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Conclusion

Over the last two years we have been able to design and construct a fully operational pilot unit working at multi ton scale and working in a real industrial environment. The system has demonstrated high levels of post combustion capture, turned the CO_2 into valuable highly efficacious products whose value has been externally tested, verified and most recently approved for sale in agriculture by the UK Fertiliser Industries Assurance Scheme (FIAS).

The project has also identified and exploited key developments relating to the use of biogenically derived feedstocks which add to both the systems carbon efficiency and the product utility. Further areas of potential development particularly, relating to enhanced heat storage capacity within the system and long term carbon sink development associated with the products, will be the subject of further work.

We have made considerable strides in the grant of our core patents internationally and have been able to file additional patents because of the advances that we have made in the project. In consequence of our technical development and the security of our IP we have been able to enter into advanced negotiations over the first large scale deployment of our technology which we expect to take place in specialised AD situations within the next 12 months.

https://www.youtube.com/watch?v=vmf1s9aliSA

Gives a high view outline of our technological approach.

Executive Summary Part One

CCm has been most fortunate to benefit from the CCEMC Grand Challenge award. The additional funding has been a very significant asset in speeding both our commercial and technical development.

The central aim of our project has been to demonstrate both the direct capture of CO_2 from post combustion exhaust gases and to quantify the additional avoidance and abatement benefits that our process is able to generate through incorporation of the CO_2 as a beneficial agent in new products.

Our process incorporates CO_2 into a range of new materials, the most advanced of which is a compound fertiliser, but it does so in such a way that the performance of the fertiliser is actually enhanced by its presence. Over the course of the project we have not only been able to demonstrate the validity of this approach but also expand its scope to improve the GHG and product benefits that our process develops, considerably beyond our original expectations; indeed we expect further improvements in the near future that will increase the scope of operation of the system and further broaden the range of benefits that it delivers as well as its scope for deployment.

Whilst our system is not the finished article we believe that it has reached an advanced state of readiness and as such is close to commercial adoption in several key application areas. We are currently at an advanced stage in negotiation with two UK based utility operators who wish to adopt the system and we hope to make similar progress in Alberta shortly. The reason for our relatively rapid advance is the underlying technical and commercial work that we have been able to undertake with the help of the CCEMC. This has allowed us to demonstrate that the process works, produces effective and consistent products (recently approved to FIAS standard) and can be developed in an economically viable manner not only producing substantial GHG reductions but also producing project IRR of greater than 15%.

In order for us to reach this position we needed to demonstrate

1. The technical validity and scalability of the process
2. The basic efficacy of the products that we produce
3. Quantify the real GHG savings
4. Confirm the economic viability of the process
5. Establish routes to market
6. Identify additional benefits and target their development

Our project has been designed to ensure that we address all these aspects in a progressive and realistic manner. In essence our task was to design, build operate and trial the pilot scale production of the first generation of carbon utilisation materials. We are pleased to report that we have been successful in all these undertakings.

1. The technical validity and scalability of the process

We have had the benefit of extensive laboratory based studies which allowed us to rapidly advance the design and construction of our pilot based unit. The unit is containerised and capable of capturing post combustion exhaust gases. The system has captured up to 1.2T CO_2 per day and producing 5T of compound fertiliser. The system has operated successful in both production and trial modes for almost a year and has not had any significant failures in operation. The operation of this system has allowed us to produce materials for trial and to develop detailed scale up designs along with capital and operational costings. These designs and costs have been developed in conjunction with external engineering consultants and the details are reported in the main report or annexes. Likely cost of a full scale production unit is £1.75M.

2. The basic efficacy of the products that we produce

The system has produced two principal grades of compound fertiliser that were trialled last year at the Royal Agricultural University, Harper Adams University and on an independent farm. The materials are delivered using standard agricultural practice and unaltered equipment. The details of the trials are available in the main report but we are pleased to report that the independent assessment of the results is ***"that the CCm product demonstrated a promotion of crop production in an entirely similar way to that which would have been expected from commercial products"*** (Professor P John, University of Reading). We are also pleased to report that our process has recently been ratified by the Fertiliser Industries Assurance Scheme (FIAS).

3. Quantify the real GHG savings

It is key to our process that the GHG savings are quantifiable and long lasting. The direct capture of CO_2 is easy for us to measure but the full carbon foot printing of the process is more complex. In the first instance we have utilised the CCalC methodology developed by University of Manchester. This has allowed the construction of a whole process analysis of our system. In summary this demonstrates the avoidance of around 79kT CO_2 PA for each unit deployed. The ultimate scale of GHG reductions will obviously be dependent on the level of adoption but initial economic evaluations lead us to forecast prospective CO_2 reductions of between 50 and 250MT over the next ten years. Importantly our development work has also identified a range of additional GHG reduction benefits associated with long term restoration of, and ultimately increase in carbon levels in soils. This work has been chosen for advanced evaluation by University of Sheffield specialist P^3 research unit over the next 3 years.

4. Confirm the economic viability of the process

Given the outstanding environmental benefits demonstrated by the process and the excellent performance of the fertiliser material, we have undertaken extensive economic evaluation of the process. Whilst we have a good deal of internal engineering and financial expertise, we chose to have the economics of the process and its investment potential examined by external consultants, Mott MacDonald. Their evaluation of the process has identified likely Capex development costs of £ 1.75M Opex in the region of £1.15M with a net IRR of greater than 15%.

Of equal importance to this initial assessment is the response we have received from a series of potential commercial operators who understand not only the benefits of additional income streams that we can generate but also fully comprehend both the GHG reductions, wider sustainability potential alongside significant waste reduction and improved plant operating efficiencies that deployment of our system will generate.

5. Establish routes to market

At the start of our project we had assumed that the most likely route to market would be in co deployment with an EfW facility. The principle reason for this was a good intermediate scale of production of CO_2 (not full scale power generation) the necessity for the EfW owner to meet basic sustainability requirements in terms of emissions and the potential to utilise the large quantities of heat generated by our process. The EfW deployment still remains likely but developments in the process have also highlighted even more attractive routes to market and higher profitability.

We have been approached by several operators of Anaerobic Digester (AD) systems whose operations are currently facing a range of challenges. These are centred on the high cost of disposal of the AD residual liquors and the difficulties in transporting high moisture content AD residue suitable for fertiliser use. In addition, high use of AD liquor close to its generation point is being found to impoverish soil fertility.

Developments of the CCm process during this project have allowed us to solve or significantly reduce all these problems by using the AD liquors as a diluent to our ammonia feeds, by using AD concentrates as plant nutrient substitutes – so reducing our Opex costs and by reducing water volumes in AD product by the utilisation of CCm process heat. Over all we are able to transform a loss making material into a profit generating one and at the same time significantly reduce CO_2 emissions. We are in advanced negotiations with several AD operators and we expect to develop an agreement that will result in first use of the technology within the next 6 months.

We are currently seeking partners for co-development in Alberta and currently in early stage negotiations.

6. Identify additional benefits and target their development

We have continued to broaden our patent portfolio over the last year and have secured patent cover for our platform technology, heat based and fertiliser targeted alternatives and look set to secure cover for our heat storage technology in the next 6 months.

In technical terms the most significant discovery during this project has been our ability to utilise biogenically derived nitrogen, phosphate and potash sources within our process. This breakthrough has multiple beneficial effects. It materially reduces GHG footprint further, reduces Opex costs, and increases profitability whilst broadening our potential markets. Most important of all it offers the potential for additional long term benefits in the product.

We have always believed that our product would have slow release profiles in terms of nutrient delivery to the soil. It appears that there is some evidence for this in our initial trial work but we are fortunate that Duncan Cameron at the University of Sheffield believes that the CCm fertiliser has the potential to have considerable restorative effects on soils and is therefore seeking to both measure the benefits from existing formulations as well and suggesting improved formulations to enhance the perceived positive effects.

