Hennock International Ltd
Consulting engineers to the land based industries.
www.hennock.co.uk

Marginal land biomass harvesting and extraction using drone assisted technology

(HEN-263-1-G)

Final report (public version)

Contents:

1. Technical description of the innovation

To develop and demonstrate an economically viable system of harvesting and utilising bracken, which is an invasive species of marginal land, with the objective of recovering a high Calorific Value (CV) biomass fuel (21 GJ/t). Since this is an energy source that is (a) existing, and (b) from land that is otherwise unused, it is an immediate gain of biomass with no correlated loss of other production. In Phase 1 the area of marginal land was quantified, and the scale of the resource was assessed at around 6 Mha in the UK.

The technical difficulties of harvesting on marginal land primarily relate to economic issues that are associated with the marginal land: obstacles (primarily rocks) causing damage to equipment, and poor accessibility (gullies and steep slopes) leading to high costs of extraction. It is important to reduce the high levels of damage that would ordinarily be sustained due to obstacles obscured by the dense bracken. Accessibility is impacted by the physical ability for machinery to operate in constricted spaces and on slopes. Extraction is again impacted by the machinery restrictions above, and a need for densification (typically baling) and a good work speed in order to reduce labour costs. Key to overcoming these issues is knowing where obstacles lie, and thus being able to avoid them. For the majority of the year bracken stands are such that many obstacles are hidden, and this applies during the main harvest period. In the winter bracken largely dies back, and much is visible from the air. For this project a proof of concept machine vision system based on drone images and GPS was developed, which will (Phase 2) permit harvesting to take place with the known GPS coordinates of the obstacles such that a course can be taken that avoids them.

Fig 1: Bracken stand

Fig 2: The drone employed

In terms of harvesting machinery the approach adopted is to adapt and utilise existing equipment as far as possible (tractor, specialist baler, banding, self-loading trailer), developing new equipment where this is not possible (mower, accumulator) and reducing the costs of harvesting by moving to a single pass process. In order to improve efficiency of combustion and reduce emissions drying is also necessary, which can be either barn dried (typically 5-10 days) or trailer dried (24 hours).

1.1 Phase 1 – proof of concept

In this first phase 1 we investigated various aspects which were for proof of concept. These included the scale of the resource, and the potentially recoverable resource. We also undertook further work on yield and chemical analysis of the soils, the crop and the combustion products. We undertook combustion trials in 4 existing biomass boilers. We have analysed the likely economics of the operation. All of these confirmed that bracken is a viable biomass fuel resource, which can be economically harvested. We also undertook research and ecological surveys on potential ecological impacts. Given the constraints of the harvest period these were almost entirely positive, since bracken is generally an ecologically poor habitat, with minor concerns that can be managed.

1.2 Alternative uses.

Clearly if there are alternative uses for bracken then this would be an issue. Our analysis shows that there are minimal other uses, the main one being for livestock bedding. Where this does occur it is very small scale (our estimate is <100 ha p.a. in UK, less than 1% of area), and only in areas where existing equipment can be utilised, typically a round baler, thus relatively unusual (for example Mynydd Illtyd Common where land ownership restrictions mean that the land cannot be 'farmed' in a normal manner).

1.3 Previous work vs. current project

Efforts to harvest bracken on marginal land have previously relied on (a) very expensive equipment, including hillside tractors, and (b) extracting a 'loose' crop rather than a densified one, and (c) multiple pass operation. This historic approach has relied upon achieving a high value for the product, to cover the high input costs, with high value / low volume. However, the approach of this project is novel due to the technology, but also since it is based upon establishing a matched market and harvest system such that it is a profitable operation. A brief description of the harvesting system (Phase 2) follows.

1.3.1 Mowing - the system has been developed around the principles of efficient cutting of a thick stalked crop with a high degree of entanglement.

1.3.2 Tractor. This is a conventional type specialist tractor, rather than a specific hillside one, in order to control costs and make the unit economic.

1.3.3 Baler. The basic unit is an existing specialist baler, with an 'Inline' pickup reel and chamber.

1.3.4 Accumulator. This is required to accumulate bales to permit more rapid collection and extraction.

1.3.5 Bale stack extraction – self-loading trailer.

1.3.6 Machine vision. Aerial photographs taken by drone using visual spectrum and infrared and processed using a variety of machine vision analysis techniques has provided proof of concept that this can provide a good level of detection.

