Wetland Biomass to Bioenergy:

Project Kade

For Department of Energy & Climate Change

FINAL REPORT

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Section 1 Executive Summary

1.1 Objectives

Excellent flexibility is inherent in the AMW/IBERS system. The partners are involved in environmental management and their depth of knowledge with regard to the variety and mass of biomass available and harvesting conditions influenced the system design. The process accepts a variety of feedstocks that are obtained routinely in managing wetlands, however the same system can accept single species stands such as rush. The primary product is in the form of briquettes, whilst anaerobic digestion (AD) provides power to the system and heat for drying.

The objectives of the project were to harvest the wetland areas using AMW's Softrak 65 the smaller of the machines developed by Loglogic and develop a way at a low cost for them to become more efficient.

All feedstocks were extracted to a suitable point which could be accessed by a tractor and trailer and stored if site designations allowed or flooding was not an issue then brought to the plant on a 'just in time' basis. Rush was baled and ensiled, reed and woodchip were stored in AgBags.

The biomass was then processed through the system, rush, the main feedstock for the screw press, was pressed, the press cake, reduced in minerals, was then dried and the press fluid fed to the AD system.

Drying capacity was increased by adaptation of the char rig to extract heat from its central burner and pass it through the AgBag drying system.

The dried biomass was converted into briquettes using a mobile briquetter, two types of briquettes were formed, 100% press cake & 65% press cake, 25% wood chip and 10% char.

1.2 Key findings relevant to objectives

a. A combustion fuel was produced with a highly improved emissions profile compared to untreated biomass.

b. A combustion fuel with a significantly higher calorific value was generated through this work when compared to unprocessed biomass from previous equivalent pilot scale research.

c. Anaerobic digestion trials have shown that biogas yields was increased by highly significant amounts through using the AMW/IBERS method compared to the methods utilized in previous pilot scale research. This energy output provides processing energy for generating the primary commercial output (combustion fuel).

d. The production of a concentrated digestate following anaerobic digestion is ongoing and this will likely become a fertilizer by-product following further analysis once the reactor has been continually running for approximately one year.

e. The construction of a functional commercial farm scale biomass processing facility has been completed and production of the primary commercial product will begin following harvesting this year.

1.3 Exploitation and expected impact

1.3.1 Protection and any use of IP related to commercialisation plans

A patent application (UK priority number 1321675.9) covering the background intellectual property for the DECC wetland biomass to bioenergy innovation competition project was filed on 9th December 2013 by Aberystwyth University (applicant). In a Sub Contract under the DECC grant the joint inventorship under the patent is recorded between Aberystwyth University and AMW Arboreal Ltd. The patent application which is entitled “Improvements in and relating to an improved combustion fuel product”, claims the novel process in the broadest inventive terms which are designed to provide a monopoly on the output of the DECC work for AMW’s commercialisation strategy.

Discussions are underway to develop a licensing framework for AMW to access all rights to the intellectual property for commercialisation activities. Furthermore, licensing discussions are ongoing with a Welsh SME that wishes to commercialise the process in Wales in a complimentary strategy to AMW Arboreal Ltd.

1.3.2 Agreements with land managers

In the interest of the sustainability of the project we would like to ask land owners to commit to a long term cutting agreement that would tie in with their agricultural grant schemes, i.e. 5 years. This could work by agents factoring a cutting programme into the applicants five year Scottish Rural Development Contract at a fixed fee as part of a habitat improvement plan. If successful this would create a network of regional/local stakeholders responsible for a variety of land types, the larger areas cross subsidising the management of the smaller sites (ongoing economic evaluation).

We are already harvesting sites throughout Scotland for clients in both the public and private sectors many of these wetlands have the potential for their harvesting areas to be increased, presently restricted by budgetary constraints. Within Strathspey we currently harvest 15ha across 2 farms, with further potential to add 100 ha, and 10 ha for the RSPB who have expressed interest in having approximately 150ha cut across Insh Marshes and Ballinlaggan reserves.

Interest has also been generated from the onsite demonstrations that were undertaken as part of phase two of the project from RSPB Loch of Strathbeg and a site located within Loch Lomond National Park.

1.3.3 Scalability and adaptability to different land types including a network of remote sites

In addition to the positive effects on climate and biodiversity that can be generated by the utilization of this project’s process, economic benefits can be achieved by making it accessible to the none specialist land manager. This would help to facilitate positive land management at a landscape scale, as well as providing them with a new income stream which would help to avoid the increasing agricultural abandonment of marginal land. Consequently increased biomass volumes for the plant (critical mass), in turn helping to achieve the aims of the Strathspey wetlands and wader Futurescape, http://www.rspb.org.uk/futurescapes/ and the Strathspey Wetlands and Waders Initiative (SWWI).

If biomass volumes increased beyond the critical mass point (in excess of the systems requirements for energy), this could potentially become another renewable energy product feeding local houses or business needs, helping to build a sustainable low carbon economy http://www.lowcarboncairngorms.org.

1.3.4 System flexibility

A number of the systems modules can be up scaled quite simply. The control panel in the main digester is capable of controlling another six AD containers this would increase current volumes of press fluid from 500 litres per day (phase two) to 3,500 litres per day. The briquetter is also designed with this in mind, further modules can be added fed off the main central hopper therefore increasing output.

As the system is fully containerised and designed to be used in a ‘plug and play’ manner it can be easily transported to other suitable locations. All modules can be stopped and restarted and be made ready for transportation within three hours.

On sites where there is a limited resource of biomass, therefore not able to satisfy the critical mass that is required for the whole system and when transport distances to the main processing area become unviable the char rig can easily be moved to such a location to undertake processing. The production of char significantly reduces the volume of the biomass and at the same time greatly increases the calorific value allowing transportation to be viable.

1.3.5 End users

The system will produce a premium quality high value solid fuel in the form of a briquette. iI will have improved combustion properties through a decreased amount of minerals and low requirements on flue gas cleaning. It will also have a high calorific value due to the wood chip and char composition. The end product is aimed at the domestic log burner owner market and will initially be marketed through a purpose built website. Talks are currently underway with the RSPB on how a national brand could be built allowing the product to be marketed in their retail outlets.

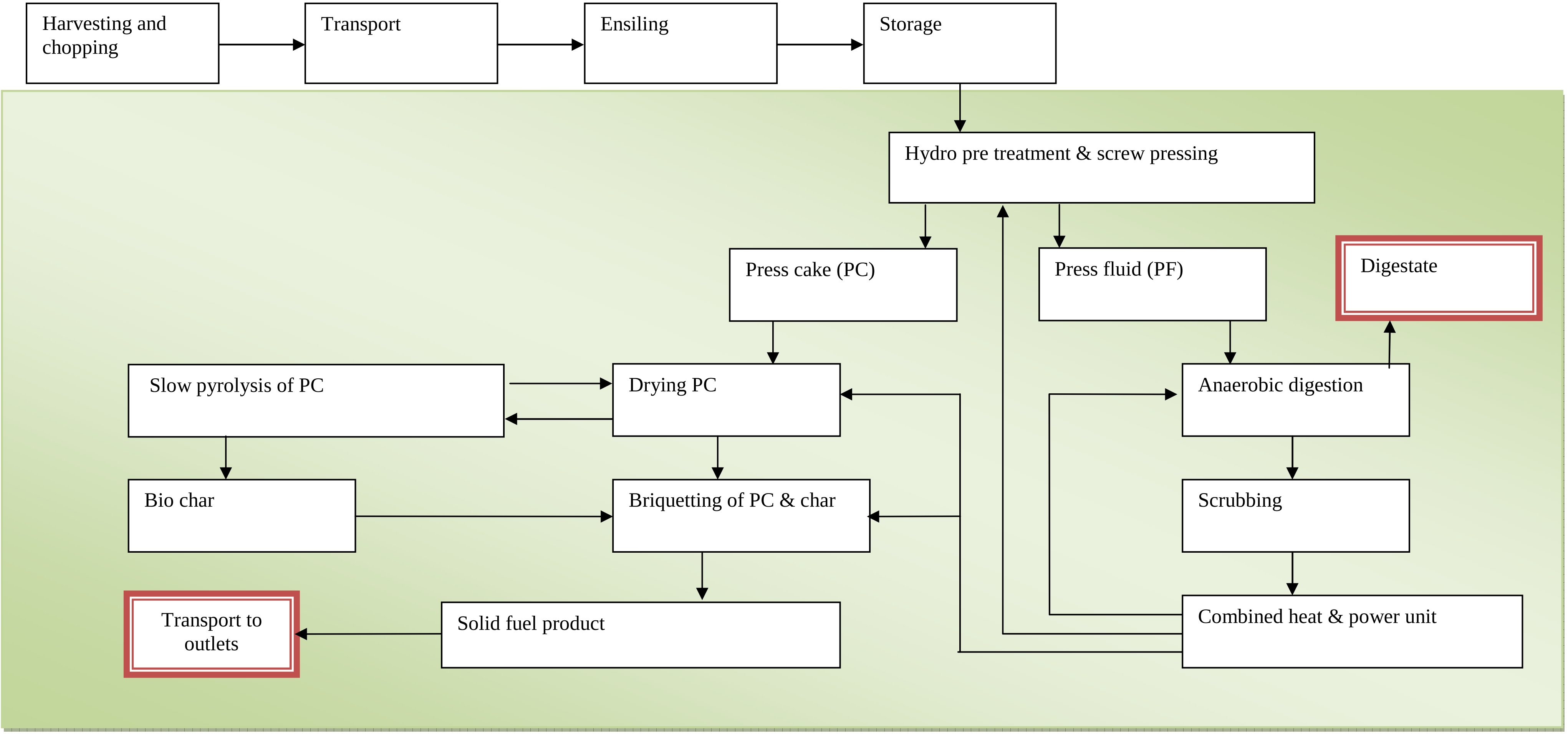


Figure 1: The system boundary for the AMW-IBERS wetland biomass to bioenergy system.

Section 2 Background

2.1 Objectives of the entire project

2.1.1 Objectives

This project aimed to demonstrate the untapped potential of using biomass produced on nature reserves generated from habitat management works, as a possible energy feedstock. A complete system was developed to provide a solution for the end to end delivery, from wetland harvesting through to energy production in an energy efficient way.

The harvesting solution employs a Softrak multiple feedstock harvesting procedure, which incorporates a cut and collect ensiling system ($8m^3$), chip and collect ($6m^3$) and reed cutter, binder and baling system. New advancements were made to increase previous harvesting production which included the development of the Sledge Cableway System (SCS) for woodchip and rush and a sledge which can be towed behind the Softrak for carrying bales of reed. Such advancements also helped to limit the detrimental effect of vehicle movements on soft substrates and enabled direct routes to be used for movement of biomass by being capable of spanning wet features and ditches.

The method for conversion is a novel procedure created by combining various processes that are proven to be efficient biomass conversion methods. The first primary method employed is the use of a hydro pre-treatment followed mechanical dehydration (HPMD; by screw-pressing), to produce a 'press fluid' (PF) that can be used as a feedstock for biogas production via anaerobic digestion (AD) and the simultaneous production of a fibrous 'press cake' (PC) for combustion (Wachendorf [1]). This will be combined with a slow pyrolysis process that will provide heat for drying and char for adding to the combustion fuel or for carbon sequestration. A digestate is also produced and may be used locally as a fertiliser or may be dried and used as part of the solid fuel mix. It envisaged at this point that briquettes will be created for the domestic market.

The main objective of the proposed procedure is to utilise PF for biogas production. The biogas produced will be used in combination with the heat produced from slow pyrolysis, via a combined heat and power system, to drive the processing and produce a solid fuel. The solid fuel will be made up of press cake and biochar. Primary points are:

Combustion fuel is the primary product.

Waste heat from slow pyrolysis in combination with biogas production from press fluid, provides the energy required for processing.

Biomass

The biomass can be derived from land containing various plant communities, these are listed below. The list below is based upon the DECC competition guidance notes (URN 12D/137).

Common reed dominant (*Phragmites australis*)
Soft rush dominant (*Juncus effusus*)
Willow, Alder, Birch

2.1.2 Phases 1 and 2

Phases 1 and 2 included the running of a number of laboratory and small scale field trials (these are included in this report for reference) including,

- Processing of soft rush and common reed into char to understand the charring characteristics and density's of the material to aid the decision making process at the design stage of the char rig to be used in phase 3.
- The production of press cake through a screw press without adding water to look at what impact this had reducing mineral composition. Previous research had added water to the process however this would greatly increase the reactor size something we were hoping to avoid. It was shown that mineral extraction is not significantly impacted by not adding water.

- Methane production was compared to pressing with water added and pressing with no water added, by adding water the yields were reduced significantly. We found that by settling the press fluid yields could be further increased, this led to system design changes at stage three with the introduction of settling tanks.

- Drying trials of press cake at phase 2 led the project to the conclusion that capacity would have to be increased.

2.1 Detailed description of the end to end process

2.1.1 Physical access to sites for harvesting machinery, processing plant and material
The containerized processing plant is housed neatly in units built in standard 20ft ISO shipping containers, ready to plug and play and can be installed in most locations including those that can only be accessed by agricultural machinery, allowing transport distances to be kept to a minimum. All harvesting machinery is suitable for working on wetland sites.

2.1.2 Multiple feedstock harvesting system
The Loglogic Softrak was developed from enquires from conservation organizations who were looking for ways to mechanise what were labour intensive tasks. The machine was designed to satisfy the unique requirements that arise from operating in wetland environments. The Softrak has been designed with road transportation in mind so easy machine transport between sites is possible. There are now a varied array of demountable implements available allowing a number of management tasks to be undertaken by the base Softrak machine. The low ground pressure and flexible rubber track ensures minimal damage to both flora and fauna in these environmentally sensitive areas.

Base machine technical specifications

- Lombardini 4 cylinder turbo diesel — 42 kW (67hp)
- Track width — 600 mm
- Ground pressure — 1.22 psi
- Payload — 1,800kg

Softrak cut and collect system
A direct cut flail harvester system, figure 2, capable of picking up pre-cut or directly cut material cleanly. It can work in standing water up to a depth of 300 mm. The chopped material is blown over the cab into a rear mounted bin available in two sizes, 6m^3 or 8m^3. These machines are ideal for harvesting rush and in dense, long rotation reed bed areas where cut and bind is not possible.

Figure 2: Softrak fitted with forage harvester

Technical specifications

- Cutting width — 1,400 mm
- Throughput — Up to 4,000 kg per hour
- Payload — 1,000 kg
- Ground pressure (unladen) — 1.44 psi
- Ground pressure (laden) — 2.0 psi
- Length — 4,220 mm
- Width — 2,440 mm
- Height — 3,006 mm
- Weight — 2,800 kg
- Fuel consumption — @ 3,000 rpm = 8 litres per hour

Softrak chip and collect system
Fitted with a converted Timberwolf 150H/PTO chipper, figure 3. Conversions include, a hydraulic pump allowing the chipper to be driven by the Softrak's front hydraulically powered PTO, extended

discharge chute enabling the chip to be blown over the roof into the rear bin and adapted three point linkages.

Figure 3: Softrak fitted with wood chipper

Technical specifications

• Max dia. Infeed	150 mm
• Throughput	Up to 2,000 kg per hour
• Ave. chip size	12 mm
• Payload	1,800 kg
• Ground pressure (unladen)	1.44 psi
• Ground pressure (laden)	2.4 psi
• Length	4,800 mm
• Width	2,200 mm
• Height	3,006 mm
• Weight	2,800 kg
• Fuel consumption	@ 2,500 rpm = 6.5 litres per hour

Softrak reed cutter bundling and baling system

For harvesting under dry biomass conditions, particularly common reed between the months of December and March. The conveying system mounted behind the harvesting head receives the cut bundles and conveys them up along the side of the Softrak to the rear baling area. Here they are manually unloaded into the baling frame to form a bale measuring 2,400 mm long with a diameter of 1,200 mm, figure 4. A plastic sheet is used to keep the reed dry, typically harvested with a moisture content of 15%, allowing storage outside.

Figure 4: Reed harvester and baling frame

Technical specifications

• Cutting width	1,400 mm
• Throughput	Up to 180 bunches per hour
• Baler capacity	80 bunches
• Payload	300 kg
• Ground pressure (unladen)	1.44 psi
• Ground pressure (laden)	1.68 psi
• Length	4,520 mm
• Width	2,440 mm

- Weight 2,800 kg
- Fuel consumption @ 2000 rpm = 5 litres per hour

2.1.3 Methodology for the four phase harvesting system

To maximise the efficiency of the biomass to bio energy conversion, material will be harvested as a four phase approach:

- Early season rush harvesting – wet biomass conditions with a moisture content > 70%, more suited to the production of press fluid as a feedstock for anaerobic digestion.
- Late season rush harvest – dry biomass conditions, with moisture content < 40%, with decreased content of alkaline chlorine nitrogen and sulphur.
- Reed harvesting – dry biomass conditions with moisture content less than 20%, for slow pyrolysis for char production.
- Woodchip harvesting – invasive wetland scrub cut for wood chip production with moisture content of < 50%, to be incorporated into briquetting and char production.

The wetland biomass will be harvested using a Softrak multiple feedstock harvesting system. The system is capable of producing 15 loads, approximately 15 tonnes of material per day. This will increase or decrease depending on site and material to be harvested. Early season rushes will be moved to adjacent drier ground for baling and ensiling, late season harvested rush requires baling only. Reed will be charred close to the harvesting site to reduce volumes. Woodchip will remain unprocessed in a loose form. Where feasible bales and woodchip will remain in situ until required, however, where site sensitivities such as designations, flood risk, etc will not permit this, the bales will be moved to a storage compound close to the biomass plant.

2.1.4 Transportation methods and distances

The biomass processing plant is located at the Dell of Killiehuntly in a disused gravel quarry; Easting 278509, Northing 800526 which is wholly within RSPB ownership. During the time period of the demonstration and for research data feedstocks were imported to the processing plant from remote sites by public highway using a tractor and trailer, as well as internally within Insh Marshes Nature Reserve.

Biomass harvesting and processing in wetlands faces two main challenges: the machinery should be adapted

- to wet sites with low carrying capacity (structural damage to the site will be caused by repeated passing over),
- to the industrial use of biomass in an effective harvesting chain (drying, compaction, transportation and storage of the biomass),

and still have high efficiency, for cost reduction and long term profitability of biomass harvesting.

The development of the Sledge Cableway System (SCS) allows 1,000kg of biomass to be securely transported up to a distance of 1,000m from the harvesting area to the processing area with a footprint of 0.2 psi when hauled over land consistent with wetland sites. SCS achieves zero footprint when transferring biomass over watercourses, a depth of 150mm is required.

Figure 5: Sledge cableway system

The sledge is simply loaded by the harvester reversing into it and tipping the collected material. A double drum capstan winch powered by the tractor then hauls the sledge to the docking station mounted at the front of the tractor. Sensors located on the sledge control its movements along the cableway, when docked the biomass is transferred to the docking stations walking floor using the rear door of the sledge. The biomass is then conveyed underneath the tractor to the baler located at the rear, the biomass is then baled and ensiled which improves transportability, storage and handling.

This system is designed to:

- help to conserve the site (prevention of mechanical disturbance of the soils, avoidance of damage to rhizomes).
- increase acreage performance and thus biomass volumes.
- prevent the need to fortify tracks or access points.
- achieve efficient set up/dismantle times (essential on sites prone to flooding).

2.1.5 Storage requirements for the harvested and processed material
An area of 500 m^2 is required for the storage of ensiled bales and woodchip the latter simply sheeted using a gortex membrane allowing the material to air dry. Once the feedstocks have been processed they must be kept dry, however storage will be short term as briquetting operations are run concurrently.