We also wish to further enhance the products from our process by integrating a heat storage system into the fertiliser production unit in order to maximise the efficiency of the system and the range of circumstances in which the main unit can operate. We believe that this approach will have the dual effect of further proving our in-house heat storage system, which is based on our existing platform technology, and further reducing GHG footprint for the system by increasing our heat harvesting and improving the quality and timeliness of heat delivery to co deployed utilisation systems. Applications can vary from heavy oil energy utilisation to domestic aggregated heat utilisation networks and we hope to further explore this potential within the framework of a continuation to our CCEMC grant.

We are very pleased with the progress of our work and would like to thank the CCEMC for both its financial and advisory input over the last two years.

Project Description Part TWO

Introduction

CCm Research is developing a platform technology that reduces carbon intensity through direct capture, utilisation and avoidance. The process is constructed around a patented capture process which uses plant derived fibrous cellulosic materials coated with nitrogenous materials to remove gaseous CO_2 from combustion exhaust streams.

The gaseous CO_2 is initially held on the fibre surface as part of a basic carbonate matrix and further stabilised, immediately post capture, into a robust carbonate which is incorporated into a range of highly sustainable and effective materials. The captured CO_2 which ultimately becomes entrained in the end product, actually enhances the way in which the product performs; in addition, all the components of the capture step are incorporated into the end product in a manner which improves the products function and utility.

The inclusion of all process ingredients ensures that the whole process is zero waste; the real utility of all the components, including the CO_2 in the end product, adds substantial value to the process. Further value is created by the process from the substantial amounts of heat that can be harvested from the strongly exothermic capture reaction. This combination of benefits results in the process generating profit from carbon capture and transform CO_2 from a cost generating pollutant into a useable and beneficial resource.

The principal products that can be created using CCm technology include:

- Fertiliser and soil conditioners
- Functional fillers for plastics
- Heat storage materials

The focus of this CCEMC project is to design, construct and operate a pilot production system for fertiliser materials and demonstrate the use of these materials within agricultural systems.

Further to these key tasks the project aimed to quantify real carbon savings, develop a commercial delivery strategy and identify key areas that would further improve process integration, economic and environmental sustainability.

We are pleased to report that the project has been successful in achieving all these goals.

Background

CCm Research was founded in 2011 to develop technology identified by Peter Hammond from his work in new materials development. Peter's work was focused on the utilisation of natural fibres, whose mechanical and processing capabilities had been enhanced by treatment with supercritical carbon dioxide. Peter has worked in the application of supercritical carbon dioxide since 1998, initially at the University of Leeds with Keith Bartle and Tony Clifford and then at the University of Birmingham as an independent research fellow.

The original work on compound polymer development identified several key areas which, when combined, could dramatically improve the economic and environmental sustainability of materials production. These improvements were linked to the incorporation of captured CO_2 into the matrix of end products in a manner that enhanced the ultimate function of the material. Lower process energy requirement related to the utilisation of non–carbon intensive feed stocks – particularly through the use of phyto-materials; and the use of substantial amounts of medium grade heat generated by the underlying exothermic nature of the chemical reactions at the heart of the chemical process.

In many ways the CCm process has always been focused on the production of economically viable high utility materials. It is this focus that has largely prioritised the order of development for CCm principal materials.

In the first instance CCm focused on the production of functional fibres for inclusion within compounded plastics. Whilst this work was very successful on a technical basis it became clear that there were significant commercial barriers to be overcome before the materials would be widely adopted. These barriers were not related to economic viability but to an unwillingness from the polymer industry to utilise new or unproven materials; we expect this mind set to change in the future but for the time being it proves a significant barrier.

The CCm process creates two other products - fertiliser and heat storage materials. The heat storage materials were at the lowest stage of technical readiness whilst the fertiliser materials were at a more advanced technical stage and more importantly were capable of being sold into a an expanding commodity based market. For these reasons development of the fertiliser application became the central focus of our work.

Importantly the fertiliser application illustrates the key benefits of the CCm process:

- Utilisation of sustainable feedstocks
- Direct capture and utilisation of CO_2
- Generation of large quantities of heat.

We were particularly fortunate to be one of the winners of the Grand Challenge Phase One and this has given access to one of the best markets for our materials. Albertan and wider Canadian Agriculture is a significant fertiliser market into which our products can be sold. Alberta in particular appreciates the real value and necessity for CO_2 abatement and avoidance. Wider Albertan industry also produces and abundance of feedstocks for our process and the heavy oil industry in particular also has a significant requirement for the heat that is produced by our system.

Scope of work and Primary Goals

Previous development at CCm in Oxford had proved the basic feasibility of our process and given us a good understanding of what was required to take the process and its products closer to market.

Our scope of work has led to the development of five key goals:

1. Development of a multi-ton scale pilot production unit working in a real environment
2. Demonstration of the utility and value of the fertiliser products
3. Environmental Evaluation of the process
4. Economic evaluation of the process
5. Process improvement and further development recommendations

These avenues of work lead to the construction of a relatively simple development programme set out in more detail below. The basic steps are described in the following section:

WP No.	WP Description	Milestone	Partners	Month (Estimated Start Date: 1 May 2014)																							
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WP-1	**Project initialisation & coordination**																										
WP-1.1	Trial site agreement		CCM, VIR																								
WP-1.2	System working parameters and diagnostics		CCM, NPD																								
WP-1.3	CCm-CCU-F production process review		CCM, NPD, ORM																								
WP-1.4	CCm-CCU-F system design review		CCM, NPD																								
WP-1.5	CCm-CCU-F demonstration outline trial plan		CCM, VIR																								
WP-1.6	Project reporting & communication strategy		CCM																								
WP-2	**CCm-CCU-F Design Confirmation**																										
WP-2.1	Confirm specification		CCM, NPD																								
WP-2.2	Define outputs		CCM, NPD																								
WP-2.3	Concept confirmation		NPD, CCM																								
WP-2.3.1	*Fibre loading*		NPD, CCM																								
WP-2.3.2	*CO2 capture*		NPD, CCM																								
WP-2.3.3	*Additive preparation*		NPD, CCM																								
WP-2.3.4	*Primary stabilisation*		NPD, CCM																								
WP-2.3.5	*Pelletiser*		NPD, CCM																								
WP-2.3.6	*System controls*		NPD, CCM																								
WP-2.4	Detail design		NPD																								
WP-2.5	Supply chain review		NPD																								
WP-2.6	Bill of material specifications		NPD																								
WP-2.7	Design ratification	1. Completion of CCm-CCU-F	NPD, CCM, ORM																								
WP-3	**CCm-CCU-F Development**																										
WP-3.1	Commission build		CCM, ORM																								
WP-3.1.1	*Fibre loading*		ORM																								
WP-3.1.2	*CO2 capture*	2. Production of auger reactor	ORM																								
WP-3.1.3	*Additive preparation*		ORM																								
WP-3.1.4	*Primary stabilisation*		ORM																								
WP-3.1.5	*Pelletiser*		ORM																								
WP-3.2	Full system integration including controls		ORM, CCM, NPD																								
WP-3.3	Quality assessment		ORM, CCM, NPD																								
WP-4	**CCm-CCU-F Commissioning**																										
WP-4.1	Health and Safety assessment		CCM																								
WP-4.2	Regulatory confirmance checks		CCM, NPD																								
WP-4.3	Develop operational procedures		CCM																								
WP-4.4	Laboratory simulation trials		CCM																								
WP-4.5	Validate system controls & performance monitoring	3. CCm-CCU-F Pilot Unit	CCM																								

PART THREE

Project Delivery and Outcomes.