1.3.7 Drone / GPS system.

2. Assessment

The project Phase 1 project sought to establish the basic proof of concept of the main issues, identifying : (i) the scale of resource, including scale and impact of any ecological constraints, (ii) issues of using the resource in existing biomass boilers, (iii) capacity to use machine vision imagery from drones to map obstacles, and (iv) the economic viability of such a system. All these objectives have been met.

2.1 Scale of resource

The scale or the resource that can be realised is dependent upon the following:

- The area of marginal land
- Percentage area of marginal land with bracken infestation
- Derelict and other land with bracken infestation
- Percentage of bracken infested areas that is recoverable.
- Yield (long term)

The approach adopted was to comprehensively review available literature to ascertain all the above. This confirms the following.

1. Marginal land area is c. 6 Mha in the UK.
2. Likely area of bracken infestation is 1.3 Mha.
3. Likely yield is 8.6 t/ha / 0.86 kg/m^2
4. Restrictions by constraints reduce the practically harvestable area to 340,000 ha (allowing for transport distances to point of use and terrain / parcel size considerations).
5. Gross Calorific Value is 21 GJ/t.

The main conclusions are as below.

1. Taking into account known areas and limiting factors the potential achievable resource is 61.6 PJ (based on 340,000 ha at 8.6t/ha and a GCV of 21 GJ/t).
2. There are many reasons why harvesting bracken off marginal land would be deemed beneficial by the landowners, notably preventing further encroachment, increasing productivity, reducing the fire risk, improving ecological diversity and visual impact.
3. There are no major reasons why bracken should not be harvested off marginal land.
4. There are minor issues where one ecological benefit is conflicted with another, but these are easily solved by operational guidelines and in particular if harvesting is at the end of the season there are no issues.
5. GHG emissions are calculated as being low, at 0.49 - 0.7 CO_2 kg/GJ.

The resource of 61.6 PJ is considerable, and as an illustration it would provide about 30% of the biomass for Drax power station, and Drax produces 6% of the UK electricity generation. Alternatively it would provide fuel for the entire non-domestic RHI biomass installations. Thus it can be seen that it is a very significant available resource.

The extent that the resource is available after the above considerations are taken into account will depend upon the following main factors.

1. Economic costs of harvesting.
2. Cost of transport
3. Land ownership
4. Distance to market.

2.2 Displacement of alternative uses.

There are no major alternative uses for bracken which a harvesting system would compete with at present. Only extremely limited harvesting for animal bedding is carried out (see section 1.2). Harvesting can be for 2 long term objectives: to extract an energy resource from an otherwise unused resource, or to extract it with the view to substantially reducing the coverage. In both cases then alternative uses are increased.

2.3 Long term viability of resource.

Annual bracken harvesting as a biomass resource is known to be sustainable in the long term. Bracken yield reduces with annual harvesting to c. 60% of that with only occasional harvesting, but thereafter remains constant with a single cut late in the season. The reduction is probably more related to the loss of litter which provide frost-protection to the emerging shoots, and thus varies according to season. Some landowners will be looking for bracken control, in which case then multiple cuts per season will reduce the yield dramatically after 3 - 4 years, and for some sites this may be seen as a useful option to achieve control with near-nil cost.

2.4 Greenhouse Gas Emissions (GHG)

There is a nil GHG to production of bracken, as this is an opportunist harvesting of an invasive weed species (contrast Short Rotation Coppice (SRC) = 4.2 g/MJ, Miscanthus = 0.85g/MJ). The harvesting and drying use diesel, and give a GHG of 0.7 g/MJ, compared to 1.7 g/MJ for SRC and 3.6 g/MJ for Miscanthus (GHG figures: Global Biomass Markets, Ricardo / BEIS TRN906/10/2014), and well below the proposed RED II limit of 13g/MJ.

2.5 Ecological constraints & benefits

This area of work was included because clearly if there is a major negative environmental impact then this would be a significant problem. The assessment was based upon the following aspects.