2.1.6 On-site processing
The biomass processing plant comprises:

- Two shipping containers (6.2m x 2.5m x 2.6m) utilising anaerobic digestion technology with a link to export energy to local or national distribution networks.
- One shipping container (6.2m x 2.5m x 2.6m) accommodating the combined heat and power plant (CHP)

- One biogas storage bladder (5m x 4m)
- One 12,000 litre bunded digestate storage tank
- One shipping container (6.2m x 2.5m x 2.6m) housing the screw press and sedimentation tanks
- One drying and char unit (6.2m x 2.5m x 2.6m)
- One briquetting unit (4m x 1.8m x 2m)

Figure 6: Processing plant site layout

The whole plant is mobile and containerised and designed to be used in a 'plug-and-play' manner which can be monitored remotely, figure 6. If the plant needs to be decommissioned at any time then it can be removed from the site very easily.

System summary

Project	Power Production pressed rush 1000 Tonnes pa
System	14kW electrical
Volume	31.00 m^3
Specific Loading Rate	5.98 kg VS/m^3/day
Retention time	35 days
Biogas Prod/day : Capacity	5.23 m^3/d
Biogas Prod : T ODM	162.25 m^3/d
Methane : T ODM	97.35 m^3/d
Biogas Yield	59,160 m^3
Methane Content	60%
Calorific Value	21.00 MJ/m^3
Biogas Prod/day	162.1 m^3/day
Flow rate	6.8 m^3/hr
Fuel Value	141.8 MJ/hr
Fuel Value	39.3 kW/hr

Combined Heat and Power, output rating and energy production

Power less parasitic load	36,681 kWh/yr
Heat less parasitic load	63,998 kWh/yr
Briquette production	376 tonnes

Process flow

Step 1. The bale is un-wrapped and loaded in to a bale breaker to break up the silage, the biomass is unloaded into the 5m^3 feed hopper, it is at this point of the process that the system becomes fullyautomated with a throughput of 300kg per hour.

Figure 7: Feeder wagon equipped with weighing system

The conveyor system also incorporates the hydro pre-treatment facility, this washes the material as it travels up the conveyor before depositing it through the roof of the shipping container into the screw press. A sensor on the roof hatch controls the flow rate of the product to optimise throughput. The biomass enters the screw press with the additional water.


Figure 8: Biomass pre treatment facility with water recycling system and container housing screw press

The 'press fluid' that comes from the dewatering of the biomass is collected into one of two 2,500 litre settling tanks located at the rear of the screw press module, the press fluid is left to settle overnight.


Figure 9: Screw press module housing press fluid storage tanks and screw press

Step 2. The press fluid concentrate is then fed into the anaerobic digester, at a particular daily volume, this is a fully automated process controlled by computer located in the digester container.

The fluid digests quickly with a hydraulic retention time of around 19 days. The digester produces biogas that is cleaned through a hydrogen sulphide filter. The biogas then enters into a combined heat and power unit and delivers thermal and electrical energy that contributes to the energy requirements of the process. A digestate is produced from the process of anaerobic digestion and can be used as a fertilizer and thereby replace current fertilizer use.

Figure 10: Connection from settling tanks located in screw press module to reception hopper which then feeds into the anaerobic digester

Step 3. The fibrous biomass 'press cake' is collected in a hopper housed underneath the shipping container. The fibrous material is then loaded by telehandler into the drying unit.

Drying and charring: In drying mode both kilns are filled with wet feedstock which is air dried using wood chip in the burner, no gas is produced during this process. In charring mode one of the kilns is filled with dry feedstock such as reed bundles, to be charred. Gas produced during pyrolysis is used to fuel the burner and excess heat is used to dry the material in the other kiln, press cake.

Figure 11a: Press cake

Figure 11b: Drying & charring unit

Step 4. The press cake, woodchip and char are distributed into the dry biomass mixing module. The mixer has an electronic weighing system which ensures that the correct quantities of each product are added, it then homogenises the biomass mix. The mix exits the mixer from the built in conveyer and delivers the mix into the briquetter silo. Shredding of the biomass before briquetting is not required using this process. The biomass mix is briquetted. The briquettes contain approximately 65% press cake, 25% woodchip and 10% char. The briquettes are collected from the briquetter in plastic bags. The bags are heat sealed. The bagged briquettes are placed on a pallet and wrapped. The pallets are loaded onto a haulage truck using a telehandler, or tractor with a loader and delivered to shops, solid fuel outlets and petrol stations within a 35 mile radius of the processing plant.

2.1.7 Production and treatment of any waste material and bi-products

It is envisaged that the concentrated press fluids (compared to the original system whereby pretreatment water was added resulting in a dilute fluid) have produced a concentrated digestate following anaerobic digestion. This is now worth further examining for its efficacy as a fertiliser. This can only be properly assessed once the digester has been running for approximately one year. This run time is essential to ensure that the digester and its microbial populations have stabilised and representative samples thereby harvested. However, the level of concentration means that there is some hope for the production of a liquid fertiliser pending future work.

There is also the possibility of incorporating carbon sequestration and soil improvement in the system by using biochar.

2.1.8 Potential use of bi-products

Fertiliser and carbon sequestration products. Please see 2.1.7.

2.1.9 Any re-cycling aspects

If process water was continued to be added into the pressing procedure, then the clarified liquid remaining following concentration of the press fluid prior to digestion can be filtered and re-used for pre-treatment in the recycling system. This would substantially reduce water usage if phase 3 did entail water pre-treatments.

The process does require the baling of reed and rush the latter being ensiled using silage wrap. Both the netting and wrap can be recycled through http://www.solwayrecycling.co.uk. The reed bales are wrapped using polythene sheeting and baler twine both can be reused the following harvesting season.

2.2 Environmental and Regulatory requirements

2.2.1 Site designations related to harvesting operations

The following designations were considered and addressed, Sites of Special Scientific Interest (SSSI), Special Protection Areas (SPA), Special Area of Conservation (SAC), Ramsar and National nature Reserve (NNR), with regards the impact harvesting operations may have on the designated features.

- Floodplain fen (Ramsar & SSSI) – harvesting operations have been planned accordingly with ground conditions ascertained through site assessment.
- Very Wet Mire (Insh Marshes SAC) – site assessment undertaken and most suited harvesting system suggested.
- Vascular Plant Assemblage (Insh Marshes SSSI) – harvesting plan has determined the appropriate cutting pattern and most suited vehicle movements.
- Whooper Swans (Insh Marshes SSSI & Insh Marshes SPA) – harvesting plan has been coordinated to consider disturbance to wintering wildfowl and feeding habitat.
- Breeding Bird Assemblage (Insh Marshes SSSI & Insh Marshes Ramsar) – harvesting operations are out with the breeding season.
- Hen Harrier (Insh marshes SPA & Insh Marshes Ramsar) – harvesting operations will not begin until one hour after sunrise and finish one hour before sunset, to avoid disturbance at winter roost sites.
- Otter (Insh Marshes SSSI, Insh Marshes SAC & River Spey SAC) – a European protected species, FCS guidance note will be adhered to.
- Invertebrate Assemblage (Insh Marshes SSSI) – harvesting plan has determined the appropriate cutting pattern and most suited vehicle movements.

A contract was drawn up for the operations between the land owners and AMW Arboreal Ltd which included environment and health and safety site specific information. Land owners who had designated sites included in the proposal had to provide a sensitivity map and programme of works authorised through ORC (Operations Requiring Consent).

2.2.2 Regulatory requirements related to plant operations

Advice was sought from the Scottish Environment Protection Agency (SEPA) they recommended the following licences and exemptions applied to the project, based on figure 12.

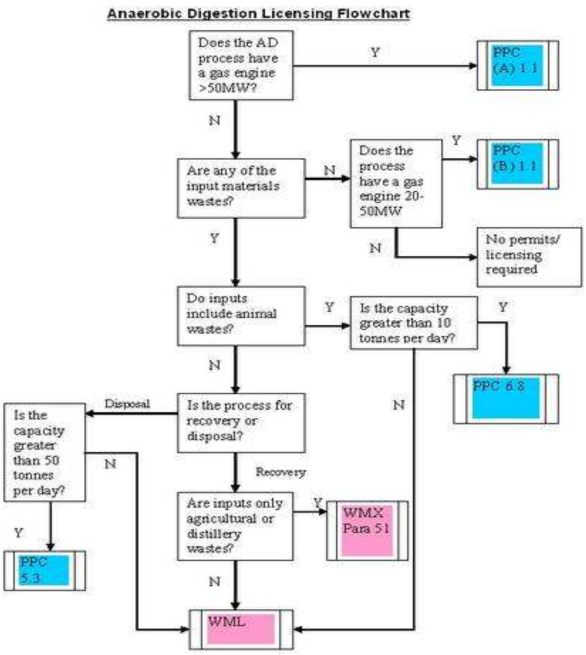


Figure 12: Anaerobic digestion licensing flow chart

STEP 1: Does the AD process have a gas engine of greater than 50MW?
The combustion plant is sized at 0.4MW.

STEP 2: Are any of the input materials waste? *If* a material is a waste the need for regulation under the Waste Management Licensing (Scotland) Regulations 2011 applies. Appendix 3 to this Guidance provides a number of waste scenarios developed by SEPA and importantly scenarios 2.and 3. There in suggest that:

> 1. *Biofuel from timber and other crops grown to be used as biofuel is not waste.*
>
> 2. *Wood chips and sawdust from virgin timber which is processed into timber products for use as eg. biofuel or chipboard manufacture, are unlikely to be waste where the processor can demonstrate that the material is not being discarded* and there is no intention or requirement to discard it during the harvesting and processing activities

However, it is unlikely that SEPA would consider the reeds, rush, grass etc. being introduced to the process as being specifically 'grown' for their proposed use and therefore this input should, for the time being, be considered as waste (until such time as a justification can be made for their not being treated as such).

STEP 3: Do inputs include animal waste?
The project is for the conversion of vegetable matter (reeds, rushes etc.) only.

STEP 4: Is the process for recovery or disposal?
It is intended that all inputs are **recovered**. Mashed reeds to be combined with biochar to form briquettes; the mash liquid is to be digested to generate off-gas for combustion (electrical and heat generation); and the digestate to produce an organic fertiliser.

STEP 5: Are inputs only agricultural or distillery wastes?
"Agricultural waste" is defined as "*waste from premises used for agriculture*". The definition of "agriculture" is taken from Section 86(3) of the Agriculture (Scotland) Act 1948, namely:

> "*'agriculture' includes horticulture, fruit growing, seed growing, dairy farming and livestock breeding and keeping, the use of land as grazing land, meadow land, osier land, market gardens and nursery grounds, and the use of land for woodlands where that use is ancillary to the farming of land for other agricultural purposes, and "agricultural" shall be construed accordingly*".

It is not clear if the definition of agricultural premises would extend to include land occupied by protected habitats – clearly this will vary on a site by site basis and will depend on whether the land is or has been used for grazing etc.

If the wastes do indeed fall under the above description then Paragraph 51 to Schedule 3 to the Waste Management Licensing (Scotland) Regulations 2011 provides an exemption from the need for a Waste Management Licence for processes for the anaerobic digestion of agricultural waste.

If the waste **cannot** be classed as agricultural then a waste management license will be required to allow receipt and processing of the various waste streams.

* Assumes less than 5000 t / yr received and processed.

WOODCHIP & BIOCHAR PRODUCTION,

SEPA's Guidance on Biochar production suggests that a Waste Management Licence would not be required provided;

- A permit under the Pollution Prevention and Control (Scotland) Regulation 2012 (PPC) is held (Application Fee £ 2490 / Subsistence Fee £4180);

- No more than 30 tonnes of waste is held; and
- Only the following types of waste are used to manufacture the biochar:

The project proposed not to store more than 30 tonnes at any one time and therefore it would not be of any value to pursue the PPC Permit route. As a waste management license (WML) is likely to be required anyway it would be advisable to include biochar production and Briquette manufacture within that WML.

> *"Please also note that, unless a case can be made that the inputs and the briquettes produced are not waste then the briquettes would be considered waste and could only be utilised by 3rd parties holding an appropriate waste exemption or waste management licence"*

Following discussions with SEPA's National Operations Waste Unit clarification has now been received regarding the classification of the feedstocks from wetland operations, SEPA issued the following response:

> *'We have had some discussions and we are happy that we can let this happen without waste controls. The biomass you propose to use is equivalent to a purpose grown crop so there is no reason why it should be treated any differently. This is on the understanding that if you change any of the inputs, it may change the way we regulate this activity.'*

The burning of domestic fuel in none restricted areas is not controlled with regards to emissions. Briquettes produced using this systems process decreases the mineral composition of the solid fuel which in turn reduces the emissions of the end product.

2.2.3 Planning regulations

Initial consultation with Highland Council indicated that the project would fall inside of the planning regulatory system. Concerns would be raised on potential nuisance impact on the Cairngorm National Park and these were seen more likely to arise from the importing of feedstocks to site. However they were keen to point out that this should not be seen as a barrier to generating the critical mass required for economic viability. With regard to this the project had to address issues of noise, odour, emissions, visual impact assessment and traffic movements.

As with any development that utilises biomass as a resource there is a perception that the operation will create odours and noise with detriment to local receptors. The adjacent farm are the closest receptors, the disused quarry proposed to locate the biomass processing plant provides a natural physical noise barrier, figure 10 and operations will be comparable to that of a working farm. Commercial wastes will not be used, only biomass generated from wetland operations will be used. The operation of the biomass processing plant in terms of compliance with regard to permitting and exemption SEPA commented the following,

> *'However, as the proposal is to trial the process over a limited period (80 day period) - then provided all necessary measures to prevent any offensive odours, smoke, or contamination of soils and/or the water environment are put in place SEPA would have no regulatory issues with the Pilot operation proceeding. Once the developer/ operator has demonstrated that the process is viable, and prior to any further continuance or increase in scale, they should discuss the need, if any, for a WML with a member of the local Operations team.'*

Siting and layout

No new access tracks were constructed as part of this development; the existing track into the farmyard and out of the farmyard on to the surrounding agricultural land was used during construction and operational phases. The positioning of the biomass processing plant took into account the findings and recommendations of the noise, odour, traffic, landscape and visual assessments. On completion of the development, once the scheme is operational, agricultural use of the area will continue. The proposed biomass processing plant is located approximately 192m southeast of the nearest residential property and approximately 221m east of the next nearest. The prevailing wind is from the southwest and views to the site are extremely limited.

Figure 13: Location of biomass processing plant

Water resources

The proposed site is within the 1 in 200 year (0.5% annual probability) flood envelope of the Indicative River and Coastal Flood map (Scotland) figure 14, however the site was chosen for the following reasons:

- Proximity to areas that require wetland management (essential for operations).
- Proximity to housing.
- Reduction in road transportation of feedstocks, allowing for biomass to be transported internally within site.
- The topography of the disused quarry and adjacent tree lines, provide natural odour, sound and noise barriers and greatly reduce the visual impact of the processing plant.
- The disused borrow pit in the past would have previously been extracted to be used as surfacing on the farm, suggesting a brown field classification.
- Past excavations has led to the flood storage been increased therefore adding the processing plant will not decrease the flood capacity.
- The site does not lie within a Special Protection Area (SPA), Special Area of Conservation (SAC), Ramsar site or Site of Special Scientific Interest (SSSI).

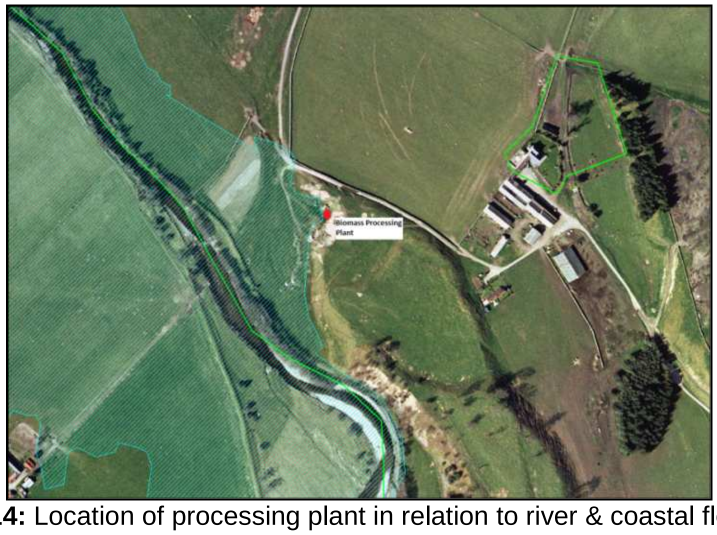


Figure 14: Location of processing plant in relation to river & coastal flood map

Mitigation against the risk of flood have been considered with regards the processing plant design, operational procedures and site features by the following means:

- Setting the processing plant back into the quarry so as not to affect the route of flow and velocity of the flood water, this will also keep the plant away from the main flow of the River Tromie.
- The layout of the individual processing modules has been designed to keep the footprint as small as possible.
- The modules can be raised off the ground.
- Design and construction of the individual units will consider the natural environment they will be operating in.
- Storage of feedstocks within the proposed processing site will be kept to a minimum and brought in on a 'Just in Time Basis'. More often than not large areas for storing biomass is available at the harvesting site. Baled material does not look out of place in the countryside.
- The whole processing plant can be efficiently and quickly transported from the proposed site if required.
- A flood risk evacuation procedure will be written into the Health and Safety management document for the project.

Odour

The system is not considered to be a source of odour, due to the design and management that is in place, this is as follows:

- The biogas can represent a source of odour but this will be used in the engine and combusted, thus neutralising any odours.
- The biomass will be stored at the adjacent farm and wrapped to prevent odour and leachate being generated. All feedstocks will be brought in to the processing plant on a 'Just In Time' basis.
- The digestate is stored in the tanks on the adjacent farm and spread as per other agricultural wastes, with the same duty of care. Volumes will be low, less than $10m^3$ per month.
- Odour, although difficult to measure in numerical terms, can be monitored and will be done on a daily basis. The proposed methodology for monitoring is as per the Scottish Environmental Protection Agency Odour Guidance documentation.
- The digester is fed little and often. The demand design criterion is approximately 1000 litres of new feedstock to be added per day (equivalent to 10 domestic dustbins) and it works on displacement, so 1000 litres will flow out automatically once the new feedstock is added. In terms of AD this system is very small and therefore does not require large scale filling and emptying, which is when odours generally occur.
- The process stores the digestate and feedstocks no different from any other farming operation. The digestate has essentially been produced from a 'mechanical cow' as the processes of digestion are similar.

Noise

The anaerobic digester unit has been super silenced to reduce noise – akin to a super silenced generator. The main source of noise from the operation will be in the running of a small combined heat and power engine. This engine is less that 15kW in output size and is housed in an acoustically controlled compartment. Note that an equivalent engine could be used as a standby generator for a domestic property or for an external site which can be super silenced to allow for continuous operating.

The noise levels at the nearest residential receptor will be low or negligible. The engine compartment is super silenced by,

- Acoustical insulating using Rockwool panels 100mm to absorb noise from the generating unit.
- The unit's air vents for cooling and air exchange are louvered and acoustically designed to prevent noise being emitted from outside the container.
- The main louvers are on the roof of the container and come with a vent with acoustic cowl to reduce any subsequent noise.
- Noise level will not exceed 56dB at 10m. To put this into context, the noise level of a typical high street is 60-70dB and inside a car is 60dB.

Access

Access to the biomass processing site is via the existing permanent track from the Dell of Killiehuntly Farm, travelling from Kingussie along the B970. The existing track has good visibility for vehicular access and is regularly used by all forms of vehicles. Traffic movements were assessed as part of the project, the preferred route for the delivery of the biomass processing plant is shown in figure 15, and traffic movements once the plant is operational. Traffic movements will be kept to a minimum and those associated with the activity will be less than three deliveries per fortnight. Based on the anticipated number of vehicles associated with construction and the traffic resulting from the proposed development the movements would not be significant based on "Guidelines for the Environmental Assessment of Road Traffic".

