on coal
Telegraph.co.uk
Its **biomass** success has been no easy feat. The **biomass** pellets have a lower energy intensity than coal, meaning one and a half times as much is ...

New research finds bioenergy could help secure future energy demand in UK
Power Technology
ETI programme manager Geraint Evans said: "**Biomass** is already one of the largest and most versatile sources of renewable energy in the UK.

Carbon microspheres from biomass could find uses in electronics
Materials Today
Biomass used to make carbon microspheres for energy storage.

UK strongly in favour of bioenergy
Bioenergy Insight Magazine
84% of people in the UK support the use of waste and 77% the use of **biomass** for energy production, according to new survey results published by the ...

Making woody biomass truly sustainable
EURACTIV
Sustainable **biomass**, including forest **biomass**, accounts for as much as 45% of all renewables consumed in the EU – considerably more than wind, ...

How can we avoid turning biomass into the Cinderella of the energy industry?
Prospect
Biomass is not getting "a fair crack of the whip", according to Ray Tucker, CEO of Real Ventures. September's government-staged energy auction was ..

'Energy dash for biomass' risks wasting potential of EU's bioeconomy – EURACTIV.com
EURACTIV
By failing to take a holistic approach and treat the LULUCF and renewable energy dossiers as separate and distinct issues, the EU is slicing Europe's ..

Production and Characterization of Biomass Briquettes from Tannery Solid Waste
MDPI
Biomass briquettes are a proven way of generating energy from waste. This study investigates the development and characterization of **biomass** ...

Biochar, the once and future agricultural mainstay
Cosmos
Biochar – a charcoal-like product made by subjecting wood or other **biomass** to heat in conditions where oxygen is limited – has been used by farmers ...

Tar Detection Systems for Controlling Biomass Gasification
Enlighten: Publications - University of Glasgow
... Detection Systems for Controlling **Biomass** Gasification. 9th International Conference on Applied Energy (ICAE2017), Cardiff, UK, 21-24 Aug 2017.

Europe Needs to Be Frank About Biomass
Bloomberg
In part, by switching to **biomass**, largely in the form of wood pellets. **Biomass** already accounts for about 8 percent of U.K. electricity generation, four ...

Biomass Burning Releases Pollutants That Cause DNA Damage
CleanTechnica
The burning of **biomass** in the Amazon releases particulate matter air pollution that causes oxidative stress as well as severe DNA damage in human ..

Rice husk-fuelled biomass project launched in Myanmar
Bioenergy Insight Magazine
Japanese construction firm Fujita Corp. has announced that it will develop a 1.8MW **biomass** power project fuelled with rice husk in Myanmar.

Can Co-Firing Biomass With Coal Help Meet International Climate Goals?
Forbes
And there's where the experts are divided: Some say that if 5% of the **coal** that ... The good **news** is that the technologies are getting better and better.

Biomass project to test new waste sources in decentralised energy system at the University of ...
Bioenergy Insight Magazine
UK-based University of Chester and **biomass** specialist Arensis will run a new research project to trial a range of new waste feedstocks to feed into a ...

IEEFA Update: UK Biomass-Fueled Electricity Generation Appears Not to Be the Answer
Institute for Energy Economics and Financial Analysis (IEEFA)
Growing doubts around the merit of burning wood and other solid **biomass** as a large-scale solution for cutting carbon emissions from power ...

Not Only, But Also
Biomass Magazine
The team at **Biomass** Magazine is closing out the year with an issue dedicated to installations that produce and use **biomass** energy on-site. We've ...

New technology converts biomass into 'coal'
Phys.Org
The University of Nottingham is partnering with the **Energy Research Accelerator** (ERA) and CPL Industries to produce a commercial scale facility capable of converting biomass into next-generation ... This converts high-moisture biomass into solid **fuels** using moderate temperatures and high pressures.

Renewable coal on the horizon
UMN News
More **research** is needed to determine the new **fuel's** future impact, but if ... The biofuels could also help salvage **energy** from trees killed by the ...