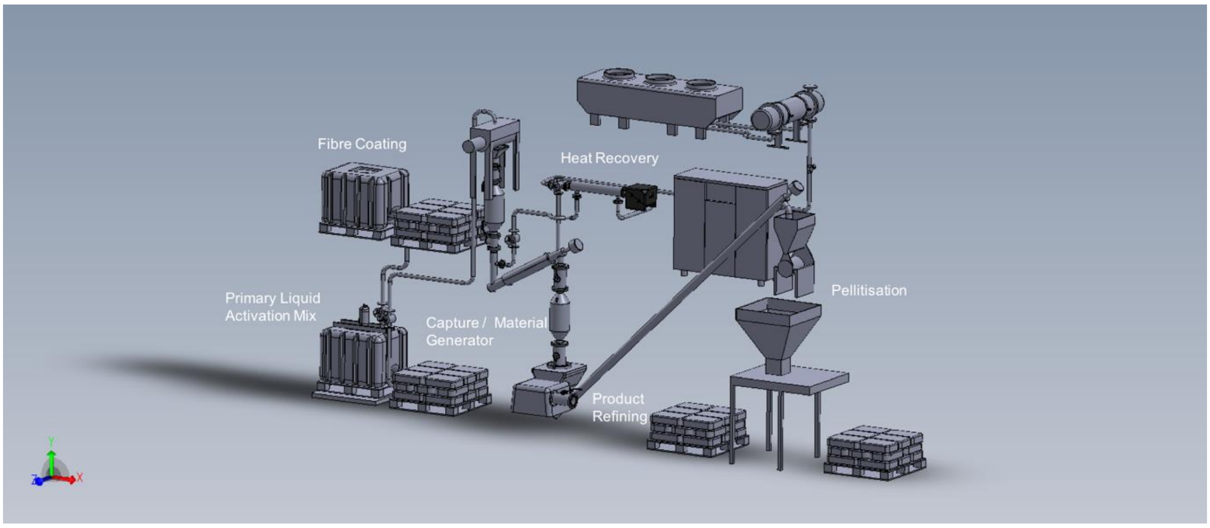
1. Development of a multi-ton scale pilot production unit working in a real environment.

In the first part of the project CCm confirmed the design of the pilot system which is summarised in the following graphic. The system which was designed needed to carry out and develop our basic fertiliser production process.

In its simplest form the CCm process is as follows:

- Preparation of capture coating liquids
- Coating fibre with capture liquid, to develop large surface area capture materials
- Exposing CO_2 containing gas stream to coated fibres, continuous counter current
- Recovery of heat generated by the capture reaction
- Final formulation of end product by the addition of top up plant nutrients if required
- Pelletisation or granulation of end product

These steps are examined in more detail within the outcomes section of the report.



The system was largely designed in house with assistance from external consultants as appropriate. The unit was fabricated externally through a range of sub-contractors and then delivered to our operational site at Ardley, North Oxfordshire. The system was designed to capture CO_2 from exhaust gas generated from biogas arising from landfill activity at a Viridor PLC owned site. Viridor are a Waste Management Business (www.viridor.com) who operate a range of electricity generating Energy Recovery Facilities (ERF's) across the UK

The equipment was housed within two 40ft shipping containers for ease of transport and delivered to the site in May 2015. The system is seen below adjacent to the gas engines from which it captures post combustion CO_2.

The CCm Pilot unit is housed within the two white shipping containers on the right of the picture. The stack of one of three gas powered electrical generators, which supply electricity direct to grid, can be seen on the left of the picture.

Commissioning and Development programme

The unit passed through a series of commissioning and safe operating evaluation prior to entering its production and operational development phase. A considerable degree of pre delivery trial work was carried out on key components prior to installation on site to ensure that the final commissioning process could be carried out as quickly as possible. This approach also had the advantage that it was able to produce a range of trial materials that could be examined during the first year agricultural evaluation programme.

The commissioning programme was accomplished over a period of three months with the following key tasks being performed:

Engineering Evaluation. **(**Appendix T)

Hazop and SOP systems had been developed in the design phase of the operation in conjunction with the main site operator Viridor. Post-delivery individual components, mixers, compressors ventilation, monitoring and principal reactor were all dry run to ensure that the control systems operated correctly. In the pre-production evaluation the system was operated using material inputs that had been extensively studied in the laboratory prior to scale operation. So for example the main fibre feed for the system was miscanthus, coated in aq. ammonia. The material was then exposed to mimic flow of different gas mixtures delivered from bottled sources to assess the basic operation of the reactor unit and the range of CO_2 concentrations over which the system could operate. Mimic gas flow were produced by delivering various mixtures of CO_2 and Nitrogen to unit. This process also allowed the calibration of the gas monitoring equipment to be accomplished. CO_2 concentrations from 5% to 100% were evaluated.

The capture reaction is carried out in a pressurised auger transfer unit, which can operate at up to 10 barg. This vessel is cooled via a water jacket allowing the heat evolved by the capture reaction to recorded in detail.

The picture (LHS) in the upper container shows a view of the primary coating mixer unit feeding into the pressurised reactor (inclined tube)

The second (RHS) picture shows the exit from the pressure reactor in the lower unit prior to final mixer unit.

The major part of the commissioning process concentrated on the materials transfer through the main reactor, the levels of capture and heat control as these a parts are key to the operation of the unit; however additional evaluations were carried out on the formulation of materials in the secondary mixing unit and pelletiser.

Post commissioning trials

Once the basic operational characteristics of the unit had been confirmed it was possible to move on to the live capture and production assessment phase of our work. In the first instance a variable range of phyto-fibre feedstocks were assessed, these included chopped cereal straws, wood fibre, paper mill residue, partially composted material and both wood and miscanthus fuel pellets. The materials were assessed for the effects of particle size and total formulation incorporation as well as potential contribution to end product nutrient profiles. The results of these evaluations are shown in the outcomes section. All materials showed good capture characteristics and effectively the process has been shown to be non-feedstock dependent; however, the additional benefits that can accrue from certain fibre formulation does affect the overall economics of the process and potentially the value of the end product. The value of the end product does not relate simply to the grade of fertiliser that is produced as specific formulations have been developed that maximise carbon capture or heat generation depending on which are the key parameters driving the economic output of the process. So for example, in the Canadian context high capture and high heat production are actually more important to the economic case for the process than in Europe where the chief goal is the production of specific targeted fertiliser grades.

A considerable amount of work was carried out relating to appropriate aq. ammonia loading (Appendix T) on the fibres; this was found to vary significantly from fibre to fibre and is a function of particle size and the "absorption" capacity of the fibre. This variability means that some fibre types are better for ultimate capture levels with, miscanthus, rye grass and wood fuel pellet fibres performing particularly well in this category – they essentially have a high ammonia loading capacity, imparting high primary capture and heat generation potentials, when compared with, for instance, compost materials which have relatively low loading capacity but can contribute a considerable amount of nutrients to the final fertiliser product.

The design of formulation effectively centres on balancing these key requirements and as a result we have developed our own calculator matrix for pre-production evaluations (Appendix T). In addition, to expand the matrix evaluation of these formulations, we also developed new mixing techniques and in so doing have made a key breakthrough which allows us to maximise ammonia loading and hence primary capture capacity whilst at the same time increasing the nutrient contribution from the fibre materials. We have achieved this by mixing anhydrous ammonia with nutrient rich, fibre based liquid stream derived from Anaerobic Digester (AD) liquors. This is a significant breakthrough and allows us to maximise the biogenic nutrient inputs into the fertiliser which has the benefit of reducing process input costs, improving nutrient availability and significantly enhancing CO_2 abatement from feedstock production. A patent has been filed relating to these new inventions.

CO_2 Capture and incorporation trials

Initial capture efficiency was established via theoretical calculation from the literature. This data was used as the basis for the construction of primary trials which focused on ammonia loading capacity of the fibres using bottled gas mixtures ranging from 5% to 100% CO_2.