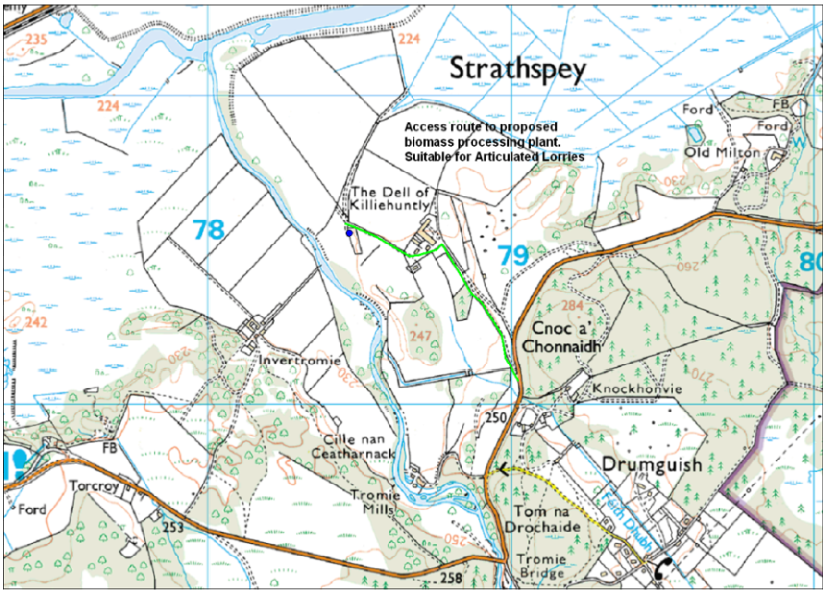


Figure 15: Access to processing plant from the B970 - suitable for articulated lorries

During the construction phase the area within the disused quarry allowed for temporary parking of site vehicles, this also allowed for vehicles to enter the site and for vehicles to turn around allowing them to exit the site in forward gear. This lasted three days.

Figure 16: The anaerobic digester arriving on to site

Health and Safety Regulations

This is essentially an industrial operation. Full health and safety was provided and noise and vehicle movements were considered. All machinery is CE marked and safe working practices followed. Full and appropriate risk assessment and method statements (RAMS) were produced as part of the project for both harvesting and plant operations. All operators of machinery and equipment received the required training. The Health and Safety Executive has no specific guidance for anaerobic digestion beyond the risk assessment that every business is obliged to carry out. However there are a wide range of regulations applicable to the project:

- The management of Health and Safety at Work Regulations 1992.
- The Control of Substances Hazardous to Health 1999.
- The Health and Safety at Work Act 1974.
- The Provision and Use of Work Equipment Regulations 1998.
- The Dangerous Substances and Explosive Atmosphere regulations 2002.

These regulations are additional to regulations dealing with first aid, personal protective equipment, manual handling and safety zones.

Section 3 Trials and Demonstration

3.1 Primary processing of Scottish soft rush

3.1.1 Hypothesis/ aims

To produce press fluid with water added as part of the pressing procedure and press fluid with no water added into the pressing procedure for the purposes of experiment 2 (below).

A reduced mineral composition in a solid fuel product is important for emission reduction and raising the ash softening temperature. What is the impact of not adding water during pressing of rush dominated silage on the mineral composition of the press cake produced?

3.1.2 Methodology

Harvesting and conservation of biomass

Juncus effuses dominant swards located at Insh Marshes near Kingussie in Scotland were cut using a Softrak flail harvester with a rear collection vessel by AMW Arboreal Ltd between 24/10/2013 and 03/11/2013. Following cutting, an artificial windrow was constructed on nearby hard standing and the biomass was baled and wrapped using conventional farm machinery and silage wrap. This experiment took place on the 13/1/2014. Two bales were randomly selected and transported to IBERS (Aberystyth University: AU).

Bale weight

One bale plus delivery vehicle was weighed on the AU farm weigh bridge. A bale was unloaded and the delivery vehicle re-weighed, the total weight less the delivery vehicle weight provided the bale weight. This was done for two bales.

Bale shredding and pressing

A bale was initially processed by unwrapping and loaded into a Stort bale chopper using a farm toploader. Each silage bale was shredded for 20 minutes.

Each bale was split in half by weight and kept separate in large cloth biomass bags. The first half was processed without washing. The other half processed with washing.

A Vincent CP10 screwpress with pre-treatment water added into the pressing augur was used (set at 50Hertz). Tap water at approximately 5℃ was used when pretreatment water was added.

Silage samples were taken randomly (three per process run) and oven dried to obtain the dry matter (DM) composition.

Figure 17: Biomass loaded into bulk bags and weighed before processing

Processing with no water added during pressing

1. One half of a shredded bale was put onto a processing conveyor by hand and pressed.
2. The press fluid (PF) was collected in a dairy cooler (at 5℃) with the stirrer turned on to maintain a homogenised fluid.
3. Samples of the homogenised PF were pumped from the cooler into 2 x 25 L carriers these were labelled and stored in a walk in freezer at -20℃.
4. The press cakes produced were dried that day (see DM composition) following random sampling after pressing for DM and mineral analysis.

Processing with water added during pressing

1. Water at 5℃ was added into the screwpress augur at 600 l per minute.
2. The press fluid (PF) was collected in a dairy cooler (at 10℃) with the stirrer turned on to maintain a homogenised fluid.
3. Samples of the homogenised PF were pumped from the cooler into 2 x 25 L carriers, these were labelled and stored in a walk in freezer at -20℃.
4. The press cakes produced were randomly sampled during pressing for DM and mineral analysis.

Repeat for Bale 2.

Figure 18a: Press fluid collected in 25 litre drums

Figure 18b: Press cake randomly sampled for DM

Dry matter and compositional analysis
Three random samples of biomass were taken from each half bale prior to processing for further analysis. Sample dry matter (DM) content was determined by measuring the difference in weight before and after drying to constant weight in an air circulated oven at 60 ℃ for 48 h.

Elemental analysis
The elemental/various mineral analysis of the samples was conducted at MEDAC (MEDAC Ltd, Surrey, UK). The laboratory is accredited to BS EN ISO9001:2008. A FlashEA® 1112 Elemental Analyzer was used for the ultimate analysis. All the tests were duplicated and means were calculated.

Data analysis
Microsoft Excel (Microsoft) was used to calculate mean yields and associated standard error of the means (SEM). Measures of significance and standard error of difference (s.e.d.) were calculated using a general ANOVA function in Genstat statistical software (13^{th} edition, VSN international).

3.1.3 Results

Table 1 The C, H, N, Ca, K, Mg, Na and P compositions of the unpressed silage and the press cakes (PC). Mean figures from triplicate samples from two bales. sed = standard error of difference.

	C	SEM	H	SEM	N	SEM	Ca	SEM	K	SEM	Mg	SEM	Na	SEM	P	SEM
PC without water wash	42.97	0.19	5.39	0.04	1.40ab	0.03	0.41	0.00	0.45	0.02	0.15	0.01	0.06	0.01	0.09	0.00
PC with water wash	42.62	0.06	5.48	0.06	1.33b	0.02	0.42	0.04	0.43	0.00	0.15	0.00	0.06	0.01	0.09	0.01
Silage	42.43	0.37	5.53	0.04	1.26a	0.02	0.42	0.01	0.50	0.00	0.14	0.00	0.08	0.00	0.10	0.00
p value	0.32		0.18		0.06		0.88		0.04		0.44		0.01		0.09	
sed	0.34		0.07		0.05		0.02		0.21		0.01		0.01		0.01	

The P and Mg composition of the press cakes are lower following pressing. The K and Na are significantly lower following pressing.

3.1.4 Conclusions

Pressing significantly reduces the composition of some minerals from silage. The addition of water in this pre-treatment and pressing system does not significantly impact upon mineral extraction during pressing of the silage.

The volatile composition and the methane production potential of the press fluids produced in this process are reported in section 3.2.

3.2 The impact of concentrating and adding process water during pressing on the methane production potential of press fluids following anaerobic digestion

3.2.1 Hypotheses/ aims

What is the impact on methane production following anaerobic digestion of press fluids if water is added during pressing?

What is the impact on methane production following anaerobic digestion of press fluids if the press fluids are concentrated through settling?

The use of concentrated press fluids or press fluids with no process water added would decrease the AD reactor size requirement hugely. This is a scale up issue not problematic during pilot scale experimentation with low throughput.

3.2.2 Methods

Concentration of press fluids/ substrate preparation

Please see section 3.1 of the experimental reports for details of the press fluid production.

Following primary processing (pressing/ washing) the press fluids were stored in a freezer in 2 x 25 litre containers. Two 25 l containers from each of the sample type were defrosted (Table 2).

Table 2 The 4 samples generated during the primary processing of rush bales.

Bale	Water added
1	No
1	Yes
2	No
2	Yes

These were removed from the freezer and thawed at approx. 10-18℃ for 48 hours. The samples were homogenised by shaking the containers. They were then allowed to settle overnight.

For one container of each ‘two container’ sample a centrifugal pump with rubber tubing was used to extract the fluid concentrate from the bottom of the container into 5 litre glass containers. The remaining container was homogenised again by shaking and then fluid was pumped from the centre of the container into 5 litre glass containers.

By way of control cellulose and water blanks were also set up (Table 3).

Table 3 The samples that were generated for use as substrates in anaerobic digestion runs.

Bale	Water added	Concentrated or Not
1	No	Yes
		No
1	Yes	Yes
		No
2	No	Yes
		No
2	Yes	Yes
		No

Inoculum collection

Digestate was collected from the municipal sewage works anaerobic digester at Aberystwyth using two 25 litre fluid carriers. Approximately 15 litres was collected in each container. The digestate was left to de-gas at approximately 18℃, under a labor atory fume cupboard with the lids undone so there was no gas tight seal. Degassing took place over 6 days.

Volatile solid determination

A dry crucible was dried in the oven at 105℃ for 2 hr and cooled in a desiccator and then weighed (B).

A sample of the substrate was placed into the crucible and weighed (**D**) and then placed in an oven at 105℃ for 24 hrs.

The samples were then removed from the oven and left to cool in a desiccator and weighed once cool and placed back in oven for 30 minutes. This was repeated until a constant weight was established.

When a constant weight had been achieved the weight was recorded (**A**). The total solids were calculated using the following equation.

$$\% \text{ Total solids} = \frac{(A - B)}{(D - B)} \times 100$$

A = Weight of crucible + dry sample (g)
B = Initial weight of crucible (g)
D = Weight of crucible + wet sample (g)

The crucible and sample were then placed in an oven at 550℃ for 12 hours. The procedure above was repeated in order to check that a constant weight had been achieved.

When a constant weight has been achieved the weight was recorded (**C**). The volatile solids composition was then calculated using the following equation.

$$\% \text{ VS} = \frac{(A - C)}{(A - B)} \times 100$$

A = Weight of crucible + dry sample (g)
B = Initial weight of crucible (g)
C = Weight of crucible + ashed sample (g)

AD run set up

Triplicate digestions were conducted on each substrate sample, cellulose and water controls were also conducted in triplicate. Digestions took place in an Innova 4300 Incubator shaker (Brunswick Scientific).

Thirty clean 1 L duran bottles were used. Checks were undertaken to ensure that the necks of the bottles were free from chips to allow for a gas tight seal and to avoid cuts. The bottles were numbered with permanent marker.

The 30 tops with gas ports were constructed with the relevant ports clips and taps. A volume of 160 ml of substrate was poured into each bottle.

The inoculum was homogenised by shaking the container (with it sealed). A volume of 340 ml of inoculum was dispensed into each bottle (a volume based on calculations relating to the comparative VS composition of the inoculum and substrates). Three bottles were prepared which contained 340 ml of inoculum and 160 ml of water added (blanks). Three further bottles were prepared with 340 ml inoculum, 0.5 g cellulose and made up to 500 ml with water.

The substrate and inoculum were missed together by gently swirling each bottle. The lids were secured and the sample headspaces were flushed with oxygen free nitrogen (sparging).

Following sparging all the bottle tops were sealed and the bottles were placed in incubator set to 35℃. The incubator shaker was set to agitate the bottle to ensure that the inoculum and substrates are kept fully mixed

The gas was measured every twenty four hours for first 3 days then as appropriate to maintain adequate gas volumes. Measurements taken were:

a. Date and time sampling started
b. Sample number
c. Gas pressure (PSI)
d. Gas volume (ml)
e. Percentage methane and carbon dioxide in sample (using a Hiden gas Mass spectrophotometer (MS)).

Gas compositional measuring procedure
The pressure sensor and gas collection syringe was attached to a bottle valve. The valve tap was turned to allow the pressure monitor to measure vessel pressure and a note of the pressure was recorded. The tap was turned to allow gas to flow to both the pressure monitor and syringe. The syringe plunger was released and gas was drawn out until neutral pressure was obtained. The valves were then closed. The gas volume was recorded (ml). The gas syringe was connected to the mass spec gas analyser. The methane and carbon dioxide compositions (%) were read off and recorded. The bottle was replaced back in the incubator and the next bottle was monitored.

Figure 19: Large lab scale digestions took place in a Brunswick Innova 4300 Incubator shaker.

The mean methane production recorded in the blanks was subtracted from the methane production recorded in the substrates.

3.2.3 Results

Volatile solids composition
The concentrated press fluids have a much higher volatile solids (VS) composition (of wet weight) compared to un-concentrated press fluid as shown in Figure 20. Figure three shows the methane production of these substrates.

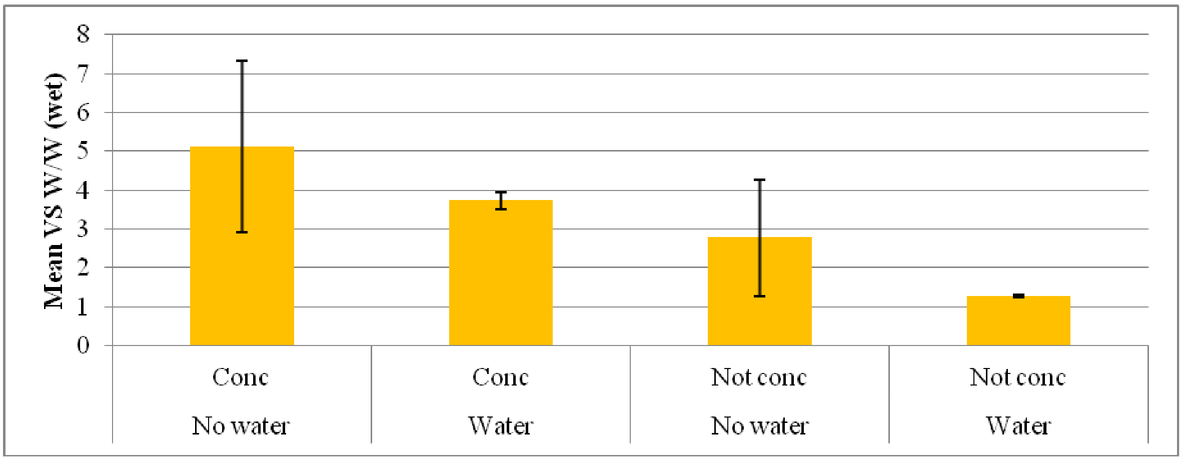


Figure 20: The impact of settling and processing with water on the volatile solids compositions of press fluid substrates used in this experiment (means from two bales). Conc = concentrated by overnight settling; not conc = homogenised samples; No water = water not added during screw pressing; water = water added during screw pressing. Error bars represent standard error of the mean.

The highest methane yields were obtained from concentrated press fluid with no water added during pressing (Figure 21; samples 6 and 2).

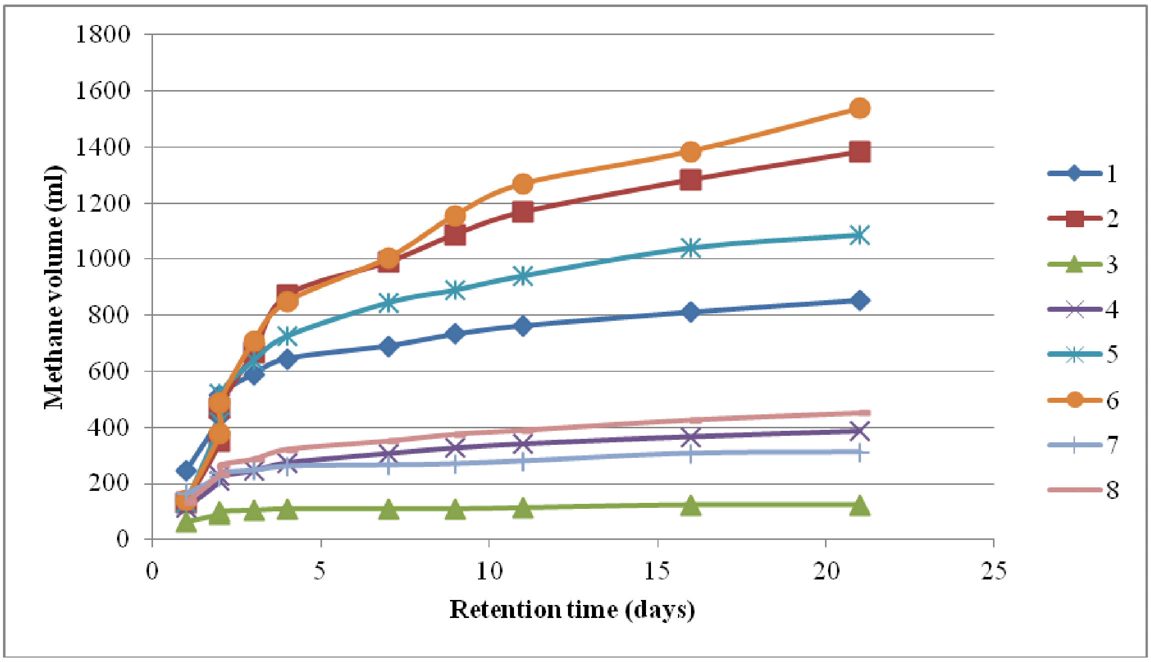


Figure 21: The cumulative methane yield over the digestion period. 1=bale 1/ no water/ not concentrated; 2= bale 1/ no water/ concentrated; 3= bale 1/ water added/ not concentrated; 4=bale 1/ water added/ not concentrated; 5= bale 2/ no water/ not concentrated; 6 = bale 2/ no water/ concentrated; 7 = bale 2/ water added/ not concentrated; 8 = bale 2/ water added/ concentrated.

The accumulation of methane over time is illustrated in Figure 21 (cumulative production). A rapid initial productivity gradually evens out.

The most productive substrates (with regard to methane) were those without added process water. The highest producer was the concentrated PF that did not contain process water. The total methane production over a 21 day hydraulic retention time is shown in Figure 22.

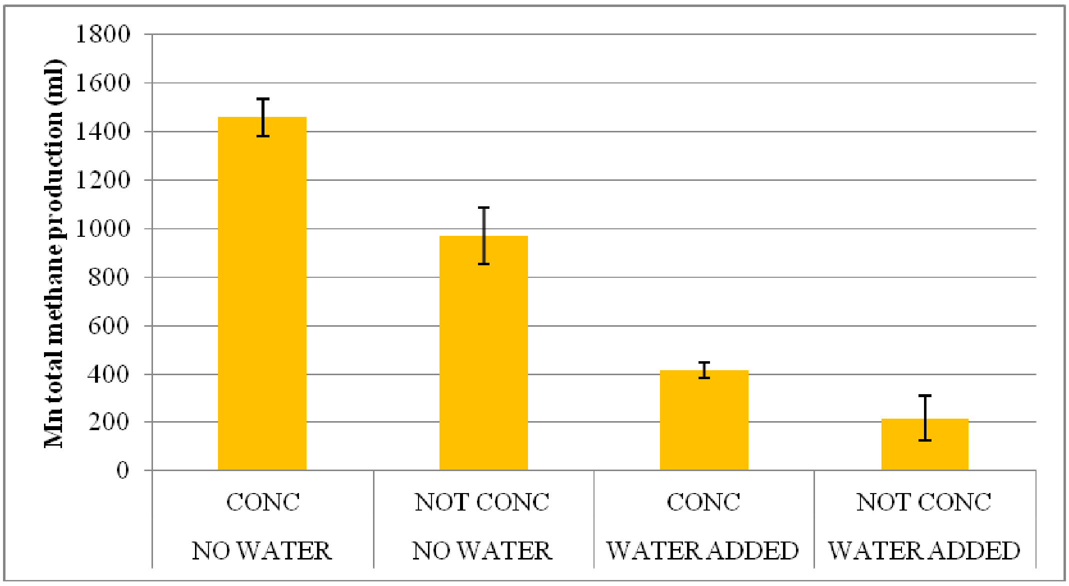


Figure 22: The impact of settling and processing with water on the total methane yield of anaerobically digested press fluid from rush silage processing following a hydraulic retention time of 21 days. Figures used are means from two bales. CONC = concentrated by settling; NOT CONC = homogenised fluid; NO WATER = no water added during pressing; NO WATER = no water added during pressing. Error bars represent standard error of the mean.