Researchers reduce CO emissions from stored wood pellets
Biomass Magazine
The New York State **Energy Research** and Development Authority recently announced that Clarkson University discovered a new process to eliminate the release of dangerous carbon monoxide (CO) **gas** from wood pellets in storage. The use of wood pellet boilers and stoves to replace heating oil, ...

NGOs call on UK government to end biomass subsidies
Bioenergy Insight Magazine
A significant amount of the UK's renewable energy generation comes from old coal-fired power stations that have been converted to burn **biomass**, primarily in the form of wood pellets imported from the southeastern US. NRDC argues that **biomass**-burning relies on government subsidies to be ...

European investors to fund $53-million bio-coal plant
MINING.com
With the idea of supplying clean energy to utility companies in Nordic countries and Central Europe, the bio-**coal** plant will rely on a torrefaction ...

CO2 RELATED

Copper catalyst yields high efficiency CO2-to-fuels conversion
Scientists have developed a new electrocatalyst that can directly convert carbon dioxide into multicarbon fuels and alcohols using record-low inputs of energy.

Solar-to-fuel system recycles CO2 to make ethanol and ethylene
Phys.Org
Solar-to-**fuel** system recycles CO2 to make ethanol and ethylene ... a DOE **Energy** Innovation Hub established in 2010 to advance solar **fuel research**.

Exploiting carbon dioxide as an asset – not a liability
Canadian Biomass
... the atmosphere and in the most basic and natural way possible – via photosynthesis; converting solar radiation to **biomass** that captures more CO2.

New System Turns Carbon Dioxide into Fuel Even Better than Plants
Inverse
If the system can break out of the lab, it could help **fuel** the world without relying on ... As the **researchers** detail Wednesday in the journal **Energy** and ...

CO2 storage test can distinguish carbon from coal, gas and biomass
Bioenergy Insight Magazine
CO2 storage test can distinguish carbon from coal, gas and **biomass** ... emissions varies with the source of emissions, such as coal, gas or **biomass**.

Breakthrough in direct activation of CO2 and CH4 into liquid fuels and chemicals
Researchers have made a significant breakthrough in the direct conversion of carbon dioxide (CO2) and methane (CH4) into liquid fuels and chemicals which could help industry to reduce greenhouse gas emissions whilst producing valuable chemical feedstocks.
Converting carbon dioxide to carbon monoxide using water, electricity
Posted: 12 Oct 2017 05:02 PM PDT
Researchers have determined how electrocatalysts can convert carbon dioxide to carbon monoxide using water and electricity.

Carbon capture costs decline, but still too expensive: scientists
Canadian Biomass
While technology for carbon capturing has advanced significantly to trap up to 90 per cent of carbon emissions from smokestacks, ...

Nrl receives patent for carbon capture device—a key step in synthetic fuel production from seawater
Phys.Org
Nrl receives patent for carbon capture device—a key step in synthetic **fuel** ... the **gas** into **energy**-rich molecules," said Dr. Heather Willauer, **research** ...

Expanding Brazilian sugarcane could dent global CO2 emissions
ScienceDaily
Vastly expanding sugarcane production in Brazil for conversion to ethanol could reduce current global carbon dioxide emissions by as much as 5.6 percent, researchers report.

UK urged to renew carbon tax pledge
Financial Times
A renewal of the policy beyond 2021 was needed to deliver the government target to phase out **coal**-fired power generation by 2025 without further ...

Using Sunlight to Convert CO2 to Methane Could Help Store Renewable Power
Seeker
That **gas** can be stored and burned to produce **energy** or used to produce other synthetic **fuels**, ... 7 in the **research** journal Nature Communications.

First CO2 rise in four years puts pressure on Paris targets
BBC News
The main cause of the expected growth has been greater use of **coal** in China as its economy expanded. Researchers are uncertain if the rise in .

Evaluation of novel hybrid membranes for carbon capture
ScienceDaily
Hybrid materials known as mixed matrix membranes are considered a promising approach to capture carbon dioxide and mitigate against global warming. These materials are derived from a polymer combined with porous nanoparticles.

Transforming greenhouse gases: New 'supercatalyst' to recycle carbon dioxide and methane
ScienceDaily
Engineers have developed a new and cost-effective catalyst to recycle two of the main causes behind climate change -- carbon dioxide (CO2) and methane (CH4).