Whilst the concentration of CO_2 in the gas stream is one of the key criteria affecting capture efficiency we also need to examine capture pressure, capture temperature and the manner in which the capture fibre system is presented to the CO_2 containing gas flow – essentially the dynamics of the counter current reactor system.

The work programme was designed with the benefit of data obtained from parallel laboratory based evaluations which were then scaled up to pilot plant evaluation. The levels of capture demonstrated at laboratory scale transferred well to pilot operation, however whilst it is possible to obtain capture levels well in excess of 95%, it was discovered that the transformation of the primary captured materials, essentially ammonium bicarbonate species into more stable true carbonate species, was slightly less efficient so that in real operating terms only around 80% of the CO_2 captured from the primary gas stream could be incorporated into the final product.

The reasons for this drop in efficiency is associated with the two step nature of our capture process (Appendix T). The CO_2 ammonia reaction transforms the gaseous CO_2 into a solid broadly bicarbonate based materials, unfortunately these bicarbonate materials are not particularly thermally stable nor are they good sources of nitrogen for plant nutrition. To overcome this problem a secondary reaction is used within our reactor unit. Calcium nitrate, which is co-dissolved with ammonia in the primary fibre coating system, reacts with the ammonium bicarbonate species to form ammonium nitrate and calcium carbonate products.

Such is the equilibrium position of this reaction that it is not economically viable to convert all the bicarbonate materials initially formed into true carbonates. It is important to note that ongoing work on this key part of the process has identified ways of improving the efficiency of this reaction, largely through the two stage which considerably enhance the conversion efficiency of the reactor.

Whilst the total effective capture level of 80% is not ideal we do expect improvement with further work. Most importantly it needs to be appreciated that the capture step of this process is only one step within an integrated materials production process which offers additional enhancements of carbon abatement so that the combined capture and abatement levels achieved by the process actually exceed those achieved by capture only processes. These net affects are discussed in the GHG section.

Heat recovery assessment

One of the key areas of our process that contributes to the high levels of carbon abatement achieved is the effective use of the heat generated by the exothermic capture reaction. Every ton of CO_2 captured by our process liberates 0.9GJ of heat – sufficient to heat 300kg of steam to 300^{o}C

In our pilot unit this heat is simply measured for specific formulations allowing assessments to be made of how the heat can be best used. Potential uses for the heat vary considerably depending on the systems along with which CCm technology is deployed. For example, in its current deployment alongside biogas generative systems, the heat can be used to dewater biogenic wastes or compost materials to significantly enhance their commercial value by improving the nutrient density and reducing transport costs. This approach has significant commercial benefits in the UK and is leading to first use deployment. Upgrading of the heat is more appropriate for other systems where the production of steam for direct electricity generation or water pre heating is possible. In these latter cases the storage of heat prior to upgrading becomes particular important and as part of this project we have carried out an additional feasibility assessment of co deploying CCm fertiliser production alongside our CCm heat storage system. This approach seems to hold considerable merit and the potential for this application is discussed further in the 'next steps' section.

Production

After the extensive commissioning work and supported parallel laboratory scale development we were able to move forward rapidly with our production trials. The focus of the production trials was to produce fertiliser formulations capable of demonstrating a broad range of agricultural applications. In our 2015 trial, materials targeted at grassland and cereal production were developed. Fertiliser formulations ranging from10 10 10 to 37 0 5 have been developed (Appendix T). These comprised two main formulations 28 10 10 and 14 10 10 NPK ratio. We are pleased to report that these materials performed exceptionally well in all the field trials; the results are reported in a later section (Appendix T).

A series of HAZOP studies and SOP's were developed in order to both ensure safe and replicable operation of the plant (Appendix T). These studies have developed into a full operational and production regime which has been officially recognised by the UK's fertiliser industry association (FIAS) (Appendix C). This official recognition now allows us to produce a range of fertiliser products using our production process and sell them on the open market. This is a significant achievement given our stage of development and is of considerable commercial importance.

Latter production was expanded for the 2016 trials based again on Grass and Cereal production but also broadened to encompass Maize (Corn) and Oil Seeds.

Design production of the system was 1T per day of product which readily achieved with maximum output of 5T per day achieved for certain formulations. CO_2 capture for these formulations varies on the final formulations mentioned earlier but ranges from 15 to 30% captured CO_2 in the final product reaching a maximum of 1500kg per day from a 9% CO_2 exhaust stream. We need to point out here that only bottled gas was used for field trial production due to UK Environment Agency waste regulations; however, exhaust based materials have been produced and are being used within pilot based trails at the RAU where their use is permissible under controlled circumstances. The results of the 2015 trials are very positive and ***"the CCm product demonstrated a promotion of grass production in an entirely similar way to that which would have been expected from commercial products"*** (Dr Hugh Martin, RAU Cirencester).

Pelletisation of the output was accomplished within the unit using a standard wood pellet mill. Unfortunately output from this unit is only 100kg per hour so it was necessary for the larger production runs to be pelletised off site at Millson and France where granulation studies were also produced.

There is some debate over which is the best format for the final product. It appears that the preferred format is for the rounded, 2–4mm granules and these materials can be readily produced for a range of potential formulations; however, there is also significant demand for pelletised materials for specific applications such as maize production and high organic content fertiliser for horticultural based production. Importantly the pilot unit design can produce formulations appropriate for either of these end uses.

The key point about the pelletisation phase is that we were able to produce standard agricultural pellets that could be distributed by the farmer using standard equipment (seen in film https://www.youtube.com/watch?v=vmf1s9aliSA). We were able to achieve this very well and all our field tests were accomplishing via standard agricultural spreading on 28m swathes.

In addition to the successful production of materials, this phase of work has demonstrated at length the key GHG capabilities of the unit. The specific results are discussed in the GHG section but in essence the unit has been able to demonstrate the direct capture from an exhaust stream, up to 300kg of CO_2 per hour (Appendix T High N elemental and Proportions of capture).

Alongside the direct capture we have also been able to demonstrate the capture of large quantities of heat from our exothermic capture reaction (0.9GJ/T CO_2 Ref Appendix T Heat Calculations). At this stage this heat has been held within a water storage system but we plan to demonstrate, in further development, how this heat can be stored for greater utility within our own heat storage unit which will be co deployed with more advanced phase two systems. We aim to develop this system as part of our Grand Challenge Part 2 Project.

As a continuation of the production trials we have been able to develop more detailed designs for larger scale production equipment. This ability has been vital in feeding through scale up production information (Appendix T) which has allowed us to fully cost the next stage of our development work. The principal outcome of this part of the study has been a detailed evaluation of the economic viability of the system which has been clearly demonstrated within the economic models developed in conjunction with Mott MacDonald consulting engineers (Appendix C). This portion of our work is discussed in greater detail in the Economic evaluation section.

2. Field Trials of Products and nature of the fertiliser Formulation

In 2015 three trials of the CCm carbon capture products were carried out. One at the Royal Agricultural University (RAU) on established grassland at their trial site in Gloucestershire, and the other two on three different cereal crops on a West Oxfordshire Farm (WOF) and at Harper Adams University trial sites in Shropshire (HA).

Cereal Crop Grown With CCm Fertiliser Oxfordshire Prior To 2015 Harvest

The centre of the field is fertilized with CCm material and the two sides with Nitram – there is no apparent visual or actual difference.

RAU Trials on Grassland

Overall the document produced by the RAU "*Report on the effect of a potential new fertiliser product on the growth and productivity of a grass crop*" (Report No: BDC/R/637, 5 November 2015) provides a clear and unambiguous demonstration of the effectiveness of the CCm product as an N fertiliser on an established grass sward.