Adding water has a highly significant negative impact upon the methane productivity (p = <0.001). Concentrating the press fluid had a significant positive influence on methane yield (p=0.016).

3.2.4 Conclusions

The large standard error of the mean VS of the not concentrated/ no water added sample shown in Figure 20 may explain the anomaly with regard to the hierarchy of productivity and VS composition (Figure 22 and Figure 20 respectively).

The addition of process water was the most significant influence on methane yield. The concentration of press fluids was also significant. The concentrated press fluids that did not contain process water produced on average seven times that produced by press fluid containing process water and left un-concentrated.

The implications of this study are that by concentrating the press fluids with simple settling tanks and avoiding the use of added process water the AD reactor size can be reduced significantly whilst potentially the methane yield can be increased compared to the reactor size required in a system that employs water washing and does not concentrate the fluid.

Part one of this research report concluded that mineral extraction was not effected significantly by the addition of process water. Therefore maximising methane yields by concentrating PF and avoiding the use of process water will not impact significantly upon the demineralisation of the silage during pressing.

3.3 Harvesting operations using Softrak cut and collect system and looking at the potential to bale the loose biomass using standard agricultural machinery

3.3.1 Hypothesis/aims

To undertake harvesting operations to produce data for the LCA as well as looking at how the loose uninformed in length material produced when using a flail mower can be processed into a standard round silage bale with regards to the development and refinement of the Sledge cableway system.

3.3.2 Methodology

Three areas of *Juncus effuses* dominant swards located at Insh Marshes were harvested using a Softrak fitted with a front mounted flail and $6m^3$ rear collection bin. The harvesting took place between 14/10/2014 and 24/11/2014. The Dell of Killiehuntly site allowed for the biomass to be transported internally to the processing plant and Invertromie Meadow involved road movements. Harvesting took place in all weather conditions.

Figure 23: Softrak harvesting in standing water at Invertromie Meadow

The harvested material was extracted to an area which could withstand numerous vehicle movements and the piles were left in situ for up to five days before been processed.

Figure 24: Baling area adjacent to the harvesting site

On the days of baling operations artificial windrows were created using a skid steer with front mounted loading grapple.

Figure 25: Artificial windrows created ready to be baled

These were then converted into bales using a Valtra tractor and a Mchale baler, the bales were then wrapped on the same day ready for storage.

Figure 26: Baling and wrapping harvested biomass at the Dell of Killiehuntly

3.3.3 Results

The following tables show the data recorded for each of the harvesting operations undertaken.

Table 4: Harvesting and baling operations Dell of Killiehuntly – Compt A

Location: Dell of killiehuntly – Compt A	**Start Date:** 14 10 2013	**Completion Date:** 16 10 2013	**Total Area Harvested (ha): 0.74**
Extraction Distance: 804 metres	**Cutting Time per Load:** 20min	**Extraction Time per Load (return):** 20min	**Bale Id:** Silver Tape – D/A

Cutting

Date	Weather	No of Loads	Biomass m^3/day	Fuel Used (ltrs)	M/C (%)	Comments
14 10 2013	Dry all day with moderate SW wind	9	54	36	70	
15 10 2013	Dry all day with moderate SW wind	9	54	36	70	
16 10 2013	Dry all day				70	12 bales made/12 bales wrapped (2 pm – 5 pm)
	TOTAL	**18**	**108**	**72**		

Baling (Tractor HP – 100 running at 1500 rpm)

Date	No of Bales	Total Time (4 mins/bale)	M/C (%)
16 10 2013	12	48	70
TOTAL	**12**	**48**	

Wrapping (Tractor HP – 60 running at 1500 rpm)

Date	No of Bales	Total Time (1.5mins/bale)	No of Wraps (2) 1 wrap = 12.5m
16 10 2013	12	18	300
TOTAL	**12**	**18**	**300**

Bale Transportation (Tractor HP – 100)

Date	Extraction Distance to Processing Plant (m)	Extraction Time per Load Including Loading & Unloading (mins)	No of bales per load	No of return trips made
09 12 2013	200	35	.12	1

Table 5: Harvesting and baling Operations dell of Killiehuntly - Compt B

Location: Dell of killiehuntly – Compt B	**Start Date:** 24 10 2013	**Completion Date:** 03 10 2013	**Total Area Harvested (ha): 2.08**
Extraction Distance: 804 metres	**Cutting Time per Load:** 20min	**Extraction Time per Load (return):** 20min	**Bale Id:** Silver Tape – D/B (D/B/T)

Cutting

Date	Weather	No of Loads	Biomass m^3/day	Fuel Used (ltrs)	M/C (%)	Comments
24 10 2013	Dry all day with moderate SW wind	7	56	28	70	
25 10 2013	Light rain showers all morning with SW moderate wind	11	88	44	70	4 bales made (4 pm onwards)
26 10 2013	Rain overnight wet vegetation up to 1pm, sunny intervals drying SW wind 1pm onwards	2	16	8	70	15 bales made/19 bales wrapped (2 pm – 5 pm)
29 10 2013	Sunny intervals with strong SW wind	12	72	48	70	Softrak fitted with 6 m^3 bin
30 10 2013	Overcast with strong SW wind, light rain 3pm onwards	12	72	48	70	6 bales made and wrapped
31 10 2013	Heavy rain 9am to 5pm	-	-	-	-	17 loads remain unprotected at balling point
03 11 2013	Dry all day	-	-	-	70	12 bales made/12 bales wrapped (3pm-5pm)
	TOTAL	**44**	**304**	**176**		

Baling (Tractor HP – 100 running at 1500 rpm)

Date	No of Bales	Total Time (4 mins/bale)	M/C (%)
25 10 2013	4	16	70
26 10 2013	15	60	70
30 10 2013	6	24	70
03 11 2013	12	48	70
TOTAL	**37**	**148**	

Wrapping (Tractor HP – 60 running at 1500 rpm)

Date	No of Bales	Total Time (1.5mins/bale)	No of Wraps (2) 1 wrap = 12.5m
26 10 2013	19	28.5	475
30 10 2013	6	9	150
03 10 2013	12	18	300
TOTAL	**37**	**55.5**	**925**

Bale Transportation (Tractor HP – 100)

Date	Extraction Distance to Processing plant (m)	Extraction Time per Load Including Loading & Unloading (mins)	No of bales per load	No of return trips made
09 12 2013	200	35	12	3

Table 6: Harvesting and baling operations Invertromie Meadow

Location: Invertromie Meadow	**Start Date:** 10 11 2013	**Completion Date:** 24 11 2013	**Total Area Harvested (ha): 6.795**
Extraction Distance: 225 metres	**Cutting Time per Load:** 14 mins	**Extraction Time per Load (return):** 6 mins	**Bale Id:** Unmarked (Silver Tape – I/T)

Cutting

Date	Weather	No of Loads	Biomass m^3/day	Fuel Used (ltrs)	M/C (%)	Comments
10 11 2013	Rain overnight wet vegetation strong SW wind 2 pm onwards	15	90	45		
11 112013	Wet material drizzle all day	14	84	42		
15 11 2013	Dry vegetation strong SW wind	15	90	45		
17 11 2013	Vegetation frosted -3 thawed by 11am calm	7	42	21	70	Baled & wrapped all cut material
18 11 2013	Rain overnight saturated vegetation strong SW 12pm onwards	14	84	42		
19 11 2013	Dusting of snow -5 frozen vegetation up to 1pm	15	90	45		
21 11 2013	Cold and sunny dry material	8	48	24	70	Baled and wrapped all cut vegetation
22 11 2013	Cold and sunny dry material	15	90	45		
23 11 2013	Cold and sunny dry material	15	90	45		
24 11 2013	Cold and sunny dry material	6	36	18	70	Baled and wrapped all cut vegetation
	TOTAL	**124**	**744**	**372**		

Baling (Tractor HP – 100 running at 1500 rpm)

Date	No of Bales	Total Time (4 mins/bale)	M/C (%)
17 11 2013	34	136	70
21 11 2013	24	96	70
24 11 2013	25	100	70
TOTAL	**83**	**332**	

Wrapping (Tractor HP – 60 running at 1500 rpm)

Date	No of Bales	Total Time (1.5mins/bale)	No of Wraps (2) 1 wrap = 12.5m
17 11 2013	34	51	850
21 11 2013	24	36	600
24 11 2013	25	37.5	625
TOTAL	**83**	**111**	**2,075**

Bale Transportation (Tractor HP – 100)

Date	Extraction Distance to Processing Plant (m)	Extraction Time per Load Including Loading & Unloading (mins)	No of bales per load	No of return trips made
12 12 2013	2.3 miles	60	12	7

3.3.4 Conclusions

It was shown that *Juncus* type material cut using a forage harvester which produces very random lengths of cut vegetation from fine particles up to 150mm can be successfully baled. The bales that were formed were of high density weighing between 750kg to 800kg.

It may be more advantageous when transporting the bales by road to undertake the wrapping at the processing area. To achieve the maximum carrying capacity of the tractor and trailer the bales had to be stacked this made loading and unloading of the wrapped bales quite time consuming as care had to be taken not to damage the plastic wrap. On more than one occasion achieving a full load was not practical using this method.

Harvesting was undertaken in most weather conditions and on a number of occasions the piles at the baling areas were left for long periods before baling there were no signs that they were starting to decompose and had very little heat in them if any, though this could be due to the time of year that the works were undertaken. We also noticed that it made little difference to the moisture content this remained stable at 70%.

Considering the Dell of Killiehuntly site compartments A and B. They both involved an extraction distance to the baling area of 800m which meant the Softrak was spending as much time removing the material as it took to cut it. By implementing the sledge cableway into the system both these areas could have been cut in half the time. The effect extraction distance can have on output is clear to see if we compare Invertromie Meadow with compartment B, looking at the total m^3 produced from both sites Invertromie Meadow produced twice the amount in a similar amount of days it should also be noted that this site had a lower yield per hectare of biomass compared to compartment B.

3.4 Trials to improve the productivity of removing baled reed from wetland sites

3.4.1 Hypothesis/aims

To undertake harvesting operations to provide data for the LCA. Develop and trial a new harvesting process for transporting baled reed.

3.4.2 Methodology

The Tay reed bed near Perth in Scotland is Britain's largest reed bed. The reed bed is divided into a number of separate areas each one been only accessible at one particular point and involves extracting material over distances further than a 1000m. Reed harvesting can only be undertaken from December to the end of March so time is also critical especially when you also have to consider that harvesting can only be carried out on dry days.

We had already developed and trialled our Softrak baling system though its carrying capacity of only two bales, figure 27, meant that further development would be needed.

Figure 27: Prototype reed cutter binder developed by Loglogic with AMW's baler and rear extension platform

This led us to design and build the sledge a cost effective system which greatly increases the carrying capacity.

Figure 28: The sledge having just been completed

The sledge is made out of aluminium, weighs 480 kg and is 4,500 mm in length and 2,400 mm wide. When fully loaded with five reed bales weighing approximately 300kg each the ground pressure is 0.2 psi. It is simply to the connected to the Softrak using wire strops. At the rear is a door which is sealed to stop water from entering when working on really wet sites, this also allows the Softrak to drive into the sledge which greatly reduces the size of transport required when moving the whole system between sites. On the bottom of the sledge is a removable hard wearing plastic protection plate to prevent damage to the 6 mm aluminium floor. Lifting eyes are also located at each corner.

Figure 29: The sledge fully loaded with five bales

Even though the Tay site comprises two thousand acres of reedbed the areas that require cutting are often quite small, making it impracticable to harvest the reed while towing the sledge so it's often left close by to the block been harvested. When a bale is complete the Softrak reverses up to it and the bale is unloaded.

3.4.3 Conclusions

A site visit was undertaken by Scottish Natural Heritage on the 19th of March 2014 to assess the impact this harvesting system had on the reed bed, it met with their approval as they felt it had little impact on the reedbed.

Using this system it is possible to extract six bales at a time if counter weights were added to the front of the Softrak then seven bales would be possible as one could be carried on the baler extension platform. Further increase in productivity could be achieved by using two Softraks and two sledges, one machine would continually harvest the reed the other continually transport the reed from the site.

3.5 Harvesting operations and storage of common reed

3.5.1 Hypothesis/aims
To undertake harvesting operations using a Softrak fitted with forage harvester and onsite storage using a portable bagging system to produce data for the LCA.

3.5.2 Methodology
Two sites, Seaside and Powgavie, of common reed dominant swards located at the Tay reedbed were harvested using a Softrak fitted with a front mounted flail and 8m^3 rear collection bin. The harvesting took place between 06/01/2015 and 14/02/2015. Both sites allowed for the biomass to be transported internally to the temporary storage area. Harvesting took place in dry weather conditions.

Figure 30: Softrak travelling along extraction route adjacent to block no 5 at the Powgavie site

The harvested material was then extracted to the temporary storage area where it was unloaded. At the end of each day the loose material was then put into the bag via a bagging machine, which the shredded material is loaded into.

Figure 31: The storage area located within the reedbed site

3.5.3 Results
The following tables show the data recorded for the harvesting and bagging operations.

Harvesting operations

Table 7: Annual Wetland Management Requirements (for demonstration)

Habitat type	Vegetation	Area hectares	Time of cut	Management history
Reedbed	Common reed	15	January & February	Cutting over part of area

Table 8: Areas harvested

Site	% of area	Area cut	No of days	Number of Loads ($8m^3$)	Total m^3	m^3 per ha
Powgavie	30%	6ha	8	52	416	69
Seaside	50%	9ha	18	96	768	85
Total	100%	15ha	26	148	1,184	

Table 9: Bagging operations

Site	m^3	m^3 per hour	No of hours	m3 per bag	No of bags
Powgavie	416	52	8	208	2
Seaside	768	52	14.7	208	3.6

Note
(a) Bag used was 1.5m in diameter and 120m in length

3.5.4 Conclusions

Reed harvesting with the Softrak and JF Stoll forage harvester presented very little problems, it cut and collected the material very effectively. The robust nature of the cutter meant that when foreign objects were encountered as was often the case on the reedbed due to its tidal nature they would not cause major damage to the cutting head. The brittle nature of the material harvested meant that the chop size was much reduced.

The maximum chop length recorded was 125mm with the smallest particles been 2mm with the remainder typically between lengths of 70-80mm. For the production of char this does not particularly create any issues however if the material were to be briquetted further processing would be required to achieve a uniform chop length.

The reed harvested was 1 year old however there were 5 compartments at Seaside that were not cut in 2014 resulting in two years of growth, which explains the variance in m^3 between the two sites. Therefore it can be assumed that a volume of $69m^3$ per ha would be achieved year on year.

The moisture content of the material was recorded at 16% and the average weight per cubic metre was 80kg therefore equating this to the figures harvested per hectare a yield of 5.5 tonnes was achieved.

The AgBag system overcomes a number of obstacles related to storage, it is relatively inexpensive and simple to set up, although it does need to operate on solid ground. Planning permission is not required as the system is not a permanent structure and in most situations it can be located adjacent to the harvesting/conversion site. The low-density polyethylene (LDPE) bags can be up to 3m in diameter and 150m in length. At these dimensions an Agbag can store over a 1000m^3 of material this will depend on the size of the chopped material and how tightly it is packed into the bag.

3.6 Processing of rush and reed into char

3.6.1 Hypothesis/aims

The AMW/IBERS process for wet crop is based on press separation of a water fraction for A/D processing and a fibre fraction, a press cake, for briquette manufacture. For the dry crops and press cake fuel briquette incorporation is possible once moisture has been reduced below 15% by drying. By processing some of these materials to char a higher briquette CV can be obtained.

Carbon Gold received from AMW two samples of harvested material; rush, baled in Somerset, and reed cleaned and wrapped from Scotland and more recently a sample of the press cake. A sample of typical Timberwolf chip was also produced to test as fuel.

Carbon Gold had available a development version of the 'Mk II' kiln and this was used for several charring runs with the two harvested materials. The press cake will be processed when the kiln is operational again in April 2014.

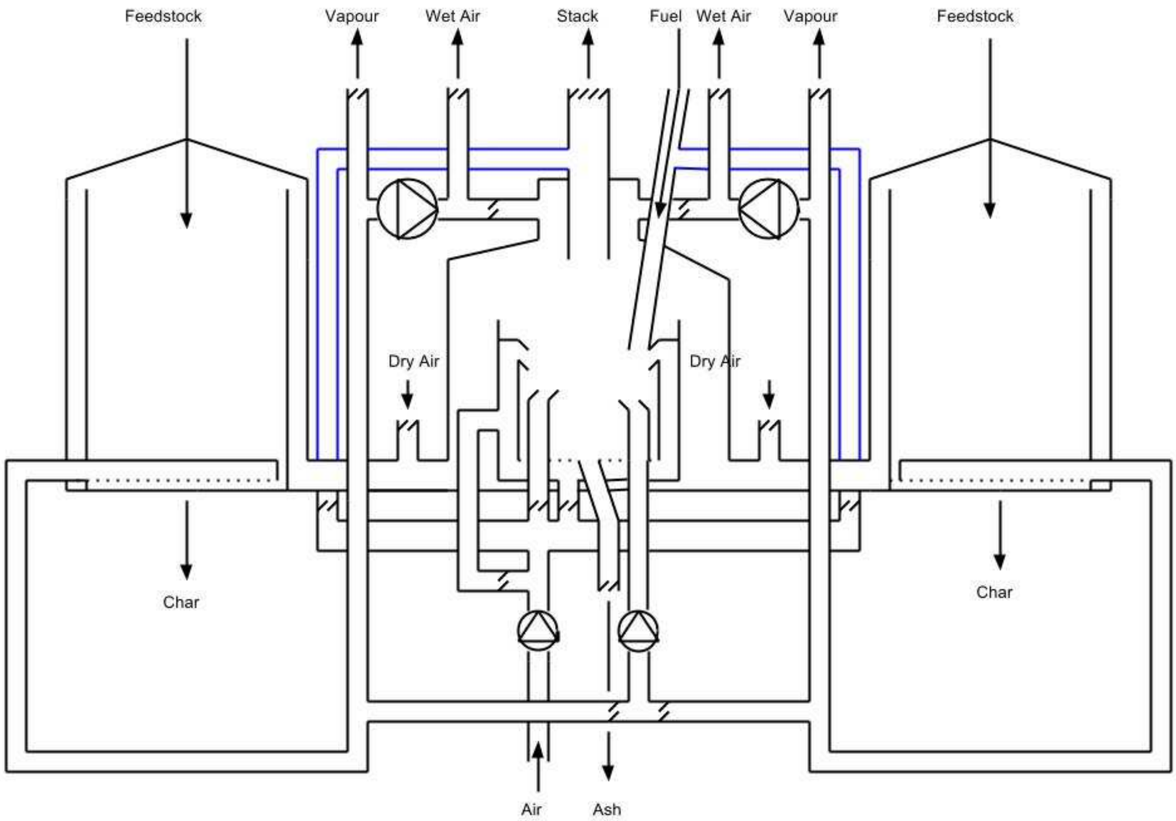


Figure 32: The kiln that will be supplied to AMW is generally in a 'Mk III' configuration with two kilns and a single combustor

This offers a greater degree of flexibility in application than is possible with the Mk II. This includes :

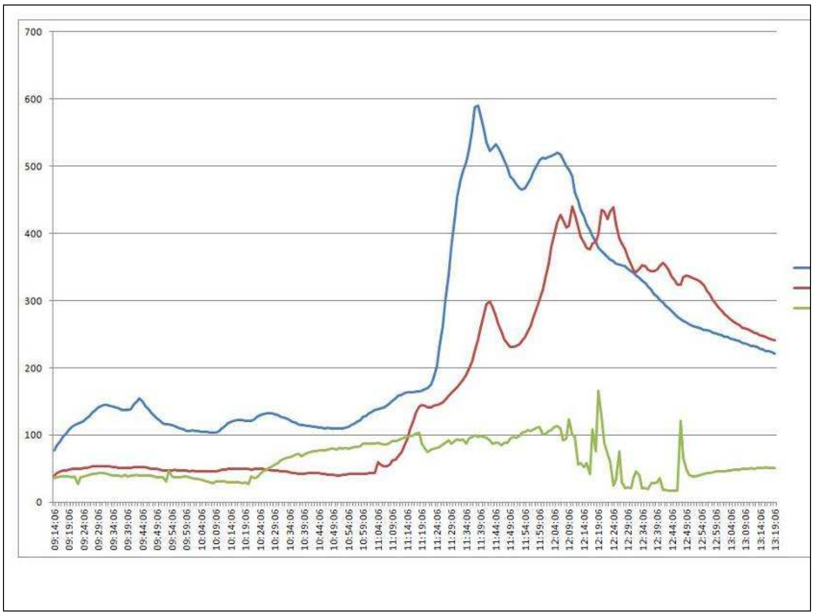
- Drying - heat generated in the combustor is used for removing moisture in both kilns.
- Single Charring - where char is produced in one kiln and the other is used for drying.
- Double Charring - where both kilns produce char alternatively.