Artificial photosynthesis gets big boost from new catalyst
ScienceDaily
A new catalyst brings researchers one step closer to artificial photosynthesis -- a system that, just like plants, would use renewable energy to convert carbon dioxide (CO2) into stored chemical energy.

COAL

Scientists Are Racing to Find New Uses for the **Coal** Utilities No Longer Want
Bloomberg
The 30-foot hull of an experimental mini-sub is helping to show how the U.S. may be able to redeploy the mountain of **coal** that power plants are no ...

New method for identifying carbon compounds derived from fossil fuels
Scientists have developed a laboratory instrument that will greatly reduce the cost of analyzing carbon isotopes.

Helium found in coal seams could aid safe shale gas extraction
EurekAlert (press release)
The discovery of high levels of helium in UK **coal** seams could help scientists to monitor the secure recovery of **coal** or shale gas from underground sites. ... accuracy of **news** releases posted to EurekAlert! by contributing institutions ...

Satellite Quantifies Carbon Dioxide from Coal-Fired Power Plants
Eos
Using data from NASA's Orbiting Carbon Observatory 2 satellite, researchers measured emissions of the greenhouse gas from individual **coal** plants ...

Why coal fired power stations don't work so well when they are old
RenewEconomy (blog)

The ageing of **coal** fired power stations is currently in the **news** with the likely shutdown on Liddell Power Station in 2022. Industrial plants and utilities ...

Formation of coal almost turned our planet into a snowball
Phys.Org
While burning **coal** today causes Earth to overheat, about 300 million years ago, the formation of **coal** brought the planet close to global glaciation.

Coal power set for one last hurrah
Telegraph.co.uk
Britain's remaining **coal**-fired power plants could enjoy an 11th-hour revival in the early 2020s despite the Government's drive to cut carbon emissions, ...

Higher carbon price needed to phase out UK coal generation by 2025
edie.net
Higher carbon price needed to phase out UK **coal** generation by 2025 ... The **news** arrives days after CDP revealed that there had been an 8-fold ...

US firm offers 'coal to chemicals' technology
DAWN.com
An American company on Tuesday offered a new technology for production of various chemicals from the emissions of **coal**-fired plants in ...

COP23 - 'Our guests will be surprised how much Germany relies on coal'
Clean Energy Wire
Germany is hosting this year's international climate summit (COP23) in Bonn while in Berlin ongoing coalition talks will shape the future of national ...

16% of all deaths are caused by pollution, commission finds
GCR
It says: "Fossil fuel combustion in high and middle-income countries, and the burning of **biomass** in low-income countries, accounts for 85% of ...

The world is abandoning coal-fired electricity at an astonishing pace
Quartz
Coal is the dirtiest of fossil fuels—it produces per kilogram the least amount of energy and the greatest amount of pollution—and the world is quickly ...

Some Chinese coal ash too radioactive for reuse
EurekAlert (press release)
IMAGE: **Coal** ash from China's high-uranium **coal** deposits, such as what is ... The level of radiation in this **coal** ash could pose human health risks, ... and EurekAlert! are not responsible for the accuracy of **news** releases posted to ...

Canada, UK team up in push to end coal-power use
The Globe and Mail
Environment Minister Catherine McKenna and her British counterpart, Claire Perry, will launch an international alliance to phase out **coal**-fired ...

Fossil fuel burning set to hit record high in 2017, scientists warn
The Guardian

The burning of fossil **fuels** around the world is set to hit a record high in ... 57 **research** institutions and estimates that global carbon emissions from fossil ... The new analysis is based on the available **energy** use data for 2017 and ...

UK Researchers First to Produce High Grade Rare Earths From Coal
UKNow (press release)
University of Kentucky researchers have produced nearly pure rare earth concentrates from Kentucky **coal** using an environmentally-conscious and cost-effective process, a ground-breaking accomplishment in the energy industry.

Polluting UK coal plants export power to France as cold weather bites
The Guardian
We are still using less **coal** than we did this time last year though," he said. Uniper, the German energy company that runs Ratcliffe **coal** power station in Nottinghamshire, said the higher usage was a response to the situation in France and colder temperatures. "Over the past few weeks, the French power ...