The trial was organised as a randomised block design with three replicates each with five rates of CCm product application, providing the equivalent of 15, 30, 60, 90 and 120 KgN/ha. Additional replicated blocks remained either untreated or treated with a commercial fertilizer, Nitram, at the rate of 60 kgN/ha. The plots measured 8.5 x 5 m, and were treated on 28 May.

Chlorophyll is a sensitive indicator of the N status of a crop, and measurements made with a "point-and-shoot" technology showed that treatments with the CCm product significantly enhanced the relative chlorophyll index of the plots. There is inevitably some scatter in the data given the variability within a grass sward, but taken together the data from 7 different dates stretching from just 7 days after treatment (DAT) to 54 DAT (pp 8, 15) show a linear response between greenness and rate of application of the CCm product; the response to Nitram was no different from that of the CCm product.

The yield of grass was measured by weighing cuttings taken on six occasions over the 98 day period after application. There is a positive relationship between yield and the rate at which CCm product was applied (p 18) throughout the season. There is a particularly convincing linear relationship to be seen when the total dry weight of grass harvested 98 DAT (3 September) is plotted against the rate of CCm product application (p 9); again the yield obtained with Nitram falls precisely on the line obtained with the CCm product. When the CCm product was applied at the maximum rate for these trials (120 kgN/ha) it gave an almost 50% increase in accumulative yield. There is a trivial error on p 18 where FW is given for the yield on 29 June (33 DAT) when it should read DW.

The benefit of the applications of CCm product is seen in a very useful way from the aerial image of the trial site provided by photography from a low flying drone (pp 9, 10). The plots that appear by eye greener (p 9) and darker when the green channel is selected (p 10) are the central plots that have received CCm product at 60, 90 and 120 kgN/ha. This subjective assessment is consistent with the data presented in the graph where mean green channel pixel level is plotted against rate of application (p 10), the lightest values here being the greenest (p 11).

Measurements of the root mass in the first 100 mm of soil depth (p 11) indicate that there may well be a beneficial effect of the CCm product, but the variability between samples does not allow for a statistically significant conclusion. Such variability is expected in a heterogeneous medium such as an established grass sward, and again an enhanced root development might have been expected given that when the CCm product was applied above ground growth increased.

The CCm product supplies C as well as N. However when the top 100 mm layer of soil was sampled 127 DAT (1 October) there were no statistically significant increases in soil C and soil N with application of the CCm product (p 12).The commercial fertilizer likewise failed to increase soil C and N. Presumably the simplest reason for the lack of any increase in soil C is that in an established sward soil levels of C would be sufficiently high not to be affected by the CCm product applications. It is known that in grassland *"soil C changes very slowly, and there is a huge pool of C within soils which can 'mask' the effect of any management changes. It can therefore be several years before any changes from the practices employed can be confirmed and then widely adopted* (http://www.fcrn.org.uk/sites/default/files/FCRN_SoilCarbon_summary_0.pdf). Regarding the lack of any effect on soil N, then it may be that by the relatively late sampling date (1 October) the supplied N had been exhausted by the growth of the grass.

1. **The overall conclusion of the RAU trial (p 13) *"that the CCm product demonstrated a promotion of grass production in an entirely similar way to that which would have been expected from commercial products"* is fully justified by the results presented.**

Cereal Crop Grown With CCm Fertiliser Oxfordshire Harvest 2015 Harvest
This is the same field as illustrated earlier in the report actual yield in the CCm fertilised section was 3% higher than the adjacent Nitram fertilised sections.

The West Oxfordshire Farm (WOF) and Harper Adams (HA) Cereal Trials

The cereal trials were carried out on plots of at least 2 ha, and showed that yields were enhanced compared with Nitram applications on the same day at a similar N level as follows:

Winter wheat (WOF) 6.3%, (HA) 3.2%; winter barley (HA) 2.6%; spring barley (WOF) 1.4%.

This trial is of limited scope, but taken together the uniformity of the positive responses indicates that the CCm product provides useful yield benefits in a variety of cereal crops; and, as a source of N, the CCm product is comparable to a commercial fertilizer, but may have additional benefits above the provision of N.

It is clear that the basic fertiliser material works well as a viable commercial alternative product. The economic viability of the product has also been demonstrated and is discussed in the commercial section. Whilst the basic capture of CO_2 has been demonstrated and the abatement of significant amounts of CO_2 occurs through the direct generation of heat by the process the additional benefits of long term carbon retention in the soil have not been fully demonstrated. We have been fortunate in receiving a considerable amount of advice from Professor Duncan Cameron his group (www.p3.sheffield.ac.uk). Both they and we are considerably encouraged by their initial valuation of our work and as a consequence a larger in depth study of the long term benefits of our materials in stabilisation and development of soil carbon and its wider physio chemical properties are to be the subject of an extensive study at Sheffield over the next three years.

PART FOUR

4 Environmental GHG

The CCm process is effectively a two stage one. The first stage is an enhanced ammonia capture system capable of efficiently extracting CO_2 from a range of gas streams ranging from 5% to 100% CO_2 content. The second stage is fertiliser production process capable of utilising a range of waste inputs which produce a low GHG product, particularly when measured in terms of conventional methods of production.

Given the dual two stage nature of the process it is appropriate to assess the two stages of the process both as individual steps and as combined process.

The first stage of the process (capture) may be regarded as an intermediate holding step; it removes the CO_2 from the target gas stream and hold the CO_2 in a stable solid form ready for onward processing or utilisation. It is important to appreciate at this point that the captured CO_2 could be utilised in a variety of ways. At one extreme the CO_2 could simply be liberated from the capture substrate (as the ammonia CO_2 reaction is thermally reversible) and utilised in its now near pure form as a material for enhanced oil recovery.

However, it our belief that the best utilisation of the CO_2 is in applications which use its long term chemical utility, permanently remove it from the atmosphere and by its beneficial incorporation alongside other biogenic materials considerably reduce the primary production of “new” CO_2 in materials production. At CCm our key materials for carbon capture and utilisation are fertilisers, plastic replacements and heat storage materials.

In this project we have demonstrated the validity of this approach in the production of fertiliser from captured CO_2

Our method of quantifying the real GHG benefits is based upon the recognised and independently developed CCalc System. The approach taken within this system is set out below and the total quantities of CO_2 which can be directly assessed are set out in the following assessment. It is noteworthy that there are very likely to be additional environmental and GHG benefits associated with the nature of our product and it this team full data is not available to quantify their magnitude however, the additional contribution to GHG reduction and wider environmental improvement is judged by independent expert (Duncan Cameron) as being considerable and of long term significance. Such is the importance of these additional developments that a targeted assessment plan is being developed at the University of Sheffield P^3 unit to assess the full impact of the materials on the wider conservation of soils and reduction of synthetic nitrogen deployment in intensive agricultural production. Whilst the additional benefits of our approach our highlighted in this discussion they do not form part of the quantified GHG savings set out below but they are likely to considerably enhance the overall effect.

For the purposes of these analysis, a Functional Unit (FU) was defined as 1 tonne of fertiliser product.

CCaLC Objectives

The tool was created by the University of Manchester (1):

- enable the calculation of carbon footprint and other environmental impacts quickly and easily while following internationally accepted LCA standards such as ISO 14044 and PAS2050;
- reduce the data collection effort by providing comprehensive databases;
- help identify environmental hot-spots and improvement opportunities; and
- enable trade-offs between environmental impacts and economic costs.

CCaLC contains two databases (1):

1. CCaLC: publicly available data compiled as part of the CCaLC project;
2. Ecoinvent: proprietary database included in the CCaLC tool with permission from Ecoinvent. Only Global Warming Potential (i.e. the carbon footprint) data is included;

1. Carbon Footprint

The most important factor affecting the carbon footprint of the end product is the raw materials, as they have the largest carbon footprints associated with their lifecycle assessments. As a result, each fertiliser formulation will have its own carbon footprint, based primarily on the quantity of each raw material used, but also how different quantities of each material are processed by individual unit operations in the manufacture process. Two formulations are presented in this report, representing relatively low and high carbon footprints, to give an idea of the range of values that can be expected from preparing different formulations.