Materials that can be successfully charred normally have a high content of woody material. Leafy materials have a low proportion of fixed carbon and generally form limited and brittle chars, typically as a by-product of combustion. It was not known how the rush and reed materials would respond under the pyrolysis conditions of the Mk II/Mk III kilns.

Figure 33: The kiln used for the char trials

3.6.2 Methodology

In the Mk II wood is used to fuel the combustor and after the moisture has been removed from the feedstock the temperature is elevated into the pyrolysis zone and the resulting gases burnt. Temperature is monitored in the top and bottom of the kiln. When the bottom temperature exceeds 400'C the material is generally charred.

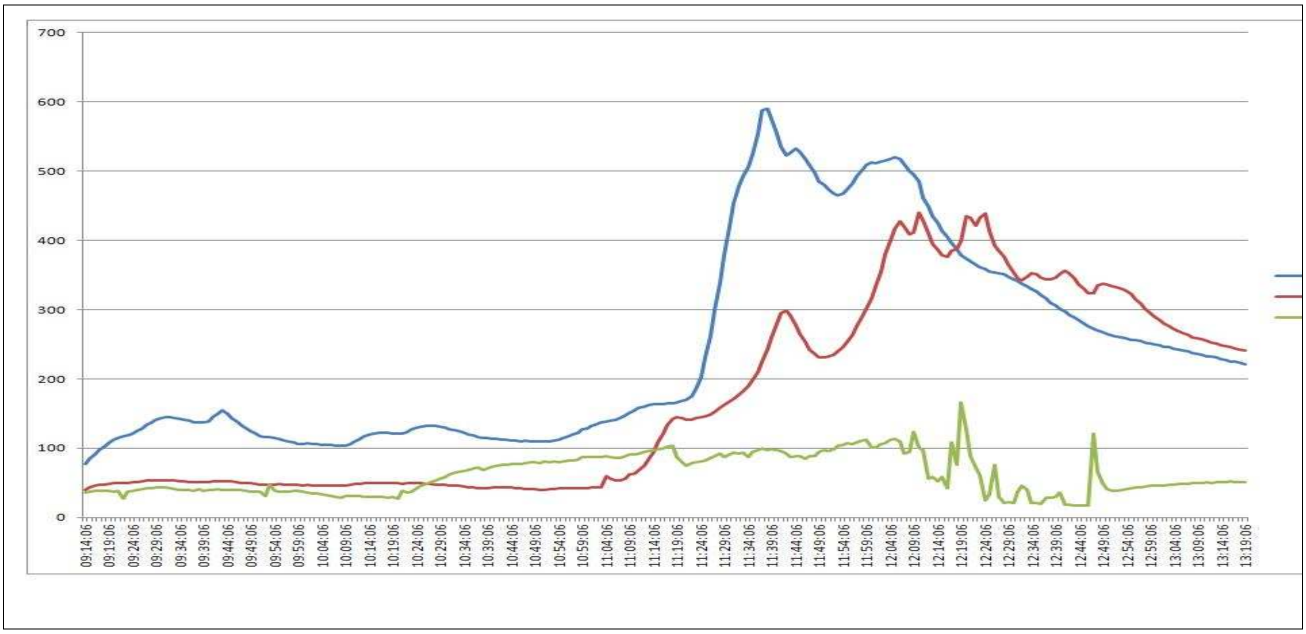


T1 = top temperature

T2 = bottom temperature

T3 = recycle temperature

Figure 34: The profile obtained with rush



T1 = top temperature
T2 = bottom temperature
T3 = recycle temperature

Figure 35: The profile obtained with reed

3.6.3 Conclusion

While it is known that straw type materials will form char. The vapour drying used at the start of the process causes the rush to slacken and mat as shown in figure 36:

Figure 36a: Effects of vapour drying of rush **Figure 36b:** The char that was formed

The reed was cut to length to measure density and formed good quality char:

Figure 37a: Measuring the density of reed

Figure 37b: Reed char

In removing the char from the kiln it is crushed and samples of the 2 chars are shown here.

Figure 38a: Rush char

Figure 38b: Reed char

The measured densities and moistures of materials were:

- Rush 50kg/m3 @ 33%
- Reed 100kg/m3 @ 15%
- Press cake 145kg/m3 @ 45%
- Wood chip 285kg/m3 @ 37%

In bale form the density of rush is approximately 350kg/m^3. In one charring run the rush was compressed towards 200kg/m^3, but this leads to a poor result as drying/charring are uneven. Press cake is small quantities can be as light as 50kg/m^3, but tends towards 200kg/m^3 in large bags. None of these materials shrinks significantly on air drying.

3.5.4 Conclusions

It was a surprise to see how easily rush charred. This introduces the possibility that char for briquette inclusion can be manufactured from all of the available materials. It is possible that wood chip be excluded from the briquette formulation in favour of char from rush and reed. Kiln operations in the field, and fixed, locations can be fuelled by dried wood chip and, as a consequence, have the potential to be automated. It may be possible to load the kiln with complete bales of rush if ways can be found of 'relaxing' the bale to take up the available kiln volume.

3.7 Kiln drying of press cake

3.7.1 Hypothesis/aims

To understand the drying characteristics of press cake and produce press cake that is suitable for briquette manufacture.

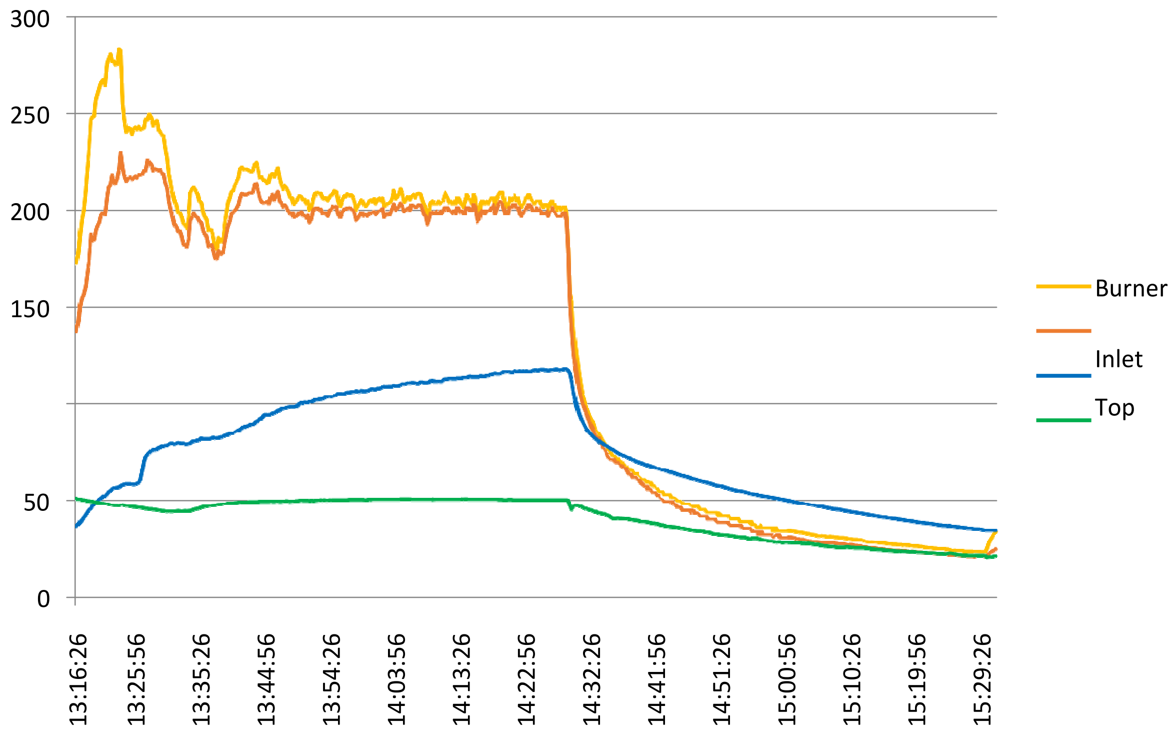
3.7.2 Methodology

The kiln for charring biomass can also be used for drying and has the capacity to dry 12m^3 of material. The kiln works as a steam drier using re-circulated vapour. Heated vapour spirals up the outside of the kiln and then is drawn down through the material to initiate drying in the kiln, this air is then extracted at the bottom of the kiln through a pipe. Surplus vapour is released at this stage and the remaining extracted vapour is reheated, by direct mixing in the combustor with hot combustion gasses and recirculated.

The kiln was loaded up on both sides with press cake using a bucket loader. The material had sat (covered) for some time so was partially composted (warm), and compacted. It was partly broken up as it fell into the kiln, and although relatively 'light' it was not particularly porous.

It was estimated that the material had a wet density of – 150kg/m3 and was approximately one third (300kg) solids and two thirds (600kg) moisture. This would give a drying time of approximately six hours – significantly more if the cake was heavier.

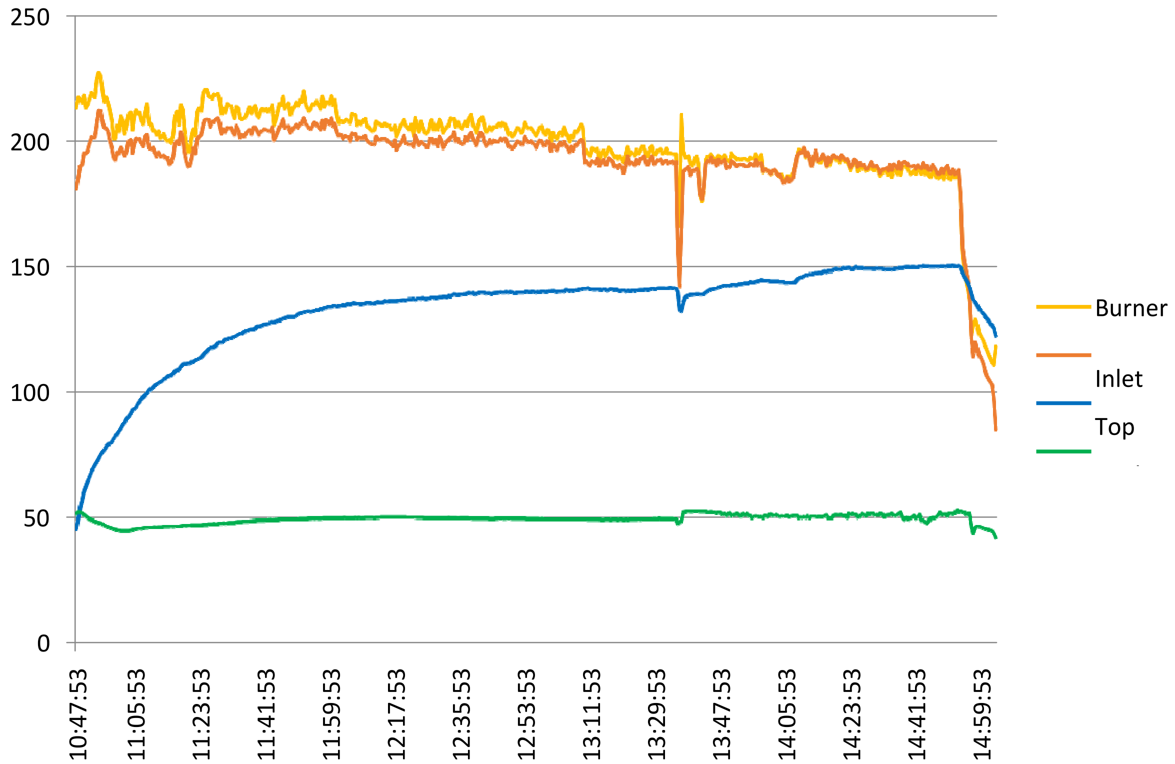
The burner was set to run at 150 kW on pellets, but this gave high inlet temperatures and the heat rate was reduced early on to 135 kW, and maintained at this level from 2:15pm:



Allowing for a one-hour warm up the material was drying in the right hand kiln for approximately one and a half hours, during the trial. The drying was stopped early to address some equipment problems - specifically the lack of inverter drive on the left hand kiln.

The drying was continued on the second trial day. The heat input was maintained at 135 kW, but was reduced I hour in at around 1pm to 120 kW to keep the inlet temperature below 200'C, as the press cake moisture reduces.

At 3.30pm the heat rate was reduced to 112.5kW. At 4:15pm the heat was increased back to 120kW by increasing the recycle fan rate from 50 Hz to 57.5 Hz (5.2 A), lowering inlet temperature, so the recirculation rate was reduced slightly at 5:15pm by opening the fan exhaust to atmosphere.
At 6:30pm the press cake was close to the drying endpoint :



The kiln was then shut down quickly, which probably did not give sufficient cooling time, and resulted in a small pyrolysis fire developing by the next morning, for safety reasons due to high winds the kiln was opened 3 days later some of the dried press cake was lost. When tested the moisture content was 15% with a drying time of eight hours.

3.7.3 Conclusions

Further testing is still required and the preferred method of operation would be to load the press cake directly from the screw press as this would avoid compaction issues, it is felt that this would reduce the drying time down to six hours.

Capacity issues have now been addressed as the original design of the kiln only allowed the system to produce 800kg of press cake suitable for briquetting per run and required supervision. The kiln now has an auto mode feature which allows for unsupervised operation so for example it could be loaded at the end of the day and left to run overnight.

To further increase the whole systems drying capacity the kiln has been adapted to allow for external use of combustor heat to supply additional drying units as discussed in section 3.8.

3.8 Press cake drying using the AgBag system

3.8.1 Hypothesis/aims

To understand the loading and drying characteristics of press cake when using the AgBag drying system.

It is important to consider the structure of the press cake as when the rush exits the screw press its particle size has been greatly reduced and the high moisture content typically at 55%.

Figure 39: Press cake particle size

3.8.2 Methodology

A CG96 bagger was used which has the capability of incorporating a plastic perforated pipe into the bottom of the bag which runs the length of the pod. Press cake totaling 14m^3 was loaded into a AgBag 10 meters in length and 1.5 meters in diameter. The braking system on both the bagger and the tractor were disengaged this avoids compaction of the press cake occurring in the bag which aids air circulation through the material.

Figure 40a: Bagger with pipes installed

Figure 40b: Loading of press cake into bagger

The bottom pipe was then connected to a 1.5kW fan which circulates ambient air throughout the bag this was operated for 10 days at 8 hours per day during the month of March. At the end of each day the fan was reversed and all the air removed.

Figure 41a 1.5kW fan used to circulate air **Figure 41b:** Fan reversed and air drawn out at night

3.8.3 Conclusions

For most part the press cake did maintain its structure when loaded into the bag this was further confirmed when the fan was started and did not stall and the bag filled with air a very good indicator that air was passing through the material.

At the end of the trial the bag was opened and the moisture content of the material was tested throughout the length of the bag, an average moisture content of 45% was recorded which would mean a moisture loss of 1% per day. However some material had through the bagging process formed into large compacted clumps in the case of these very little drying had taken place.

Figure 42a: Compacted press cake **Figure 42b:** Pipe configuration inside of bag

Such material compaction could be avoided by adding in material with more structure for example wood chip this would also aid circulation.

AB Systems, (AgBag suppliers) suggested that running on sunny days blowing from midday to 4pm would achieve a moisture loss per day of 5%. This could be further increased by blowing hot air into the bag through a top pipe inserted into the bag, shown in figure 42b, and sucking this through the material via the bottom pipe. This air could be drawn from either the AD system or the kiln.

3.9 Briquetting trials

3.9.1 Hypothesis/aims

To find an achievable output from briquetting mixed materials including press cake wood chip and char, and the energy consumption per tonne of briquettes produced.

To look at the briquetting characteristics when trying to form such types of materials into a final saleable end product and finally understand weight comparisons when compared to other similar fuels.

3.9.2 Methodology

The briquetter that was used was a Biomasser mini mobile, type MDM3 (manufactured by ASKET in Poland). The material was loaded into the central hopper which uniformly distributes the material to the three briquetting presses, allowing for simultaneous operation. The briquettes are formed by passing the biomass through a heated chamber fitted with a screw auger they then travel along a guide rail which allows the briquettes to degas and stabilize. In order to obtain the required briquette density, weights fitted onto the guide rails can be adjusted.

Figure 43: Mobile briquetter with a throughput of 3,000kg per day

It is recommended that the moisture content is below 30%, however for the purpose of the trial the following moisture contents were recorded,

- Press cake 15%
- Wood chip 15%
- Char 5%

Two briquetting runs were undertaken the first using 100% press cake and the second a briquette mixture comprising 65% press cake, 25% wood chip & 10% char approximately.

3.9.3 Conclusions

The trials undertaken with briquetting press cake only were very successful. The material briquetted well due to the fibre length created through the pressing procedure. The briquettes were easily produced through the system and very little adjustment had to be made to the briquetter's controls. The briquettes produced were consistent and compact.

Figure 44: The final end briquette product

The trials undertaking the briquetting of press cake, wood chip & char mixture were not as successful. It proved quite difficult to produce a consistent product. Although the mix compacted well on most occasions producing a final briquette with similar characteristics to the press cake briquettes, there were instances during the processing where briquettes were produced that were unstable and flaky. From observations this appeared to be due to a higher concentration of char in that part of the mix. It should also be noted that the operator had to be far more vigilant with the press as fine adjustments were needed throughout.

Figure 45a: Cracking forming in the briquette

Figure 45b: cross section of a mixed briquette

A important factor when using this particular type of briquetter is the length of the cooling rail in this trial and for both types of briquettes the rail used was set at 4.5m. It is felt especially when trying to produce briquettes with a combination of materials that a longer length rail would be more beneficial as this may improve the briquettes stability and durability. This is due to the briquette having a longer travel time allowing the briquette to cool for longer which would produce a more solid briquette.

Table 10: Wight comparison to other similar formed briquettes

Biomass	Length (m)	Weight (kg)
Press cake	1	3
Press cake, wood chip & char	1	2.5
Reed	1	2.8
Wood shavings	1	4.5

The following table shows the average energy consumption per tonne assuming that there is no shredding required and all three presses working simultaneously.