- Literature review
- Site visits
- Desk studies

There was universal correlation that, given certain minor constraints, the harvesting of bracken has a significant positive impact on ecology. The most visual proof of this was the comparison site in the Brecon Beacons, with areas that had been harvested annually for cattle bedding adjacent to patches with no regular harvesting. The site study showed at least 8 additional plant species, increased bird, reptile and mammalian activity plus fungi, and no negative aspects. Natural England stated recently that many SSSIs of ecological importance are in a 'poor condition' due to invasion by bracken at up to 60% cover.

An additional benefit is that this offers a viable alternative to spraying with Asolux, the only true chemical control and which is under threat of withdrawal.

The only negative environmental impacts relate to specific locations where the fritillary butterfly is known to exist, which uses bracken litter as basking material. This is at the margins of bracken stands, and only where the common violet is located too, and in certain parts of the country. These sites can be identified by desk investigation as they are known, and by working in conjunction with the local Natural England office. The negative impact identified and associated with bird nesting is not relevant, since the harvest period is outside of this activity.

3. Use of resource

The fundamental approach of the project relies on the bracken being suitable for combustion in thermal systems, primarily as a replacement for straw and wood. Knowing that the Calorific Value is good there remain two potential issues: emissions and fouling. Since one of the project fundamentals is that in order to be immediately economically viable there needs to be an existing market, and the obvious sector is existing biomass boilers operating under the RHI scheme, then the emissions have to meet the RHI limits (expressed in g per GJ of energy input to avoid issues of 'massaging' the emissions through excess air) of NOx (150 g/GJ) and Particulate Matter (30 g/GJ) for the majority of boilers of the size being considered.

In addition to emissions it is also important that the use of bracken does not lead to fouling, as related to deposition on the heat exchanger surfaces, and slagging, the agglomeration of ash into large particles which impede combustion airflow. Fouling is a known area of concern for biomass boilers, and historically has been associated in particular with silica. In order to have some idea of the potential scale of the issues when using bracken as a fuel the a brief review of the technical issues involved was produced, and how their effects may impinge on this project.

3.1 Combustion trials

Combustion trials were undertaken on 4 existing boilers, as below. These were chosen to give a broad spectrum of type and size.

	Rated output	Type	Fuel
Site 1	3 MW	Moving grate	Wood chip
Site 2	1 MW	Moving grate	Wood chip
Site 3	130 kW	Downdraught gasifier	Sawlog
Site 4	1 MW	Whole bale	Straw bale

Table 1. Combustion trial system data

Emissions tests were undertaken on 4 boilers using isokinetic sampling. The boilers chosen covered a variety of types, from 130kW to 3MW output, wood chip and straw fuel, 2 with moving grate, and 1 gasifier. No settings were changed on the boiler controls.

3.1.1 Nitrogen Oxides (NOx)

Studies have shown that NOx can be controlled successfully by a variety of measures, but principally by correct setting of the primary excess air. Our results agreed with this, and the order of NOx results correlate well with the excess air ratios, as below.

	Excess air	NOx (g/GJ)	PM (g/GJ)
Site 1	11%	95	19
Site 3	51%	161	>800
Site 2	137%	182	751
Site 4	580%	831	757

Table 2. Combustion trial results

The Nitrogen (N) content of bracken decreases through the season, and with a post-October harvest date when the fuel N is <1%, the likelihood of high NOx emissions is low.

3.1.2 Particulate Matter (PM)

Work has shown that production of PM is also strongly influenced by excess air and fuel Moisture Content (MC). The combustion trials undertaken in Phase 1 illustrated the issues of high moisture content bales and PM, which was as expected. This was for several reasons: firstly the bracken was harvested earlier than was desirable due to the short project schedules, and secondly due to equipment issues the crop was left cut but not baled for many days in a period of rain. Finally in moving grate combustion systems there is a 3 stage process: drying, volatisation / combustion of volatiles, and char combustion. With the trials undertaken on the 2 moving grate boilers these had to be run with bales loaded through the furnace door, thus a batch system instead of continuous, which negates the entire design philosophy. The trials demonstrated that good combustion could be achieved, and visual monitoring revealed periods of good combustion with low PM emissions, which do not show in the continuous 30 minute test.

We are confidant from these results that under a situation where the boiler is set-up with a proper feed system, dry fuel and controls tuned to it then the emissions for all boilers will be within limits.