A detailed example of the analytical approach is contained in Appendix T. CCalc summarised below are the key steps undertaken in the development of the footprint for any particular formulation.

The results of any particular analysis can be summarised in the manner set out below:

Raw material	Amount (ton/FU)	CO_2eq (ton/ton raw material)	CO_2eq (ton/FU)	Database section	Production stage
Ammonia	0.108	1.912	0.206	Ecoinvent/Materials/ Chemicals & related	1. Solution Preparation
Compost	0.276	0.362	0.100	CCaLC/Materials/ Agricultural inputs	2. Fibre Loading
Calcium Nitrate Tetrahydrate	0.244	0.597	0.146	Ecoinvent/Materials/ Agriculture	1. Solution Preparation
Carbon dioxide	0.135	0.000	0.000	CCaLC/Materials/ Chemicals & related	3. CO_2 Capture
Digestate	0.200	0.000	0.000	langagead.com	1. Solution Preparation
Potassium chloride	0.016	0.299	0.005	Ecoinvent/Materials/ Agriculture	4. Additives
Triple Superphosphate	0.020	0.976	0.020	Ecoinvent/Materials /Agriculture	4. Additives
Total	1.000	**Total**	0.476		

This data is then combined with the additional production data which can be summarised for a whole process as:

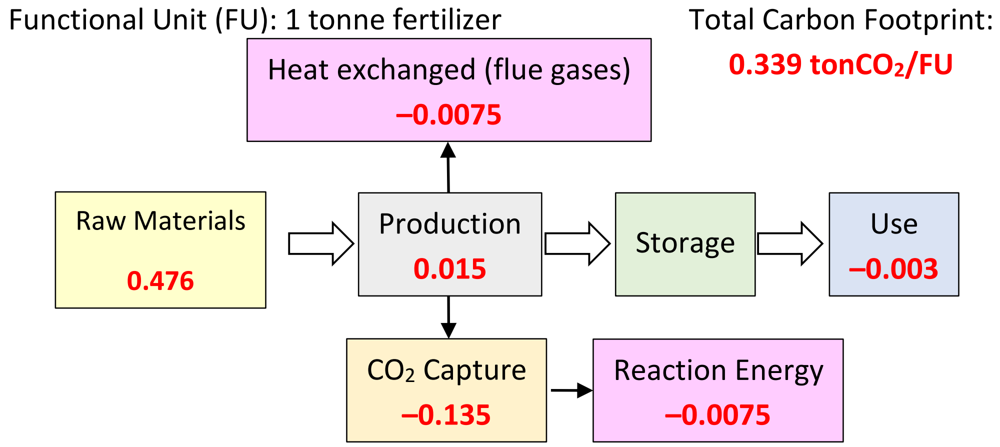


Figure 1-1: Diagram of carbon footprint stages for NPK 18:2:3 fertiliser

Figure 1-1 shows a Block Flow Diagram of the main stages involved in carbon footprint analysis. The numbers in red represent the carbon footprint of that stage. The study reveals that the net carbon footprint of the product lifecycle is 0.339 tonCO_2eq/FU.

The raw materials are inputs into the production stages where they are used. A mass and energy balance used to input data required about the process in CCaLC. Outputs from the production stages, as well as storage, can be defined in terms of mass or energy flows. Each output flow or co-product must have a different name even if they go through stages unchanged, to allow the system to distinguish between flows in different stages (1). Each stage is mass-balanced, so material outputs show up in the relevant transport stage and as a mass input at its destination stage (production, storage or use). Transport can only be defined if there is a material flow between stages (1). Figure 1-2 shows a diagram of the production stages required to make the fertiliser, with a carbon footprint for each stage, based on electricity requirements to power unit operations.

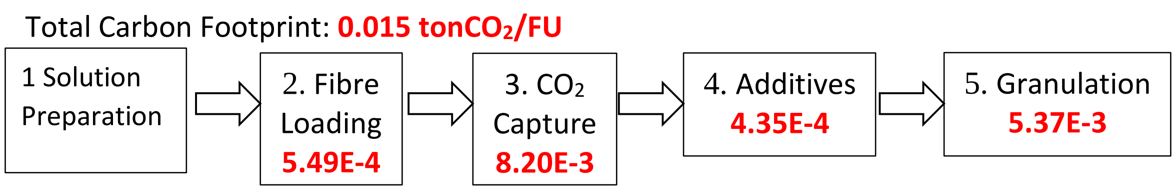
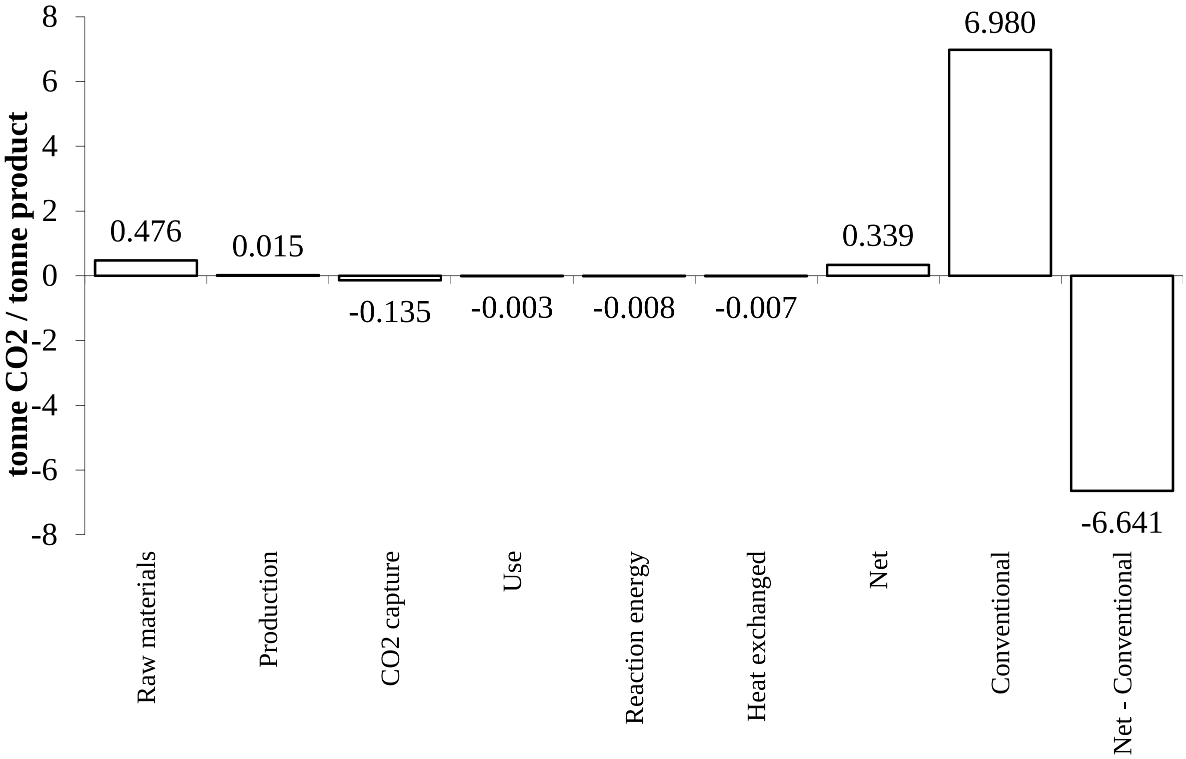


Figure 1-2: Diagram of carbon footprint for production stage of NPK 18:2:3 fertiliser

This whole process can be represented graphically as below:



Total GHG savings relating to specific formulations

Biogenic N 1 All materials recovered from waste streams in PAS 100 condition or better. This formulation contains no mineral N P or K

Biogenic N 2 Principal materials recovered from waste streams in PAS 100 condition or better. This formulation contains no mineral P or K **but does contain mineral N**

Biogenic 3 Some ingredients recovered from waste streams in PAS 100 condition or better. This formulation contains mineral N P but biogenic K (AD Mix)

Biogenic 4 Some ingredients recovered from waste streams in PAS 100 condition or better. This formulation contains mineral N K but biogenic P (Sludge mix)

Mineral 1 All virgin material. This formulation contains no biogenic inputs 28 10 10 mix

Mineral 2 All virgin material. This formulation contains no biogenic inputs 10 10 10 mix

The following formulations were used to develop assessments of the GHG saving potential of the system; as referred to earlier, the savings highlighted here only relate to the direct production of the materials and its use on the field, they do not include long term additional benefits which are the subject of an ongoing long-term study at the University of Sheffield.