Table 11: Average energy consumption per tonne

Biomass	kg per hour	kWh per tonne	kg per day (based on a 8 hr shift)
Press cake, wood chip & char	420	58	3,360
Press cake	360	67	2,880

When comparing the average outputs from the briquetter of the two types of briquettes it was found that the press cake throughput per press was in the region of 140kg/h where as the mixed briquettes were produced at a rate of 120kg/h. The lower output for the mixed briquette was probably due to instances where the mixture became unbalanced and the press had to be stopped and restarted again. From the trials it is clear that these materials can be successfully briquetted.

3.10 Emissions from presscake and mixed composition briquettes – a comparative trial

3.10.1 Hypothesis/aims

Domestic solid fuel burning is typically inefficient and unabated, leading to high emissions of gaseous pollutants such as carbon monoxide (CO), oxides of nitrogen (NOx) and particulate matter (PM) (Williams et al., 2012). Particulate matter emissions legislation typically refers to particles below 10 micrometers (PM10) and 2.5 micrometers (PM2.5). However, many of the particles produced are known to be below 1 µm in diameter (PM1) which are the most hazardous to health as they can pass deep into the lungs (Bølling et al., 2009). Biomass burning is also associated with high emissions of organics such as polycyclic aromatic hydrocarbons (PAH) which are known to be mutagenic and carcinogenic (Naeher et al., 2007). The fuel properties of domestic solid fuels have a profound influence on their combustion behaviour and emissions. Due to the resurgence of interest in biomass as residential energy source, a number of novel feedstocks are being considered; such as waste biomass from managed habitats. It should be noted that the Renewable Heat incentive has set emission regulations for particulate matter and NOx (RHI website, 2015) and there is interest in extending regulation in this area.

Two briquetted fuels were investigated in the current work:

- Presscake
- Mixed Briquettes (Presscake, wood chip and char)

These were compared against standard dimensioned pine logs as a baseline fuel. Fuel characterisation and analysis was outside the scope of this report and was performed elsewhere.

Figure 46. Test fuels (a) Presscake, (b) Pine.

3.9.2 Methodology

A Waterford Stanley Oisin multifuel stove was used for all fuels. The appliance is rated by the manufacturers as having a maximum non-boiler thermal output of 5.72 kW and an efficiency of 78.8%. The dimensions are 535 x 408 x 415 mm (HxWxD). There is just one (primary) air supply which is manually controlled via a damper. The general arrangement of the test equipment was based on BS EN 13240, whereby the stove was mounted on a set of scales on a trihedron, as shown in Figure 46. The unit is mounted onto a balance to determine burning rate, although this is only reliable for significant sample masses due to the influence of thermal expansion during heating.

The stove is a single combustion chamber design which is typically used for space heating and does not incorporate secondary air or other emissions control design. More advanced stoves and boilers are not generally suitable for burning briquettes of this type.
Sampling ports were installed in the flue at a height of 1.43 m. The flue is insulated as has an internal

diameter of 125 mm. Sampling was done in-stack and there was no dilution of the flue gas. The stove was mounted directly underneath a laboratory extraction system which was used to apply a continuous draught of 12 Pa which is required for the nominal heat output test in BS EN 13240.

Figure 47. Laboratory test rig.

A pre-weighed batch of 1600g of briquettes was tested on each run, with no re-loading. 30g of broken kerosene firelighters were used to ignite the fuel and no samples were taken during the first 10 minutes to allow them to burn out completely, and to allow the flames to become established. The damper was fixed at a dilation of 10 mm for all fuels to allow for comparison.

The tests were completed in duplicate. The results presented here are averages of the two runs. Due to the limited amount of runs, there has been no statistical analysis of the data, however based on past experience the estimates of error are expected to be within 10%.

Flue gas composition was measured on a wet basis using a Gasmet DX400 FTIR gas emission analyser. The capabilities of this equipment include a range of gases including O_2, CO_2, CO, NO, NO_2 and SO_2. Errors were +/-5% with minimum detection of ~5ppm. Flue gas velocity and flow rate were calculated by measuring the dynamic pressure change in the flue, using a Wöhler DC100 pressure computer and an S-type pitot tube, in accordance with BS EN ISO 16911-1.

PM_{10} and $PM_{2.5}$ was determined following a method based on USEPA Method 201a and BS ISO 25597. Briefly, in the standard methods a probe featuring a set of cyclones, pitot tube and thermocouple is inserted directly into the flue. Flue gas is drawn through a pre-selected nozzle into the cyclone separators and then through a heated probe into a set of impingers, before a dry gas meter. A schematic is shown in Figure 48.

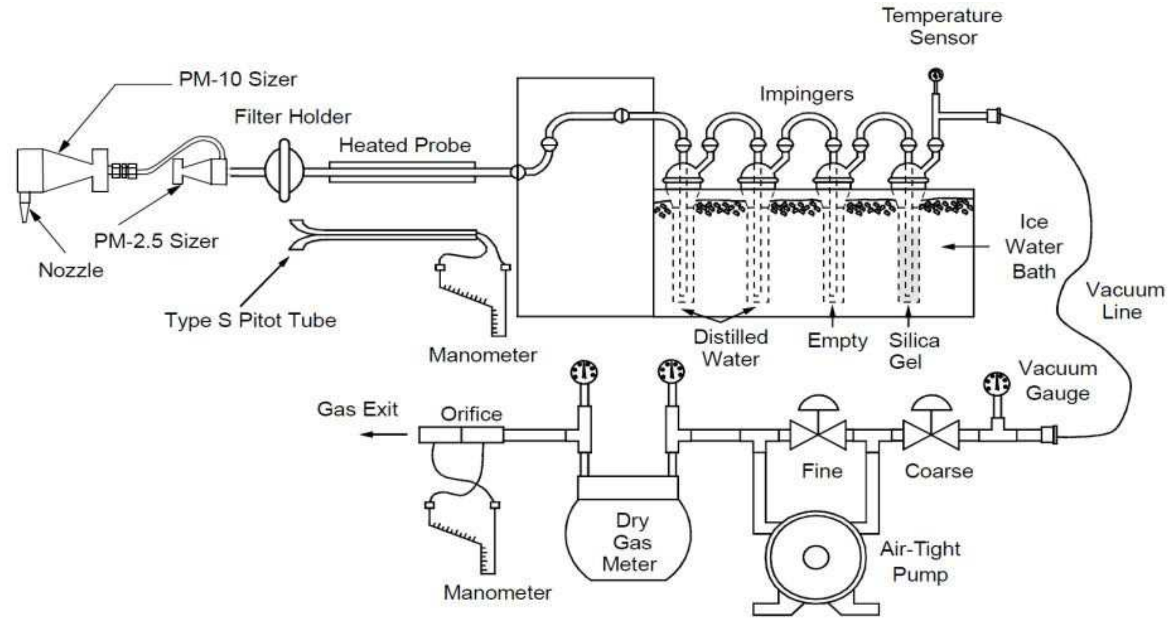


Figure 48. Schematic of the PM_{10} and $PM_{2.5}$ sampling train. Source: USEPA Method 201a.

Due to the small flue size of the test rig it was necessary to mount the cyclones externally to the flue. In the standard methods, the cyclones are inserted into the flue for a period of around 30 minutes for temperature equilibration. Due to the cyclones being mounted externally, a heated jacket and PID controller was used in lieu.

Isokinetic sampling was not required due to the low flow rate in the flue (< 1.5 m s^{-1}) and nature of fine particulate originating from stoves (Cottone and Messer, 1987). Personal communication with the equipment manufacturer (Smurthwaite, 2014) determined the sampling rate, which was fixed at 10 L min^{-1}, as required for Method 201a in order to maintain the cut point of the cyclones.

Particulate mass was determined gravimetrically by sampling onto pre-conditioned Whatman GF/F filter papers using a Richard Oliver Particulate Smokemeter. The sample was transferred to the smokementer via a heated line at 120℃ to preve nt water condensation. The filter temperature was 70℃ in accordance with recommended standard me thods (British Standard DD CEN/TS 15883:2009).

3.9.3 Results

Combustion performance

Each batch of fuel was assessed for ignitability. It was found that both of the fuels would produce good flaming combustion within 5 minutes of ignition of the firelighters.

There was little visible difference between the combustion of the two briquette types. In both cases, the flaming zone spread gradually across the samples, with a flaming phase lasting around 40 minutes, followed by a smoldering phase lasting for a further 20-30 minutes. There were few measurable emissions after a total run time of 60 minutes.

A thermal balance was outside the scope of this work, however the temperature of the stove front was monitored as an indication of the heat output for each fuel. The temperatures across the tests are shown in Figure 49. It can be seen that the strong flaming combustion corresponding to higher temperatures is observed between 20 and 35 minutes for all the fuels. The temperature profiles are very similar for all the fuels also. In each case, the temperature drops as the proportion of smouldering combustion increases.

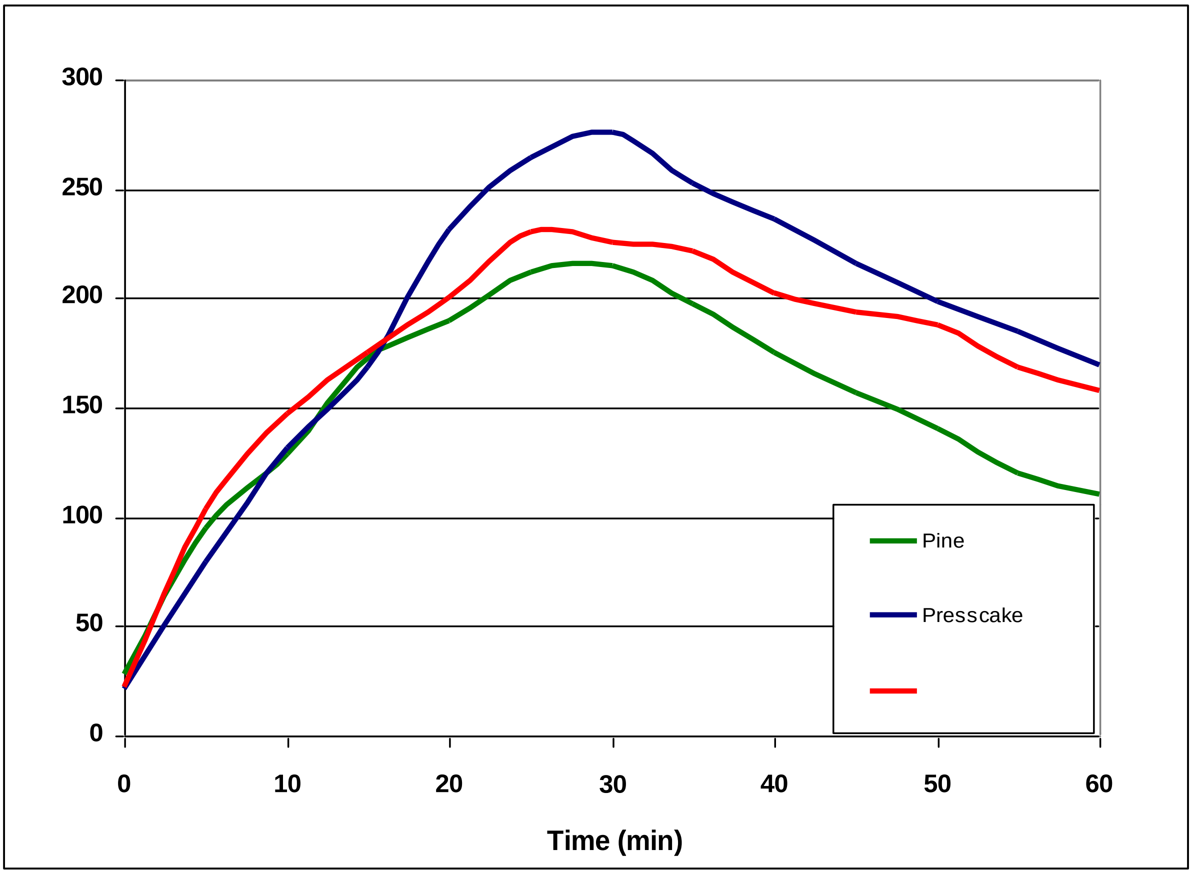


Figure 49: Variation of stove front temperature with time

The total burning time for all runs was approximately one hour, although there was some evidence that the briquettes continued to smoulder after this time, despite no visible glow. Figure 50 shows a comparison of the initial flaming combustion of the presscake and the final stages of smouldering combustion. The briquette ash maintained approximately the same size and shape as the original fuel. This was also observed with the mixed composition briquettes. It was noted that the fibrous, small particulate nature of the briquettes would have an effect of the available surface area and gaseous diffusion characteristics of the fuels in comparison to pine. The density of the briquettes would also have an impact of the burning characteristics.

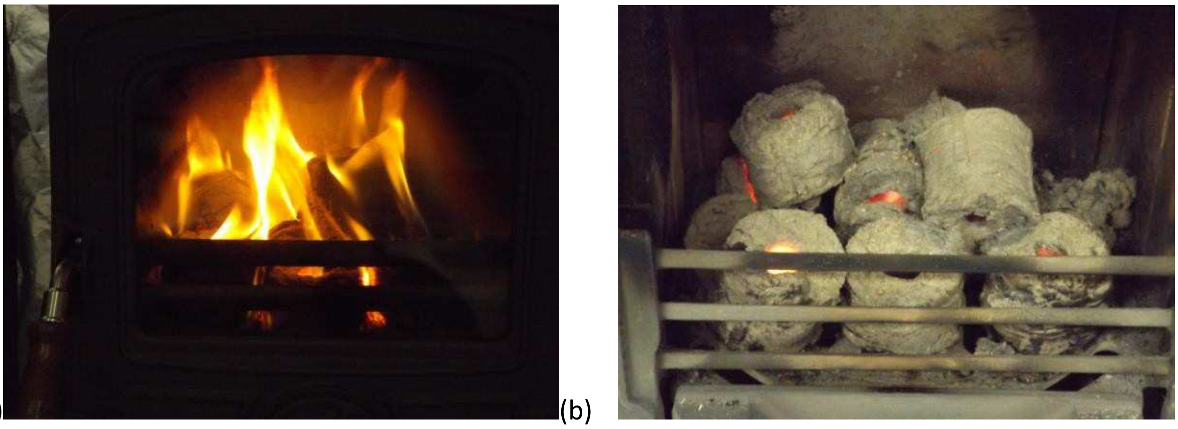
(a)  (b)

Figure 50. Presscake briquette (a) ignition, (b)smouldering combustion phase

Gaseous emissions variations

Gaseous emissions which were measured over the duration of the experiments are shown in this section. The nature of combustion causes different gases to be evolved during the initial 'flaming' part of the combustion compared to the later 'smouldering' phase of combustion.

The fluctuations in values with time are characteristic of stove combustion using large pieces of biomass as fuels, and are due to the non-uniform break up and movement of the fuels during the tests. Other combustion systems, such as continuous feed pellet boilers, would give more consistent and steady emissions due to the constant re-fuelling.

Carbon Monoxide

The carbon monoxide concentrations over the tests are shown in Figure 51. It can be seen that the briquette fuels had comparable CO compared to pine during the flaming phase, but higher emissions during the smouldering phase. Regular refuelling would maintain the flaming phase for longer due to the availability of volatile matter. The mixed composition briquettes had better performance compared to the presscake.

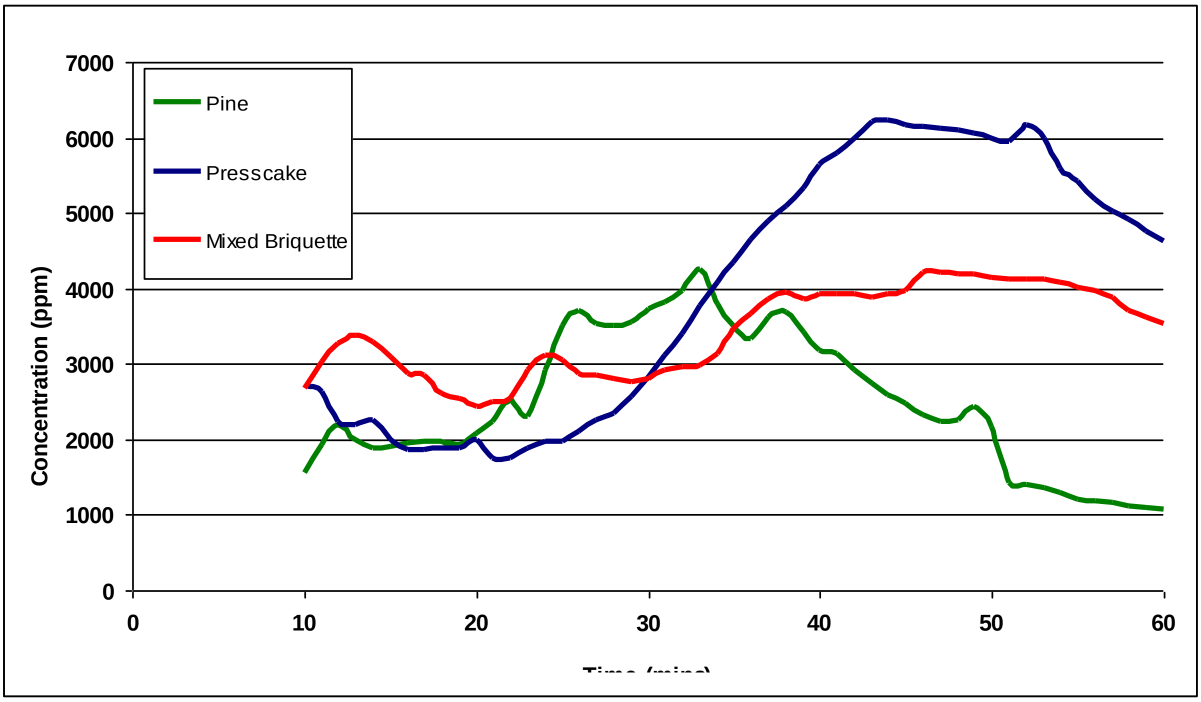


Figure 51. Variation of Carbon Monoxide with time

Nitrogen Oxides

The nitrogen oxides and total NOx values are given in Figures 49-51. It should be noted that whilst values are given for NO and NO2 separately, there are reactions occurring in the sampling system that convert between the two species, consequently the total NOx values should be quoted.