3.1.3 Deposition / smoke tube fouling

The analyses and study of the chemistry of bracken and combustion shows that the risk of deposition on the smoke tubes can be militated against by harvesting a mature crop, with significantly (87%) lower Potassium (K) content. The likely consequence of this is that the bracken will have gone into senescence, and that it is probable that harvesting will be in wetter weather. Whilst the stems do not absorb much moisture the pinae will do so, and therefore the MC of the crop will be higher.

3.1.4 Summary
The adiabatic flame temperature is likely to be in the region of 1700°C.
The furnace temperature will be lower than this (850 - 1200°C).
Not all mineral inclusions will be vapourised at this temperature.
Bracken has low sulphur and chloride content which is beneficial, and the sulphur:chlorine ratio is high and means that the corrosive elements of deposition due to alkaline chlorides will be low.
Bracken can contain relatively high silica and potassium levels, which will potentially lower the melt point of ash particles. Potassium levels are dependent upon maturity.
Due to the higher vapourisation temperature of silica it is likely that silicate ash will be larger particles, with the majority in the bottom ash.

3.1.5 Conclusion
Potassium is likely to be the main cause for concern for deposition, but harvesting a more mature crop reduces this significantly and down to acceptable levels.
Corrosive deposition is not likely to be a problem.

3.1.6 Strategies to militate deposition
Harvest a clean crop. A harvested crop free of soil is important, and should form a part of the design basis of the harvesting system.
Harvest a mature crop to reduce K content.
Combustion temperature and residence time. These are two of the aspects that can be controlled, and means that moving grate boilers are likely to be well suited to bracken combustion.
Target furnace cooling in combustion equipment design. The use of Flue Gas Recirculation (FGR) and other measures to assist in reducing the temperature in the combustion chamber and reduce deposition in smoke tubes and slagging in bed ash, and also reduce NOx emissions.
Soot blowers are generally effective at dislodging potassium based deposits, but more frequent operation may be required.

3.1.7 Ash content.
The ash content from the analyses varied from 2.6 - 5.5%, and is acceptable. This is within the range for other energy crops, such as Miscanthus (2-8%), and less than that for straw (4-12%). Ash quantity is not foreseen as a problem.

3.1.8 Drying
Limited drying was undertaken in Phase 1, since drying trials had been undertaken prior to the BEIS project and the concepts of barn hay drying are well known. As part of Phase 2 drying will be included to demonstrate a complete approach, based on 2 options: in-trailer drying (high speed, diesel as drying fuel, purpose designed unit) and barn drying (using bracken as the heat source).

4. Machine vision / drone for locating obstacles.

The work undertaken included obtaining drone data for multiple sites and at various stages of maturity. The 'target' obstacle for the machine vision analysis was rocks, since this are the main issue, and also the hardest to identify aerially.

Both visual spectrum and infra-red images were taken, and software developed to differentiate and identify rocks.

Fig 3 below shows an example of the final overlay of segmented objects from the thermal image analysis against an original RGB image.

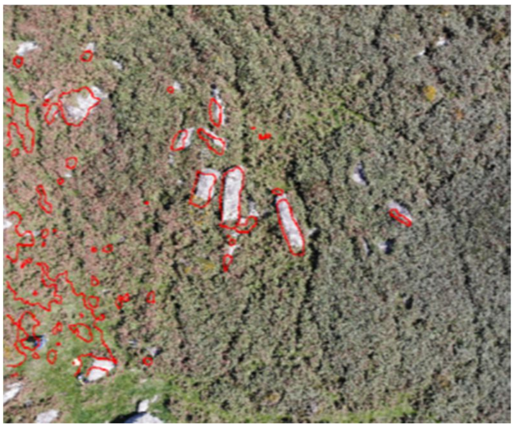

Figure 3. Outline of results from the thermal image roughly overlaid on visual image

5. Economic viability

Our analysis for economic viability is based on comparing the costs of bracken harvesting and utilisation with a known 'drop-in' equivalent: straw. Straw is the lowest cost mainstream biomass fuel, and ranges from £40 - 105/t ex field, see Figure 4 below.