GAS

Drax plans to turn more **coal** power into gas
Sky News
The Government announced in 2015 that all **coal**-fired power stations would be closed by 2025 and, as a result, Drax has already switched three of its ...

A new way to harness wasted methane
ScienceDaily, October 17th 2017
Scientists have identified a process that could be used to harness methane that is now wasted by being burned off at wellheads.

New membrane makes separating methane and carbon dioxide more efficient
Science Daily, October 18th 2017
To make natural gas and biogas suitable for use, the methane has to be separated from the carbon dioxide. This involves the use of membranes: filters that stop the methane and let the CO2 pass through.

UK Government, Shale Gas and Climate Change
Center for Research on Globalization
Instead of making a genuine push for renewable **energy**, the government insists that nuclear power, as in new builds Hinkley Point C (being built by the French state-owned company EDF, and others built by China and South Korea), and fossil **fuel** in the form of shale **gas** is the only way to keep the ...

GENERAL

Firebricks offer low-cost storage for carbon-free energy
Researchers draw from an ancient technology in their latest solution to enabling rapid expansion of wind, solar and nuclear power. Heat-storing firebricks could be used to level electricity prices for renewables, they propose.

Seaweed as fuel? Grants help fund research in Mississippi
Bristol Herald Courier (press release) (blog)
A federal grant will help pay for scientists at the University of Southern Mississippi do **research** on the uses of ...

Giant energy storage battery installed at Sheffield biomass plant
The Engineer
In a claimed UK first, energy supplier E.ON has completed the installation of a 10MW energy storage system that will be used to help smooth the flow ...

Drax to work with Sheffield University to revolutionise energy production
Yorkshire Post
Having transformed half of its coal fired power station to sustainable **biomass** to become the UK's largest single site renewable generator, Drax is ...

Optical diagnostic to help improve fuel economy while reducing emissions
ScienceDaily
A new optical device that helps researchers image pollutants in combusting fuel sprays might lead to clearer skies in the future. An optical setup can now quantify the formation of soot -- particulate matter consisting primarily of carbon -- as a function of time and space for a variety of combustion processes.

A new way to store thermal energy
Sciencedaily
A new phase-change material provides a way to store heat in a stable chemical form, then release it later on demand using light as a trigger.

HYDROGEN

Tidal **energy** site in Orkney in hydrogen 'first'
BBC News
A Scottish test and **research** centre has claimed a world "first" by generating hydrogen **gas** from tidal **energy**. The European Marine **Energy** Centre ...

New nanomaterial can extract hydrogen fuel from seawater
A new hybrid nanomaterial harvests solar energy and uses it to extract hydrogen from seawater, cheaply and efficiently.

A new way to produce clean hydrogen fuel from water using sunlight
Researchers combined graphitic carbon nitride and black phosphorous to make a new metal-free composite photocatalyst capable of producing hydrogen from water.

Cobalt and tungsten key to cheaper, cleaner hydrogen
ScienceDaily
Electrolysis, splitting the water molecule with electricity, is the cleanest way to obtain hydrogen, a clean and renewable fuel. Now, researchers have designed a new catalyst that reduces the cost of electrolytic hydrogen production.

Hydrogen fuel from water by harnessing red and near-infrared regions of sunlight
ScienceDaily
Scientists have synthesized a compound that absorbs near-infrared light to produce hydrogen from water. The compound contains three ruthenium atoms connected by an organic molecule. The absorbed light stimulates electrons to 'jump' into orbitals that do not exist in other, similar compounds.

Bridging the gap: Potentially low-cost, low-emissions technology that can convert methane without forming carbon dioxide
ScienceDaily
A potentially low-cost, low-emissions technology has been designed that can convert methane without forming carbon dioxide.

RECYCLING & PLASTICS

Ilona Amos: Confusion over recycling is wasting valuable resources
The Scotsman
Ilona Amos: Confusion over **recycling** is wasting valuable resources ... Results from the second annual UK **Recycling** Index, compiled by **waste** firm ... if we don't step up the amount of **waste** that is **recycled** or used to create **energy**.