Results of Key formulations provide the following impacts:

Formulation	**Content N P K**	**CO_2eq (ton/ton end product)**	**CO_2eq (ton/FU)**	**Database section**	**Net saving TCO_2**
Biogenic 3	28 10 10	0.3	- 0.317	Ecoinvent/Materials/ Chemicals & related	7.297
Biogenic 4	10 10 10	0.3	- 0.812	CCaLC/Materials/ Agricultural inputs	7.792
Mineral 1	28 10 10	0.3	0.581	Ecoinvent/Materials/ Agriculture	6.4
Mineral 2	10 10 10	0.2	0..239	CCaLC/Materials/ Chemicals & related	6.741
Biogenic N 1	20 10 10	0.3	-1.780	langagead.com	8.760
Biogenic N 2	28 10 10	0.3	0.799	Ecoinvent/Materials/ Agriculture	7.779

The Ardley pilot unit has produced 23 Tons of material for fertiliser trials in 2016. Production of these materials has resulted in the direct capture of 5.65T of CO_2

The use of CCm fertiliser for these trials has avoided the production of 147 T of CO_2

An intermediate scale production unit based on the first use plant described our business development programme 10kT Fertiliser Product output would directly capture 3000T of CO_2 and be responsible for the direct avoidance of at least 72,970 T of CO_2

<u>10 year impact</u>

Our current expansion plan foresees the development of 8 fully operational units over the next 5 years rising to 32 units worldwide within ten years. We regard this progression as conservative; the forecast below only considers CO_2 abatement directly associated with the process itself and the materials that it produces. At present no account is taken of the additional benefits that the process is likely to bring in the improvement of soil environment in terms of total carbon loading and over all soil health. This work is ongoing in conjunction with the University of Sheffield and we expect to be able to increase our total CO_2 reduction forecasts in the light of these studies in the next 18 months.

We are currently in discussions with two UK major water utility operators and 5 independent Anaerobic Digester (AD) operators. There are currently 750 AD units in the UK and 875 in Canada with additions planned in both territories principally as waste reduction systems. On this basis the conservative nature of our forecasts can be understood. AD units are likely to produce 10kT of output and Energy from Waste (EfW)/ Heavy oil systems around 100kT of output.

Type of Plant (Nature of Codeployment)	Number of Plants 5 years	Number of Plants 10 years	Annual CO_2 Abatement T CO_2 Per Class	Total CO_2 Abatement over 10 years T CO_2
AD	5	25	1.825 MT	13.688 MT
Energy From Waste	2	5	3.649 MT	27.368 MT
Heavy Oil	1	2	1.459 MT	10.943 MT
Total	**8**	**32**	**6.933 MT**	**50.999 MT**

A more aggressive sales forecast could produce dramatically higher savings and it would not be unreasonable for the above the above forecast represent not a global saving but a national as both the capacity for co deployment plants and product utilisation exists throughout the EU, in Canada, China and the US – so on this basis ten year savings in CO_2 production could easily reach **250MT.**

Development of Patent Portfolio

Over the last 12 months we have continued to develop our patent portfolio (Appendix B). Our strategy remains to build on our core patent technology with a series of specifically targeted filings directed at new development in our technology in key market areas.

The core patent, granted in the UK in 2013, continues to progress well through its international development phases and as yet no significant barriers have been identified in its progress in any of the targeted countries. Additionally, we have secured two UK grants of patent in areas relating to the utilisation of heat from the CCm process and most importantly in the fertiliser sector.

The heat storage application has been examined in the UK and the results appear most favourable making it likely that we could achieve an additional grant in this area within the next 6 months. This will mean that we have secured cover not only for our platform technology but also for a range of specific embodiments targeted at clear commercial opportunities central to our future development.

A further patent application relating to recent developments in AD technology was also filed in January 2016.

Fertiliser Field Trial Results Summary

Objective

To ascertain the relative performance of fertiliser produced by the CCm method and Industry Standard materials. The principle properties examined in this trial were crop yield and ease of application.

Method

CCm carried out a range of field scale fertiliser trials during 2015. The trials format has been developed in conjunction with the Royal Agricultural University (RAU) and Harper Adams University under the supervision of Professor Philip John from the University of Reading.

The growth trials took place at the Agricultural Universities trial sites and on a West Oxfordshire Farm. In all cases all cases fertiliser was applied to the trial plots using recognised good agricultural practice and standard equipment.

Cereal Trial Scope

The crops nominated for trial were winter and spring sown cereals and grass. In the case of the cereal crops trial plot sizes were a minimum of 2Ha. CCm High Nitrogen Formulation (N28%P2%K0%) was applied on 3 occasions throughout the growing season on the same day as Nitram (32%N) was applied to adjacent plots in the same field.

Results

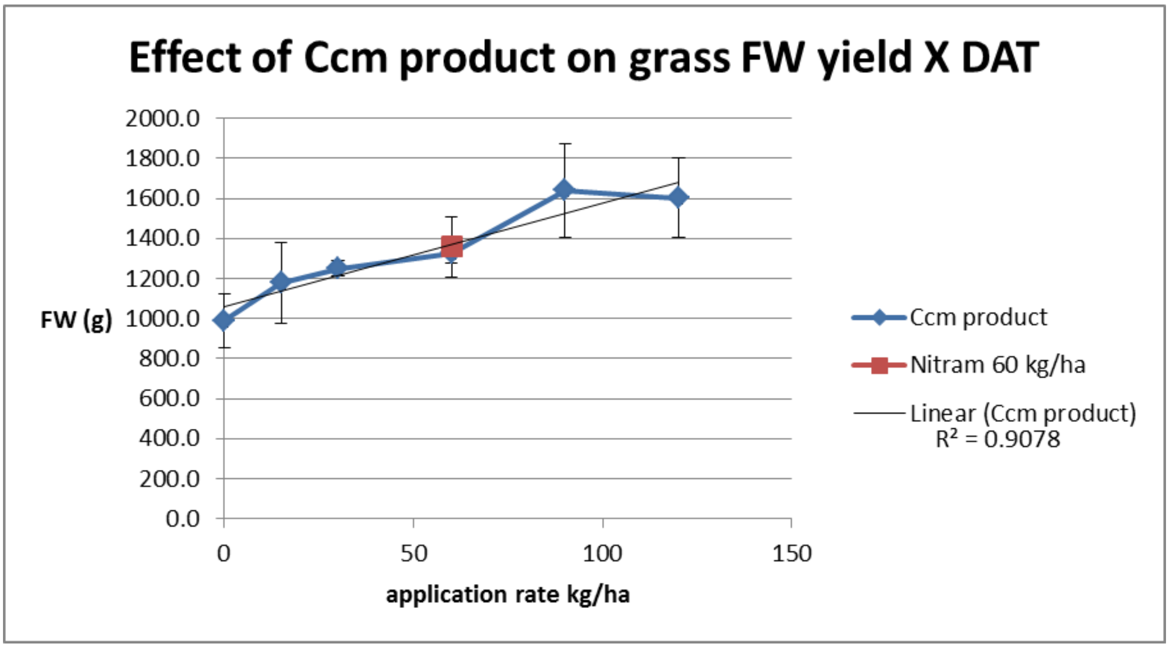
Site	Crop	Yield Field (T/Ha)	Yield CCm (T/Ha)	Apparent % Enhancement
Crown	WW	3.16	3.36	+ 6.3
Crown	SB	4.35	4.41	+ 1.4
Harper	WW	4.12	4.25	+ 3.2
Harper	WB	4.25	4.36	+ 2.6

Key

WW - Winter Wheat; SB - Spring Barley; WB – Winter Barley

Grass trial Scope

In the case of the Grass trial smaller plot sizes were used to allow more frequent application of CCm Low Nitrogen Formulation (N14% P 6% K8%) in order to gain a more detailed picture of the crops Nitrogen response throughout the season.