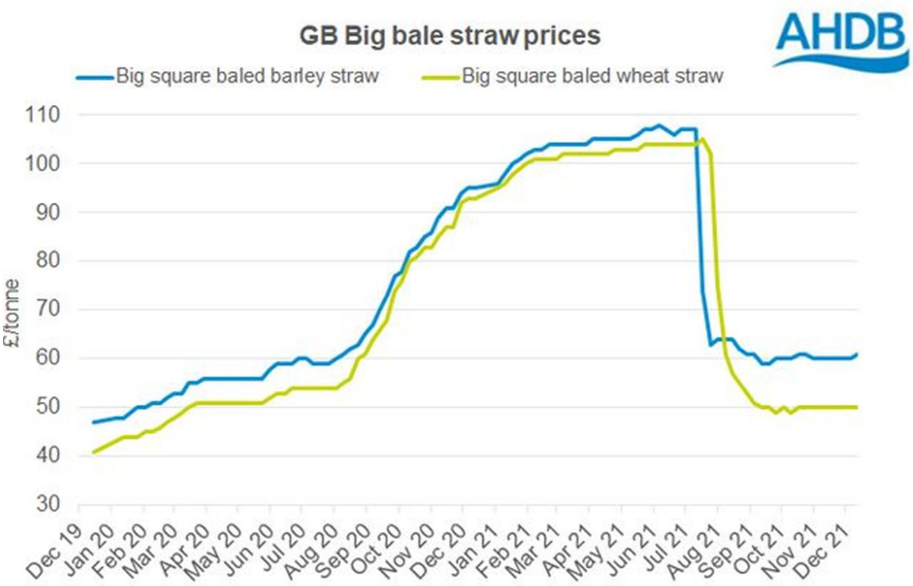

Figure 4. Historic UK straw prices

We have employed a figure of £45/t which is based on the pre-price rise of the winter of 2020, and is lower than the current fairly static price of £55 (average). It is significantly lower than wood chip (currently £70 - 75/t ex delivery), and thus it is a reasonable assumption that if bracken can compete with straw economically then allowing for the extra CapEx for conversion and minor additional OpEx then it can certainly do so with wood chip. Figure 5 below (ForestResearch) shows the price for small round sawlogs since the introduction of the RHI. Whilst this does not entirely correlate to that for sawlog for chipping it is not far off. Chipping adds a further £10 -15 /t. Prices are ex-forest, so equivalent to the basic straw price employed.

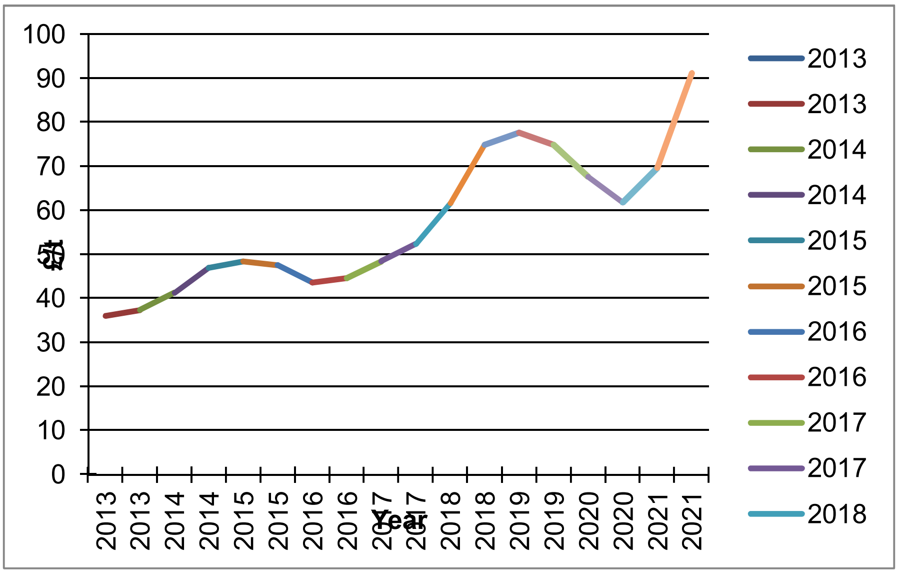

Figure 5. Historic UK small round sawlog prices.

Straw boilers are less common than wood chip, and tend to be on farms. The three main reasons for this are that farms have the available fuel resource, they also have the handling machinery for large bales, and have more or less continuous on-site labour availability. Some commercial greenhouse sites also have straw boilers, mainly in the east of England where surplus straw is more available. They typically have the same capability as farms for materials handling and labour.