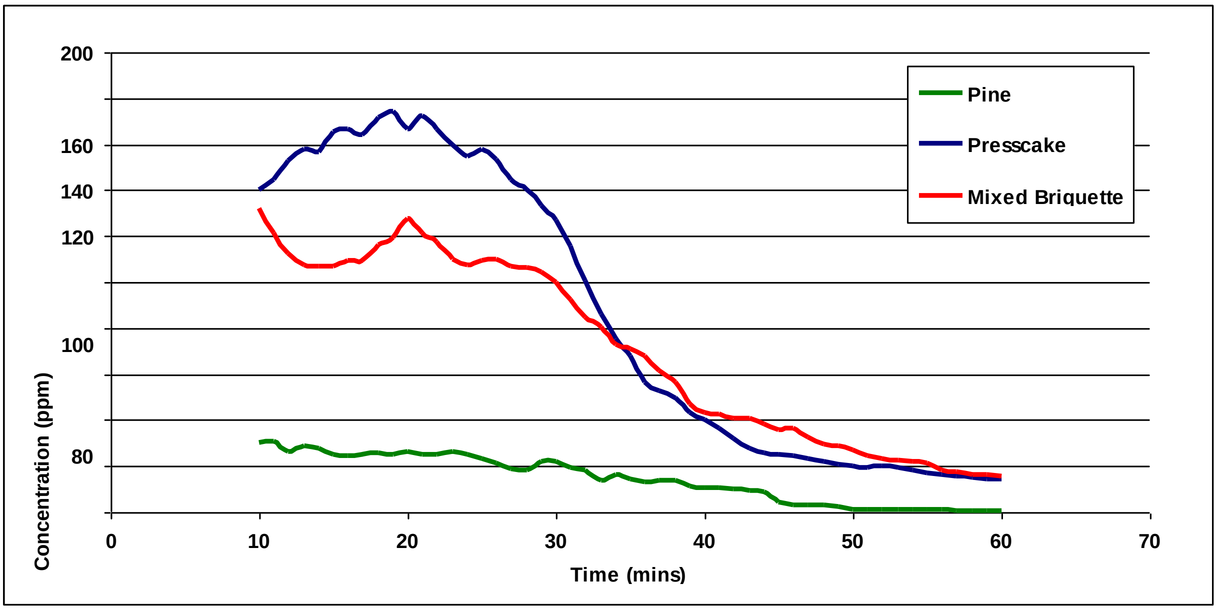


Figure 49. Variation of Nitric Oxide with time

Nitrogen Dioxide

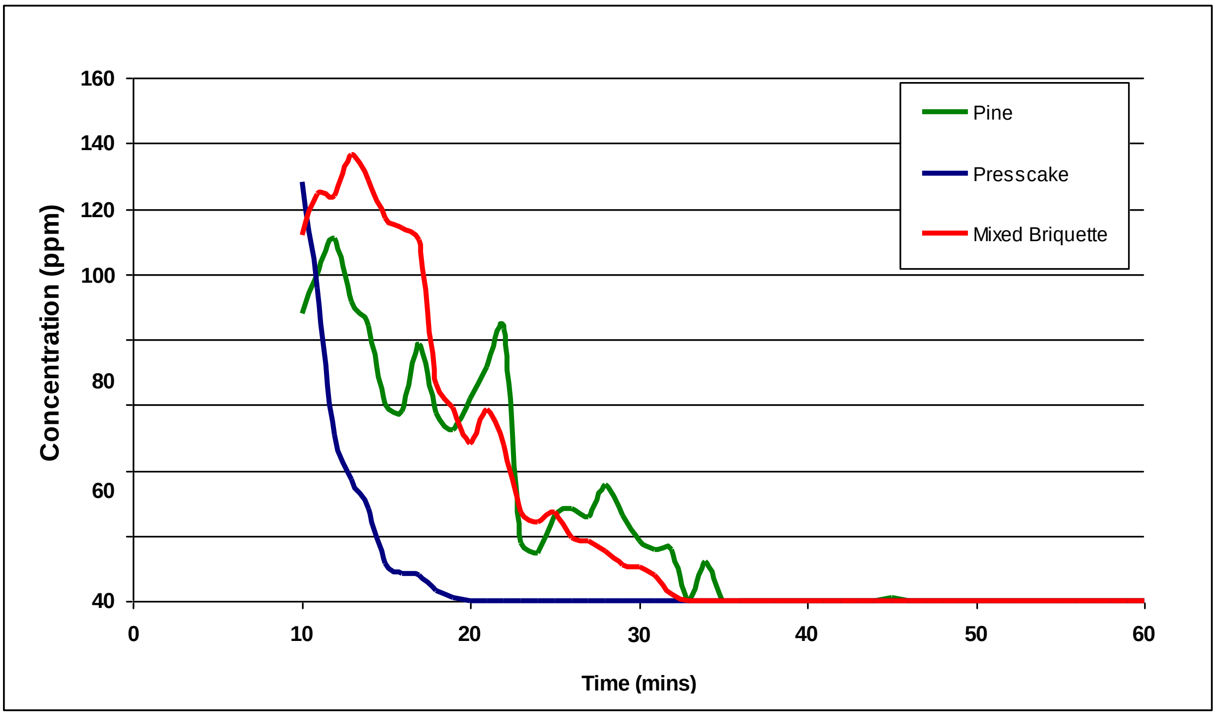


Figure 50. Variation of Nitrogen Dioxide with time

Both briquette fuels release higher NOx compared to the pine baseline, however there is little difference between the two briquette types. The peak burning rates correlate with peak temperature and so influence peak NOx emissions. Higher temperatures are associated with higher NOx. However, the NOx emissions at the relatively low temperatures in a domestic stove are mostly as fuel-NOx and so dependent on the N content of the fuel. Fuels with low nitrogen contents would be expected to have lower NOx emissions. It is therefore recommended that the results are correlated against the ultimate analysis of these fuels in order to see whether the fuel nitrogen could be responsible for the higher total NOx.

Total NOx Emissions

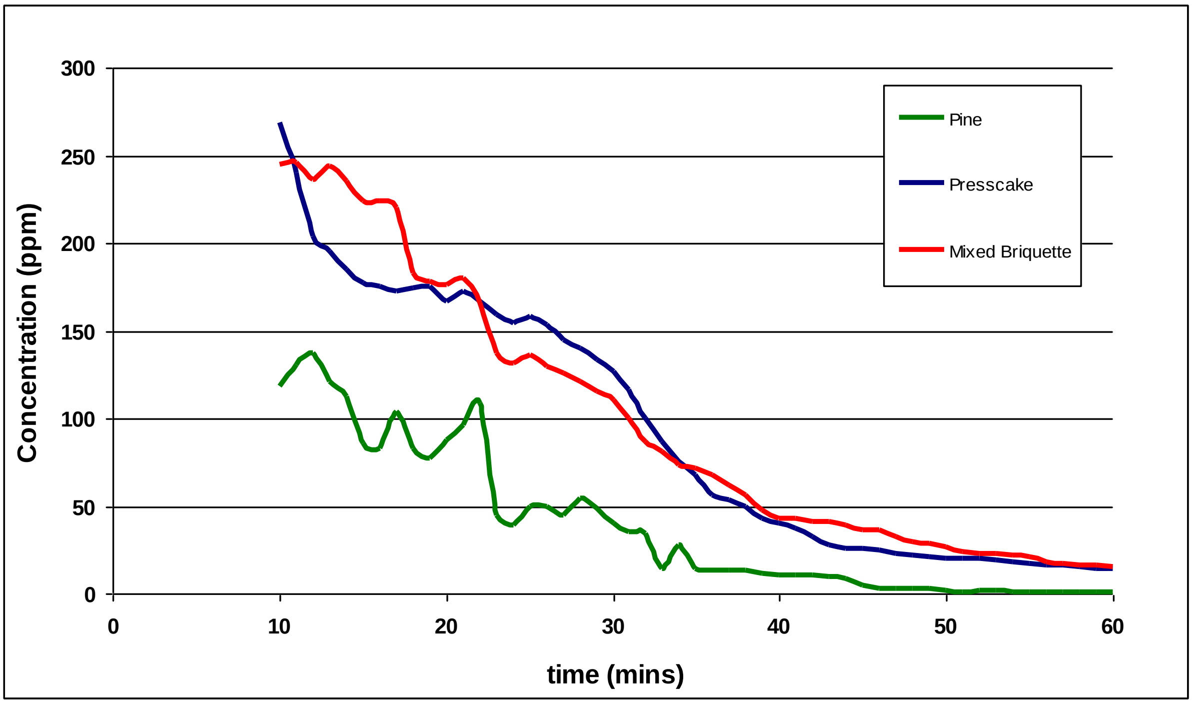


Figure 51. Variation of Total NOx with time

Sulphur Dioxide

Sulphur dioxide measurements are shown in Figure 52. SO_2 was observed at only low levels, suggesting that the sulphur contents of the fuels are low. The highest values are observed with the presscake fuel, however there is a rapid drop correlating with the time at which the briquettes were smouldering. Reduction of SO_2 can be achieved by reducing the sulphur content of the fuel, for instance by blending with a low sulphur fuel.

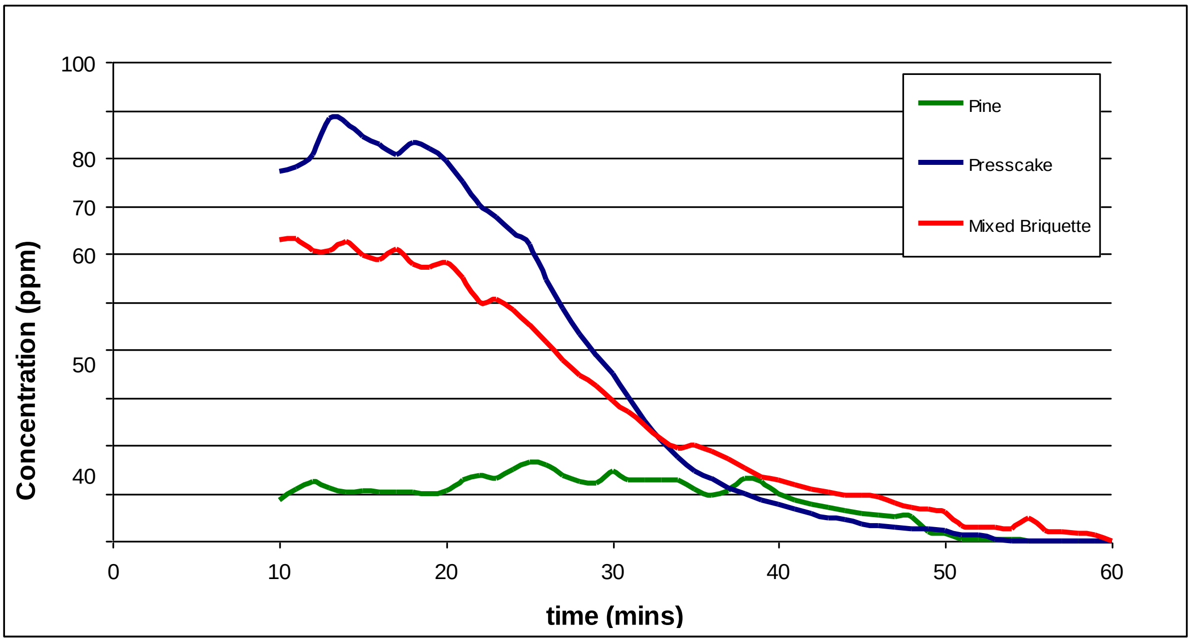


Figure 52. Variation of Sulphur Dioxide with time

Average Emissions

Average emissions over the sampling period are given in Table 12. CO and NOx are higher for the briquettes compared to pine, particularly for presscake. The CO levels are indicators of poorer combustion, which may be improved by changing the briquette physical characteristics or moisture content. The SO_2 levels are low.

Fuel	Average Concentration ppm				
	CO	NO	NO_2	NOx	SO_2
Pine	2499	8	5	13	6
Presscake	4043	74	7	81	27
Mixed	3387	62	23	85	22

Table 12. Average emissions concentration over the duration of test.

In order to calculate the emissions index, it is necessary to have detailed information on the fuels elemental composition. The calorific value can be used to calculate emissions in terms of energy content. In the case of biomass, there is great variability between samples and detailed data specific to the briquettes was not available at the time this study. Consequently an estimate of the EI is shown in Table 13, based on a typical calculation of stoichiometric air:fuel ratio, 11% flue oxygen basis and the results in ppm from Table 12. This gives an indication of comparative values using this specific stove system. It should also be noted that the fuels would behave differently according to different capacity stoves and refuelling characteristics.

Fuel	Emissions Index Estimate g/kg fuel	
	CO	NOx
Pine	205	7
Presscake	309	10
Mixed	258	11

Table 13. Estimated Emissions Index for gaseous emissions at 11% flue oxygen

Other Emissions

A range of other gaseous emissions were investigated during the tests including hydrogen chloride, ammonia, formaldehyde and methane. These results are shown in Table 14.

Fuel	Average Concentration ppm				
	Hydrogen chloride	Ammonia	Formaldehyde	Methane	Ethane
Pine	0	4	8	111	12
Presscake	27	30	10	45	97
Mixed	12	45	19	102	24

Table 14. Average emissions concentration over the duration of test.

Fuels containing high levels of chloride can produce HCL upon combustion, which is corrosive and can lead to flue damage. The HCL levels seen here are only at trace amounts, suggesting that chlorine is not significantly high in these fuels.

Ammonia, formaldehyde and hydrocarbon emissions are all indications of partially burned fuel fragments. Higher levels of these were seen for the briquette fuels indicating poorer combustion quality compared to pine. The formaldehyde and ethane were particularly high during flaming combustion, whereas the ammonia and methane emissions were higher towards the smouldering phases of combustion. Changes to the briquette size, structure and composition could help improve the combustion characteristics. The moisture content would also affect the burning characteristics and should be minimised.

Particulate emissions

The particulate emissions are shown in Figure 53. It can be seen that highest mass emissions are produced at the early stages of combustion. This corresponds to the flaming phase when release of volatile matter from the fuels is incompletely burnt. The particulate matter consists of elemental carbon as well as condensed volatile organic matter and ash. Fuels with higher %VM tend to produce more smoke, so these results should be correlated against the proximate analysis data.

The particulate mass emissions from the mixed briquettes and the pine were similar, however the presscake produced slightly higher emissions during flaming combustion. Particulate emissions during the smouldering phase were similar for all fuels. The high initial emission after ignition corresponds to the cooler stove temperature which is insufficient for good smoke burnout.

The current work is based on a simple stove with no re-loading. Other combustion systems which incorporate continuous feeds of fuel would have lower average emissions because they would maintain a temperature sufficient for more complete combustion. An effect of reloading would be to disturb the ash layer, causing smouldering char to break up more and potentially leading to more complete combustion. Some of this disturbed char may also be emitted however as particulate matter.

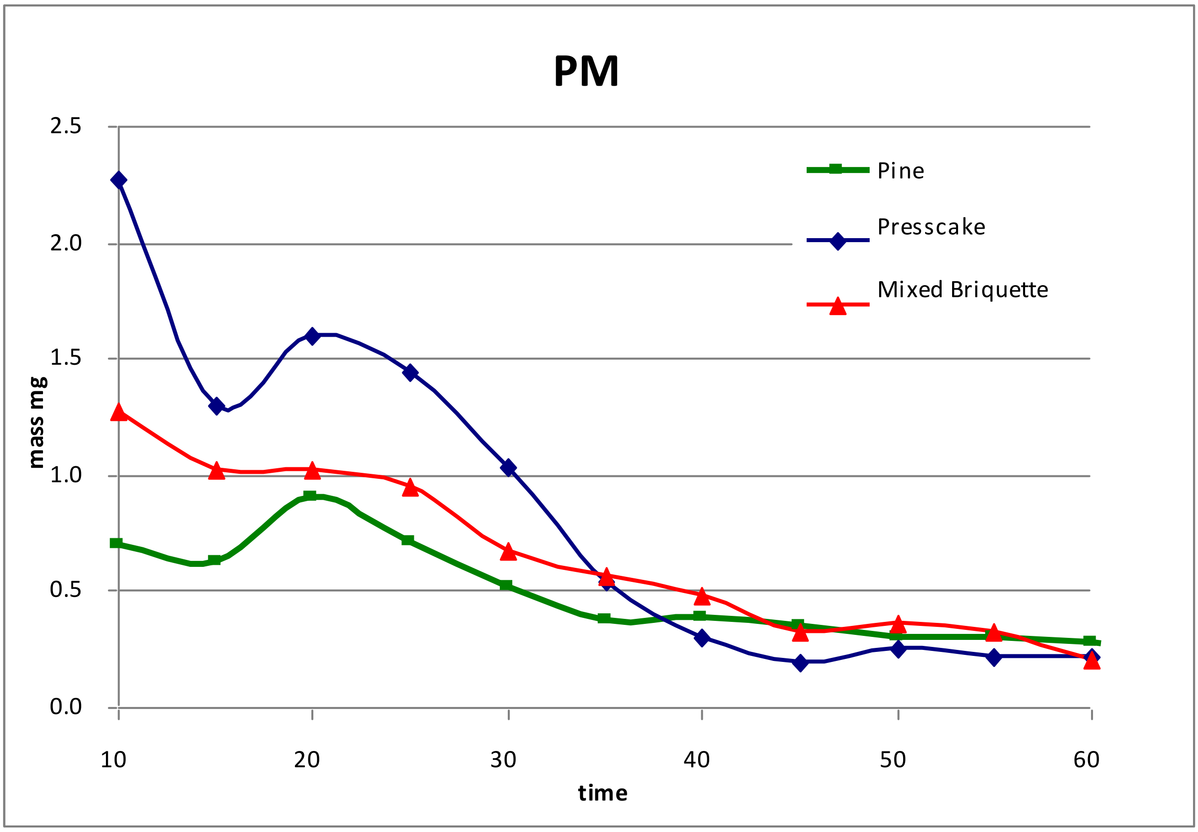


Figure 53. Variation of Particulate Mass with time

Figure 54 shows the relative proportions of PM10, PM2.5 and PM1 size fractions.

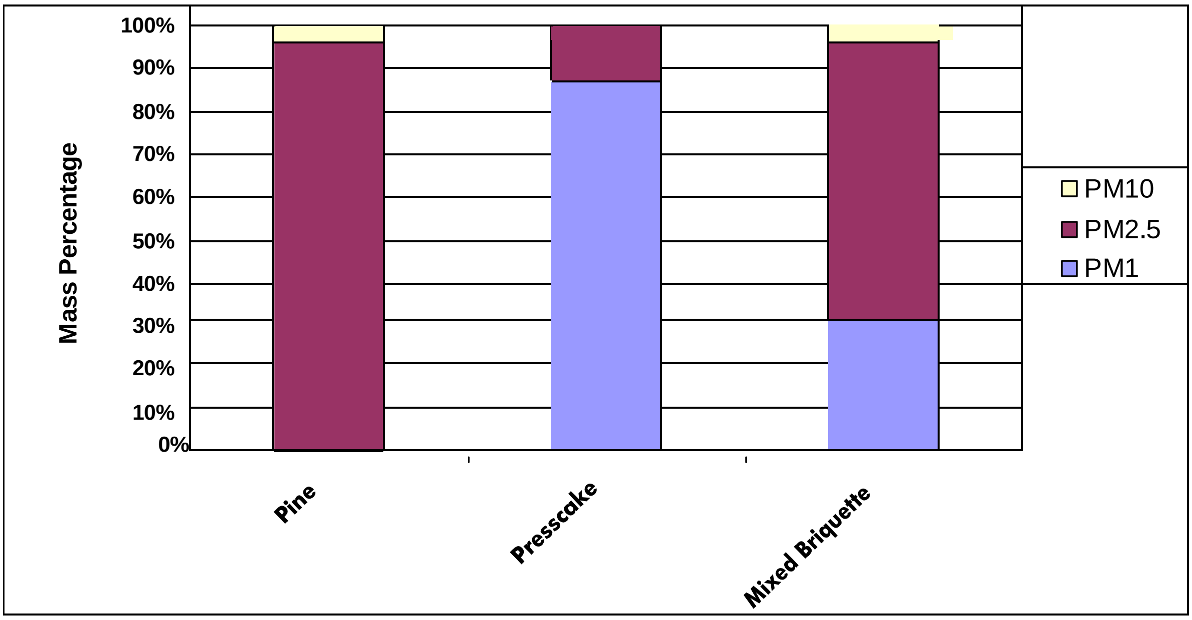


Figure 54. Particulate size fractions for all fuels.

The results from the cyclone tests also show that a wide variation in fractions, with an unexpectedly high proportion of PM_1 for the briquette fuels, especially for the presscake. However this is consistent with the literature which show that the majority of particles are expected to be below $PM_{2.5}$ and even PM_1 (McDonald et al., 2000). Further analysis of the particulate fractions is recommended to investigate the proportion of condensed organic carbon compared to elemental carbon. The relative amounts have implications for health and climate. It is likely that the PM_1 material contains a higher proportion of organic carbon rather than the solid elemental carbon. It is also likely that small ash fragments are present from the inorganic content of the fuels.

The time at which samples are taken for particulate analysis would have a substantial influence on the final figure for the emissions factor. For example, the higher volatile fuels release a highly carbonaceous dark aerosol during flaming combustion. Sampling during this period leads to a higher emissions factor. Longer sampling times for the higher volatile fuels may extend beyond the flaming phase, when PM production reduces. The total PM measured is given in Table 14. The particulate emissions for presscake were higher than the levels observed with pine or mixed briquettes.