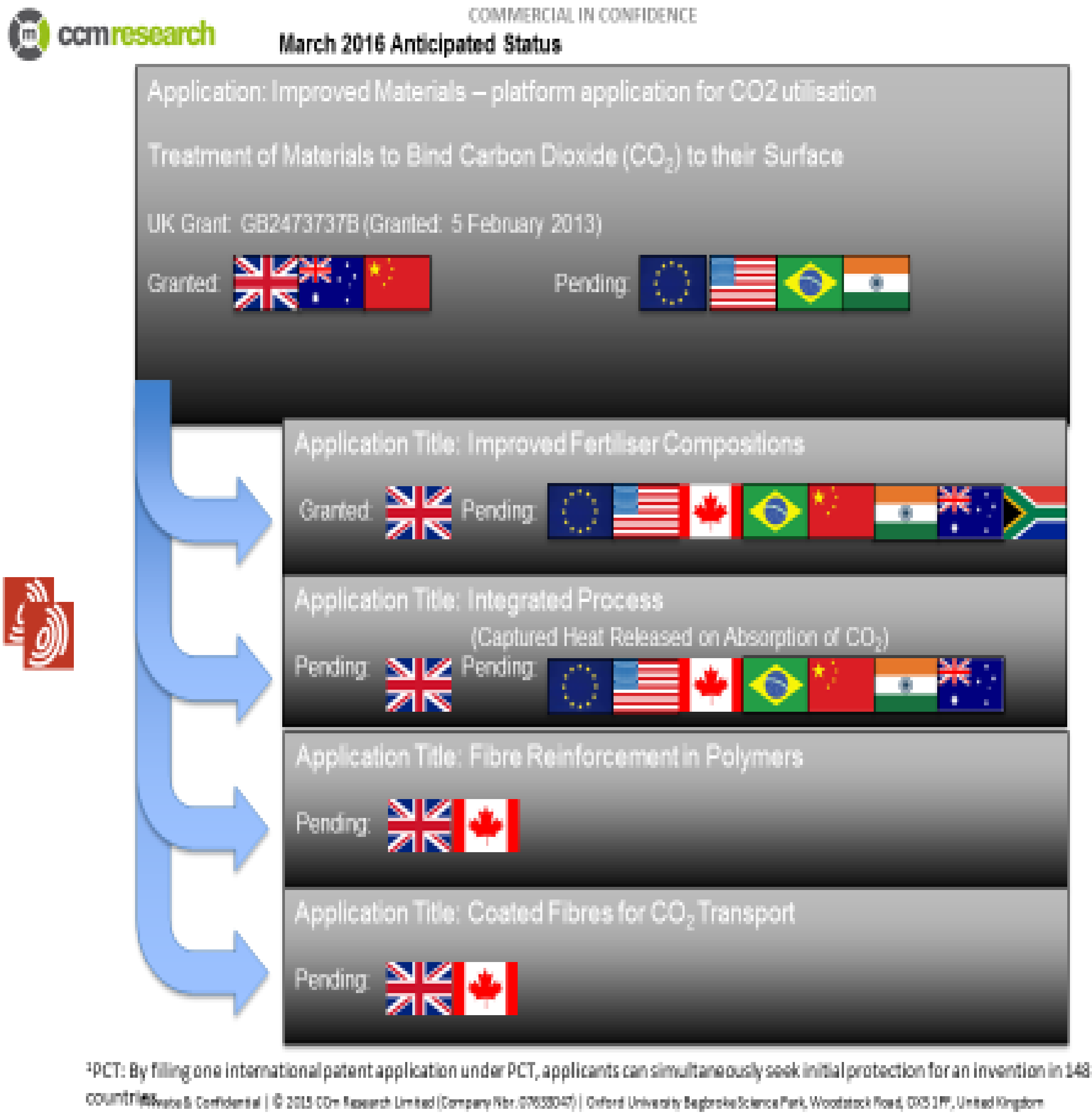
The grass trial at the RAU will continue into the late autumn of 2015. The focus of the extended trial will be the assessment of soil chemistry and sub surface plant growth. The purpose of this work will be to gain more information concerning the long term fate of carbon within the soil horizon and to inform the development of ongoing trial and formulation work.

Conclusion

The initial trial results confirm that CCm Formulations can be readily applied to a range of agricultural crops using standard agricultural practice and that the resultant crop yields are directly comparable those produced by existing commercial products.

Patents

The following patents have been granted or applied for in relation to the development of our technology.



We expect to publish further data in the near future as soon as commercial sensitivities are reduced.

Next Steps

The project has also identified and exploited key developments relating to the use of biogenically derived feedstocks which add to both the systems carbon efficiency and the product utility. Further areas of potential development particularly relating to enhanced heat storage capacity within the system and long term carbon sink development associated with the products will be the subject of further work.

We aim to integrate our heat storage technology into a new pilot development unit which will demonstrate both the production of valuable materials in the form of fertiliser and prove that the heat developed by the production process can be both stored for time shifting and upgrading. We aim to seek support for the development of this unit in both the UK and Canada, if possible with the help of the CCEMC Grand Challenge.

We have made considerable strides in further grant of our core patents internationally and have been able to file further patents because of the advances that we have made in the project. In consequence of our technical development and the security of our IP we have been able to enter into advanced negotiations over the first large scale deployment of our technology which we expect to take place in specialised AD situations within the next 12 months.

We are at present negotiating with Yorkshire Water and Viridor in the UK for the formation of a joint development company which will carry out first use of the CCm technology at an AD site with the capacity for Biogas to grid injection; both companies own such facilities. We are also negotiating with Iona Capital and Foresight Capital who specialise in AD investment over the construction of similar arrangements.

We have also held initial meetings with Canadian heavy oil producers over the potential for larger scale operations. Husky, Suncor and Conoco Philips have all been supplied with outline information and will be updated further with our progress this summer when we visit Alberta.

Information containing our basic commercial offer is held in Appendix C.

Whilst our system shows the potential for deployment in niche sectors with particular pressures reducing their commercial performance, it is clear that we need to carry out further work particularly in relation to the long term fate of the carbon we capture and in the development of fertiliser formulations which optimise the effect of our process. We expect to embark on a significant research programme, this summer, in conjunction with The University of Sheffield P^3 Centre under the supervision of Professor Duncan Cameron who has taken a personal interest in our work. Funding has already been agreed by the EPSRC in the UK for this work. We hope to extend the study to trials in Canada although the P^3 Centre is capable of replicating Canadian (as well as tropical) growing environments.

There is a tremendous amount of commercial and academic interest in the value of our approach. We aim to maintain the momentum that we have been given by the support from the CCEMC, UK Grant Bodies and our Investors – the crucial step for us now is to develop a meaningful commercial demonstration plant. We hope to secure support for this in 2016.