In terms of market uptake of bracken as a fuel, then it will be based on 'total' costs. Two scenarios are given below, for an existing straw bale user, and for a wood chip installation which requires some expenditure to convert to bracken..

	Straw bale	Wood chip conversion
CapEx alterations	n/a	£24,400
OpEx - bale handling	No change	£3,430
OpEx - bale chopping	n/a	£1,960
Saving – fuel costs	£2750 p.a.	£24,700 p.a.
Simple payback	n/a	1.3 years

Table 3. Financial analysis existing boilers

(Above based on straw price of £45/t, bracken price £45/t, wood chip price £85/t, transport costs similar, labour at £175/day, net CV of straw = 16GJ/t, bracken 18GJ/t, wood 16GJ/t).

As such it can be seen that as a 'drop-in' replacement for straw there is a small financial benefit at £45 / t, but given the current price of straw at £55/t and the volatility of it there is an incentive to choose bracken, financially.

For a conversion to bracken for a wood chip boiler where the conversion is relatively simple then the simple payback is 1.3 years which is a very good return on investment. As such the market appears relatively straightforward.

For the contractor a summary of the economic analyses is given in Table 4 below, based on 2 operating scenarios (single pass harvesting plus drying, and 2 pass, no drying).

Economic analysis (per year)				
			Trailer drying	Barn drying
Forward speed	5000	m/h		
Width	1.6	m		
Bracken yield (dry basis)	8	t/ha		
Baling rate	0.64	ha/h actual		
Total operation	0.43	ha/h total		
Annual throughput	100	days		
	7	h/day		
	2.99	ha/d		
CapEx			£159,500	£163,500
Finance charge			£24,879	£25,503
Labour	25	£/h	£21,000	£21,000
R & M			£7,975	£7,975
Diesel (tractor)			£20,463	£20,463
Twine			£5,310	£5,310
Strapping			£1,858	£1,858
Drying fuel			£14,942	£800
Total OpEx inc finance charges at	6%		£96,428	£82,909
Income (farm gate) at	£45	per t	£134,400	£134,400
Profit			£37,972	£51,491
P/E			28.3%	38.3%
Simple payback (years)			4.2	3.2
IRR			21.5%	32.0%

Table 4. Economic viability analysis

The key assumptions of Table 4 above are as below.

- Bracken is a nil cost, nil benefit item to the harvesting operator, i.e. it is free to remove without reward (currently most contractors are actually paid to control bracken, so this is a conservative assumption).
- Transport cost will be equivalent to that for straw, wood chip. Bracken bales are denser

than wood chip, and similar to straw.

Sensitivity analysis
By far the greatest costs associated with the operation in the analysis are as shown below, with the 2 scenarios (A - single pass, with crop drying; B - double pass, weather dependent).

	Trailer drying	Barn drying
• Labour	22%	25%
• Finance charges	19%	19%
• Diesel fuel	37%	26%

Summary
The above analysis demonstrates that at the conservative value of £45/t bracken harvesting can present a viable economic model to contractors, with an IRR of 38% for the barn dry option. It can be an economically attractive biomass fuel resource, fully competitive with straw, wood chip and miscanthus, with payback for conversion of wood chip boilers at just over 1 year. Investment in the machinery system can provide an economically attractive option to a contracting business.

6. Phase 2 plan

Phase 2 comprises 6 Work Packages, as below.

WP1 Combustion
WP2 Drying
WP3 Machinery
WP4 Obstacle detection
WP5 Demonstration
WP6 Financial analysis
WP7 Management

6.1 Timelines

The project is heavily weighted to the first 2 years of development, with the 3rd year being mainly for demonstration and dissemination activities.

6.2 Work packages

These are as below.

WP1 Achieving accreditations necessary for market acceptance.
WP2 Development of bale drying system
WP3 Machinery development
WP4 Drone and machine vision systems development
WP5 Demonstration
WP6 Economic modelling
WP7 Management

6.3 Project delivery team.

This will remain the same as for the Phase 1 project, with an additional member of staff recruited for software development. Whilst we recognise the need to scale up from

Phase 1 we also recognise that the existing team has worked extremely well, and wherever possible we wish to maintain the approach of working with contractors that we have worked with in the past and know we can rely upon.