Electronic junk is a growing problem, and here we dispel the 7 myths about e-waste management
e27
Recycling e-**wastes** conserves more **energy** than mining, manufacturing or lumber. Since the metals are present already in their pure form in metals, ...

UK public 'confused and concerned about recycling'
Energy Live News - Energy Made Easy
That's according to a new report from **recycling** and **waste** management firm Viridor, which highlights public frustration with product labelling and ...

Finnish firm to start recycling waste tyres, turn them into oil
YLE News
Finnish firm to start **recycling waste** tyres, turn them into oil ... used again, but most are **recycled** into other materials or burned for **energy** production.

How to Turn Trash Into Energy in 12 Hours
Bloomberg
The sorting hall at Dong **Energy's** Renescience **waste energy** plant in ... that can be used to create electricity, **recycled** or sold on to a scrap yard.

UK Clean Growth Strategy Welcomed by ADBA – But Food Waste Collections Needed
Waste Management World
... play a central role in decarbonising heat, electricity, transport, and farming, as well as **recycling** organic **wastes**, increasing **energy** and food security, ...

Waste-to-energy benefits highlighted in new research
Bioenergy Insight Magazine
Argonne **research** shows that we can generate **energy** and mitigate ... and gasification are all able to create **fuel and energy** from municipal waste, ...

NIC concern over carbon emissions from burning plastics
letsrecycle.com
The Commission also recognises that **energy** from **waste** infrastructure has ... However it cautions that as the carbon intensity of the **energy** grid falls, ... depends on supporting policies such as **recycling** targets and the landfill tax.

Here's a solution for the global plastic and energy crises
eco-business.com
That is, the "dirty plastics" which rarely get **recycled** could be transformed into **waste**-derived-fuel for everyday **energy** needs. Of course it is best to ...

Waste plants in China will soon recycle electric car batteries
The Express Tribune
Waste plants in China will soon **recycle** electric car batteries ... According to the International **Energy** Agency, China accounted for more than 40 per ...

Making it easier to recycle plastics
ScienceDaily
Researchers report new approaches could dramatically increase the amount of plastic waste that can be successfully recycled.

Reduce, reuse, reboot: why electronic recycling must up its game
The Guardian
Out of all the electronic **waste** we send for **recycling**, 80% ends up being shipped (some legally, and some not) to emerging and developing countries. China is ... The Eco-vert label denotes low-**energy** manufacture and avoidance of toxic materials and appears on some printers and computers.

WASTES

New method makes bioethanol from waste -- in existing plants
ScienceDaily
It is possible to produce bioethanol from agricultural and industrial waste in existing plants in a socioeconomically sustainable way, according to new research from Sweden.

Method to Recycling Waste Energy with 2D Electron Gas Developed
Electronics360
A new approach utilizes high mobility, 2D electron gas, boosting thermoelectric conversion efficiency. More than 60% of the **energy** produced by fossil fuels is lost as heat.

Waste coffee grounds helping power London buses
Canadian Biomass
bio-bean founder Arthur Kay won Shell LiveWIRE's Innovation Award in 2013 and the Mayor's Entrepreneur Programme in 2012 with his ideas about turning coffee waste into fuel. bio-bean has since gone on to produce **biomass** pellets and briquettes called Coffee Logs, before this latest biofuel ..

Indian team produces high surface area graphene from waste peanut shells
Graphene-Info (blog)
The team's objective of using **biomass**-waste is not only to solve the problem of waste recycling but also to generate value-added materials like conductive graphene for renewable energy storage devices such as supercapacitors.

A Power Plant Is Burning H&M Clothes Instead of Coal
Bloomberg
The combined heat and power station in Vasteras, northwest of Stockholm, is converting from oil- and **coal**-fired generation to become a fossil fuel-free ..

MPs claim overcapacity of EfW in UK
Materials Recycling World
An Early Day Motion (EDM) has been launched in Parliament calling for a moratorium on new **energy**-from-**waste** (EfW) facilities. ... than it is forecast there will be genuinely residual combustible **waste** to burn; further notes that incineration overcapacity can be a barrier to achieving the **recycling** society; .