6.4 Risks and risk management

A risk table is given in Annexe 1. Of these we have categorised them into 2 primary types: what may be deemed in the loosest sense 'politically related', which are outside our control but can have a very serious impact, such as travel restrictions, inflation and so forth (shaded olive). It is hard to plan for them because by their nature they are the result of 'point' interventions as opposed to longer term forces which may be seen developing. Secondly technology related, shaded blue. We consider these to be medium to low, and can be militated against by planned actions.

6.5 Quality assurance

QA for the project as a whole will be by the project lead, and be based on the approach adopted in Phase 1. We have anticipated for independent verification of our economic models by the Lot 2 project provider, however if this is not forthcoming we can arrange an alternative appraisal.

The equipment developed in Phase 2 will need to be certified for conformity (CE mark), which we will undertake internally having undertaken similar for other companies over many years.

6.6 Project controls and governance

Our Phase 2 project timetable is detailed and we run Open Workbench project management software to show critical paths and dependencies. This highlights issues as they arise, and especially if delays have serious knock on effects. Having a well-conceived plan, with all those involved knowing what they are trying to achieve is critical to good progress, and avoiding sub-contractors or others undertaking non-core work or not understanding their task is critical. This is especially so on Phase 2 which is a larger and more complicated project than Phase 1, with a greater number of significant dependencies. Being informed of progress is essential, and we are always in regular discussion with subcontractors.

6.7 Reporting

Our phase 1 reporting worked well, with monthly meetings with the MO, and quarterly reports submitted to the MO a few days before each quarter end meeting. The monthly meeting included supplying an updated GANTT chart, and brief comments on progress and any outstanding issues, prior to the meeting. Quarterly reporting covered all relevant work packages, any issues arising and how they would be dealt with, and how any issues previously notified were being dealt with. We would aim to continue in a similar manner.

7. Commercialisation plan

For the project to become a commercial success the first component is to ensure that the market for the fuel both exists and will accept the product. The former has been demonstrated in Phase 1. The latter aspect is the key to uptake, and this is covered further below.

The second is that the harvesting equipment meets the approval of the intended end users.

Thirdly the manufacture, sales and support for the equipment.

7.4 Promotion and dissemination
An additional sector for promotion is the large land owners and customers of these contracting businesses with bracken issues, for example the National Trust, National Park Authorities, Duchy of Cornwall.

In addition to the above we will write articles for the Trade Press (Farm Contractor, Farmers' Guardian) and also a refereed paper for a Journal.

Appended annexes
1 Risk assessment

Annexe 1. Risk assessment

Risk (Key project risks, including: financial, technology, supply chain, regulatory, etc.)	**Overall risk rating:** (Probability x Impact) High, Medium or Low	**Mitigation actions** (Describe the actions taken or planned responses to reduce the impact and/or probability of the risk)	**Residual risk rating, after mitigation applied:** (Probability x Impact) High, Medium or Low
Inflation	High	Enter as many fixed price contracts as possible; reduce CapEx to a minimum in final year.	High
Travel restrictions / other political interventions	High	These are unknown, we have to respond as best we can.	High
Delayed delivery of equipment	Medium	We have existing equipment which is not as appropriate but would be a stand-in. We have in house capacity for repair.	Low
Catastrophic damage to critical equipment	Low	As above.	Low
Supply chain issues affecting availability of materials directly and indirectly	Medium	Maintain close communication with suppliers to get as much advance warning as possible. Have back-up plans. Order materials well in advance and stockpile where possible.	Medium
Unforeseen problems with harvesting technology and reliability	Medium	Whilst we believe at this stage we have thought of it all, it would be unwise to think that unforeseen issues cannot occur. We are good at engineering our way out of problems, so maintaining an close watching brief on all aspects to identify any issues early on so that they can be dealt with is crucial.	Low
CV19 spread	Low	The main inter-actions will be outdoors, with low associated risk. For internal ones (combustion	Low

		testing) protocol to include appropriate social distancing and PPE. Travel to site to be assessed and planned according to individual situation at the time.	
Protection of IP	Medium	Use of integrated electronics (drone / GPS etc) makes this more secure compared to merely machinery.	Low