Discarded cigarette butts: The next high performing hydrogen storage material?
ScienceDaily
Discarded cigarette butts are a major waste disposal and environmental pollution hazard. But chemists have discovered that cigarette butt-derived carbons have ultra-high surface area and unprecedented hydrogen storage capacity.

RESEARCH UPDATES

New research updates will appear in the next issue of the newsletter

CALENDAR OF FUEL AND ENERGY RESEARCH MEETINGS AND EVENTS

Date	Title	Location	Contact
Thursday 25th January 2018	Rushlight Awards Party and Rushlight Show	The Royal Geographical Society, 1, Kensington Gore, London	Mr. Clive Hall, Chief Executive Eventure Media Ltd. 32, Elsynge Road, London, SW18 2HN E-mail : cjh@eventuremedia.co.uk Website : www.rushlightevents.com/rushlight-awards
Wednesday 11th April 2018	**FERF 2018 Annual Meeting and Inaugural Seminar of the FERF Environment Interest Group, "Materials for Energy Technologies"**	**The Diamond Centre, University of Sheffield, 32 Leavygreave Road, Sheffield S3 7RD**	**Dr. David J.A.McCaffrey, Secretary of the Fuel & Energy Research Forum, Tel : 01242-236973. E-mail : mail@tferf.org Dr Bill Nimmo, Environment Interest Group Co-ordinator, University of Sheffield, Tel : 0114-215-7213. w.nimmo@sheffield.ac.uk**
Date to be advised	**"New Realities for Power Generation in the UK; How the Market has Changed and What it Means for Research Priorities", Inaugural Seminar of the FERF Advanced Power Generation and Gasification Interest Group**	**Venue to be advised**	**Dr Robin Irons, Advanced Power Generation and Gasification Interest Group Co-ordinator, University of Nottingham, Tel : 0115-748-4098. E-mail : Robin.Irons1@nottingham.ac.uk**
2nd and 3rd May 2018	All Energy Exhibition and Conference 2018	SEC Glasgow, Exhibition Way, Glasgow G3 8YW	For more information visit:- http://www.all-energy.co.uk/

3rd to 8th June 2018	9th International Freiberg Conference on IGCC & XtL Technologies, "Closing the Carbon Cycle", organised by the Institute of Energy Process Engineering and Chemical Engineering and the IEA Clean Coal Centre	The InterContinental Hotel Berlin, Berlin, Germany	TU Bergakademie Freiberg, Institute of Energy Process Engineering and Chemical Engineering, Fuchsmuehlenweg 9, 09599 Freiberg, Germany Tel : +49 3731 39- 4511 Fax : +49 3731 39-4555 E-mail : gasification@iec.tu-freiberg.de Website : www.gasification-freiberg.com
Wednesday 5th to Friday 7th September 2018	**12th ECCRIA Conference, The European Conference on Fuel and Energy Research and its Applications, (ECCRIA 12). Conference Website : www.eccria-conferences.org.**	**Cardiff University, The Queens Building, Newport Road, Cardiff**	**Dr. David J.A.McCaffrey** **12th ECCRIA Conference Chairman** **Secretary of the Fuel & Energy Research Forum** **Tel : 01242-236973** **E-mail : mail@tferf.org** **Dr Robert Berry** **12th ECCRIA Conference Secretary** **Tel. 02058-331-9401** **E-mail : r.j.berry@gre.ac.uk**
10th to 14th September 2018	CHoPS 2018, 9th International Conference on Conveying and Handling of Particulate Solids	University of Greenwich, Greenwich Maritime Campus, London	Conference Secretariat Deborah Reed-Aspley at Constable & Smith Events E-mail : deborah@constableandsmith.com 4, Vincent Avenue, Beeston, Nottingham, NG9 1GU Tel : 0115-922-9422 Website : www.chops2018.org
10th to 12th September 2018	3rd International Conference on Energy Production and Management, Energy Quest 2018	New Forest, U.K.	Wessex Institute, Ashurst, Southampton. +44 (0)238) 029 2853. Email wit@wessex.ac.uk