Fuel	PM mg/kg
Pine	4.4
Presscake	5.6
Mixed	4.6

Table 14. Particulate Matter emissions during test period normalised to 1kg fuel loading

The undergrate (usually fine ash) and overgrate (usually unburnt fuel) losses are shown in Figure 55. The briquettes retained their original size and shape (approximately) as ash, and so there was very little measurable undergrate ash. However the overgrate ash levels were very high, particularly for the presscake, which could lead to operational issues during fuel refilling. The proportion of ash loss to the original mass of fuel indicates poorer efficiency for the briquettes compared to pine, especially for the presscake.

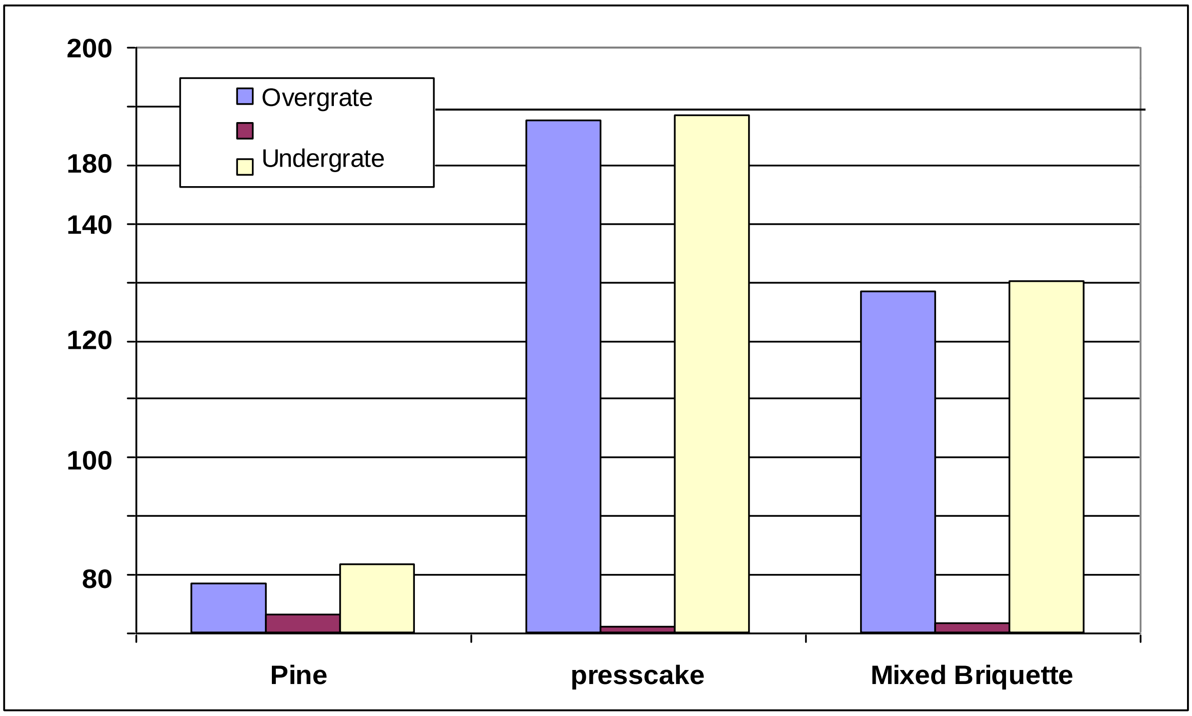


Figure 55. Undergrate and Overgrate ash losses.

Figure 56. Mixed briquette ash: (a)at end of test, (b) during weighing

3.9.4 Conclusions

The proximate and ultimate analyses of the fuels should be determined and correlated with the emissions results for better understanding of the fuel behaviour.

The briquette fuels had comparable CO compared to pine during the flaming phase, but slightly higher emissions during the smouldering phase. Both briquette fuels release higher NOx compared to the pine baseline, however there is little NOx difference between the two briquette types. Differences in the fuel-N content are expected to correlate with the NOx emissions. Sulphur dioxide was observed at only low levels, suggesting that the sulphur content of the fuels are low. In general, a better emissions performance was observed with the mixed composition briquettes compared to the presscake briquettes.

The presscake produced slightly higher particulate emissions during flaming combustion. however particulate emissions during the smouldering phase were similar for all fuels. The overgrate ash levels were very high, particularly for the presscake, which could lead to operational issues.

Emissions abatement technologies could be considered for the briquette fuels to further minimise peak emissions. Changes to the briquette size, structure and composition could help improve the combustion characteristics. The moisture content would also affect the burning characteristics and should be minimised. Regular refuelling would maintain the flaming phase for longer due to the availability of volatile matter, however the build-up of ash with these fuels might be an issue to overcome.

3.11 Summary of entire system

Harvesting trials proved to be very positive, the Softrak 65 is a very versatile machine and can cope with almost all ground conditions. However it has suffered criticism in the past due to its slow production rate, we have shown that with a little innovation that this can be overcome. Softrak working alongside SCS means that the harvester is continually cutting so will increase production rate by at least 50%. Using a simply designed low cost sledge towed behind the Softrak when reed harvesting increased capacity from one bale to six bales.

Loose material can be difficult to handle and transport by baling the material at the harvesting site we were not only able to increase handling efficiency but were also able to increase transport distances. Wrapped bales also have the advantage of not looking out of place in the countryside.

Figure 57: Baling loose material extracted from the Softrak cut & collect system

A significant advantage of the AMW/IBERS system is that harvesting can take place in very wet conditions both ground and weather this means very little downtime is lost in what sometimes can seem a very short harvesting window. The exception to this is reed for char production as this must be done in dry weather conditions.

Screw pressing trials proved not to be as successful, the production capacity of the screw press did not achieve our expected outcome of 1 tonne per hour as claimed by the manufacturer. We achieved around one third of this, we also discovered how difficult the material can be to handle when using conveyor systems as it has a tendency to bridge when moving from one to another. This we feel can be overcome by incorporating agitators at the bridging points.

The anaerobic digester designed and installed by QUBE renewables was delivered to site and installed within a matter of hours, it is very simple to operate once some basic training has been undertaken and there were no issues recorded while the plant was operational. When the settling tanks were full the system could be left to run for a period of five days unsupervised.

The AgBag is a recognised method of storage and it was demonstrated that equipped with the right aeration capacity it will also perform drying. The advantage of the AgBag over the kiln drying which was trialled is the ability to dry large volumes at low cost. The downside however is longer the time needed to complete the drying compared to the kiln, which took a matter of hours. We had hoped to experiment with using heat from both the AD system and the char rig to accelerate the drying time in the bags however this is now something we will need to look into in the foreseeable future.

The trials undertaken on the char and bulk density of material provided very interesting and positive results illustrating the point well about the value of the kiln to increase bulk density and reduce volume on site before the material is transported long distances to be incorporated into the process. A conversion rate of 3 to 1 for reed would suggest that is viable to char the reed stored on Tay reed bed, Errol and transport to the processing plant at Insh Mashes, Kingussie a distance of 90 miles. It should be noted that the production of char is very labour intensive.

Briquetting of the materials had mixed results press cake on its own produced a uniformed dense briquette and the briquetter required very little manual operation during their production. The briquette mixture however proved a little more difficult with constant supervision required having to make fine adjustments to the machine, however with a little more time this could easily be overcome.

We are presently exploring the potential to commercialise wetland biomass briquettes, if we wish to benefit from RHI subsidies then two options have been identified.

- Sell wetland biomass fuel to domestic or non domestic installations accredited under the RHI.
- Burn wetland biomass fuel in AMWs own RHI accredited installation and sell heat to heat customers.

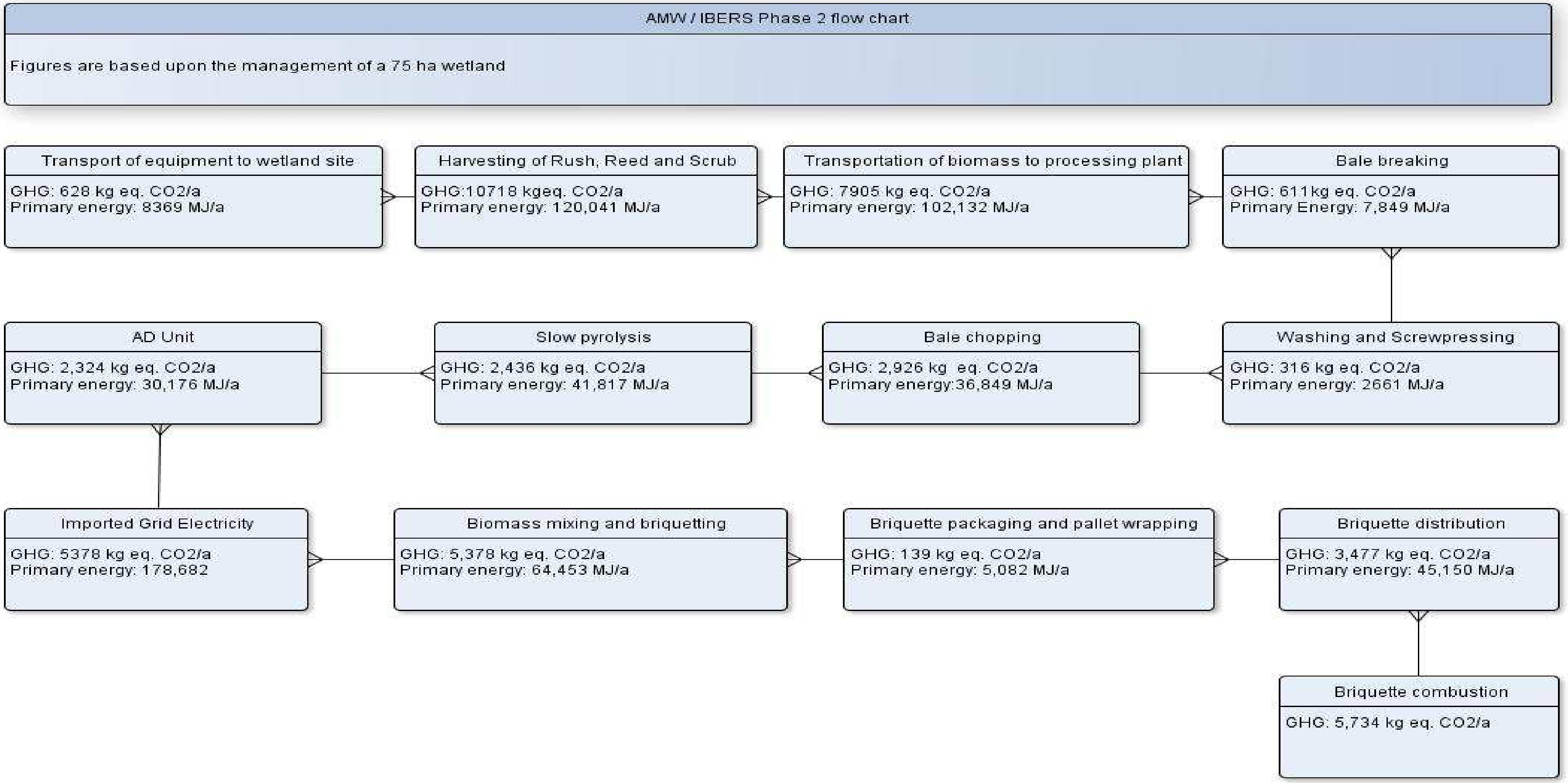
Both options have significant technical and financial challenges. To avoid the difficulties of RHI accreditation the briquettes could be sold directly to customers without RHI accredited installations such as open fires and log burners. There is inherent uncertainty regarding the Government's continued level of support through the RHI and it is therefore sensible to develop plans that make financial sense even without RHI support.

An optioneering study of the alternative commercialisation is currently been undertaken by Mott MacDonald to compare the pros and cons for the three options described above.

There is potential for the system to claim non domestic RHIs on heat used from the char rig and the AD unit for drying press cake.

Section 4 Technical Analysis

4.1 Process flow diagram



4.2 Greenhouse gas (GHG) and energy life cycle assessment (LCA)

DECC WETLAND BIOMASS TO BIOENERGY: AMW-IBERS Phase 3 Final LCA Report

(Version 26.04.15)

4.2.1 Summary of Main Process Changes

The process, under further development at the end of Phase 3, was similar to that evaluated at the interim point in Phase 3. The main changes consisted of removing bale chopping as part of rush processing and assuming charring of all reed at the harvesting site instead of at the processing site. All data available at the end of Phase 3 were used in the life cycle assessment (LCA) although some limitations were encountered especially regarding data on wetland biomass transportation from harvesting sites to the processing site, transport within the processing site, transportation of pyrolysis equipment, and electricity requirements for artificial drying of press cake.

4.2.2 Current Process Flow Chart

The process flow chart is represented in the Unit Flow Chart worksheet of the latest version of the MS Excel workbook (AMW-IBERS Process Phase 3 v10.xlxs) for evaluating primary energy inputs and total greenhouse gas (GHG) emissions. The process is highly-integrated to enable briquettes, as the principal output to be derived from wetland biomass consisting of rush, reed and woody scrub. Each type of wetland biomass is harvested selectively and processed accordingly.

The rush is baled and transported to the processing site where the bales are broken open and the rush is fed into a screw press to extract press fluid and press cake. The press fluid provides feedstock for an anaerobic digestion (AD) unit which produces biogas for a combined heat and power (CHP) unit. Electricity generated by the CHP unit is supplied to processing site equipment, as and when required, with any surplus electricity being exported for sale to the grid. Heat from the CHP unit is supplied to the AD unit with the potential to sell any surplus for other uses.

Reeds are charred by pyrolysis at the harvesting site and then transported to the processing site. Woody scrub is chipped and transported to the processing site where the wood chips, along with the press cake, can be stored and dried in Agbags. Some of the wood chips are used as start-up fuel for reed pyrolysis. The remaining dried wood chips and all the dried press cake are mixed with charred reeds and then converted into briquettes. During processing in the briquetter, heating due to friction dries the mixed biomass feedstock to the desired moisture content for the briquettes. After packaging and wrapping on pallets, the briquettes are distributed to end users with suitable biomass heating systems. Consequently, the main output is heat from briquette-fired heating systems, with supplementary outputs in the form of surplus electricity and heat from the CHP unit and digestate from the AD unit.

In terms of default values, the area of harvested wetland biomass is taken as 75.0 ha. It is assumed that the yield of rush is 9.85 t/ha at 70% moisture content, the yield of reeds is 7.06 t/a at 15% moisture content and the yield of woody scrub is 33.50 t/ha at 60% moisture content. After drying in Agbags, the moisture contents of the press cake and wood chips are 15% and 20%, respectively. The default composition of the mixed biomass feedstock prior to briquetting is 65% press cake, 10% charred reeds and 25% wood chips. After briquetting, the moisture content of the briquettes is 5%.

4.3.3 Life Cycle Assessment Results

The mass yields, net calorific values and potential energy yields for the sources of wetland biomass accessed by the AMW-IBERS process are summarised in Tables 15 to 18 for Phase 1, Phase 2, Phase 3 (Interim) and Phase 3 (Final), respectively. As can be seen, although there are no changes to data for woody scrub between the Interim and Final stages of Phase 3, there have been modifications to the yields and moisture contents of rush and reed.

Table 15: Mass Yields, Net Calorific Values and Potential Energy Yields of Wetland Biomass Feedstocks Assumed in Phase 1

Type of Wetland Biomass Feedstock	Moisture Content (%)	Yield (t/ha.a)		Net Calorific Value (MJ/t dry)	Potential Energy Yield (MJ/ha.a)
		Wet	Dry		
Rush	65	15.40	4.00	15,850	63,400
Reed	15	12.05	10.25	15,850	162,463
Woody Scrub	60	35.00	15.50	18,110	280,705

Table 16: Mass Yields, Net Calorific Values and Potential Energy Yields of Wetland Biomass Feedstocks Accessed in Phase 2

Type of Wetland Biomass Feedstock	Moisture Content (%)	Yield (t/ha.a)		Net Calorific Value (MJ/t dry)	Potential Energy Yield (MJ/ha.a)
		Wet	Dry		
Rush	65	15.40	5.390	18,550	99,984
Reed	15	4.50	3.825	17,880	68,391
Woody Scrub	60	33.50	13.400	18,870	252,858

Table 17: Mass Yields, Net Calorific Values and Potential Energy Yields of Wetland Biomass Feedstocks Accessed in Phase 3 (Interim)

Type of Wetland Biomass Feedstock	Moisture Content (%)	Yield (t/ha.a)		Net Calorific Value (MJ/t dry)	Potential Energy Yield (MJ/ha.a)
		Wet	Dry		
Rush[1]	65	15.40	5.390	18,550	99,984
Reed	15	4.50	3.825	17,880	68,391
Woody Scrub	60	33.50	13.400	18,870	252,858

[1] Rush data based on harvesting for Phase 2

Table 18: Mass Yields, Net Calorific Values and Potential Energy Yields of Wetland Biomass Feedstocks Accessed in Phase 3 (Final)

Type of Wetland Biomass Feedstock	Moisture Content (%)	Yield (t/ha.a)		Net Calorific Value (MJ/t dry)	Potential Energy Yield (MJ/ha.a)
		Wet	Dry		
Rush[2]	70	9.85	2.955	18,550	54,815
Reed	15	7.06	6.000	17,880	107,298
Woody Scrub	60	33.50	13.400	18,870	252,858

The estimated annual energy balances for the AMW-IBERS process for Phase 1, Phase 2, Phase 3 (Interim) and Phase 3 (Final) are given in Table 19. It will be seen that there are differences in the biomass energy input and the delivered energy output between the Interim and Final stages of Phase 3. Differences in biomass energy input are mainly caused by a change to the composition of mixed biomass feedstock in briquettes. This change affects the delivered energy in heat from briquettes. There are also differences in the delivered energy in the surplus heat and electricity from the CHP unit due to changes in the heat and electricity requirements of the processing equipment and the AD unit. Overall, this has resulted in an increase in the bioenergy efficiency of the process to 68.7%.

Table 19: Annual Energy Balance for the Process in Phases 1, 2 and 3 (Interim and Final)

Contributions	Annual Energy Balance (MJ/a)			
	Phase 1	Phase 2	Phase 3 (Interim)	Phase 3 (Final)
Biomass Energy Input:				
- rush	3,994,200	5,003,414	3,828,399	3,220,057
- reed	1,462,163	636,543	1,352,529	1,107,598
- woody scrub	1,263,173	1,440,065	1,911,838	150,035
- *total input*	*6,719,535*	*7,080,022*	*7,092,765*	*4,477,688*
Delivered Energy Output:				
- heat from briquettes[a]	3,398,907	4,826,800	3,619,765	2,694,352
- surplus heat from CHP unit	(b)	55,123	341,195	224,452
- surplus electricity from CHP unit	(b)	69,393	282,045	158,560
- *total output*	*3,398,907*	*4,951,316*	*4,243,005*	*3,077,364*
Bioenergy Efficiency	**50.6%**	**69.9%**	**59.8%**	**68.7%**

Notes

(a) For consistency with the assumption in Phase 1, the seasonal thermal efficiency of a briquette-fired domestic boiler has been taken as 70% here.

(b) Data not provided in Phase 1.

The estimated breakdowns for annual total greenhouse gas (GHG) emissions for the AMW-IBERS process in Phase 1, Phase 2, Phase 3 (Interim) and Phase 3 (Final) are provided in Table 20. This

[2] Rush data based on harvesting for Phase 3

shows some significant increases in estimated GHG emissions associated with the process between Phase 3 (Interim) and (Final) due to updated information on harvesting, based on current harvesting data, particularly for rush and reeds, and on current rush processing. Additionally, combustion emissions data for biogas in the AD unit have been revised using a coherent dataset from a more reliable source on biogas combustion in gas engines.

Reduction in the dry yield of rush, which is only partly offset by the increase in the dry yield of reeds, and alterations to the composition of mixed biomass in the briquettes have decreased the annual amount of briquettes produced from a wetland area of 75 ha from 284 t/a to 208 t/a. This, combined with a small fall in the net calorific value of briquettes, has reduced the avoided GHG emissions from coal-fired heating that is displaced by briquette-fired heating. A marked decrease in the surplus electricity from the CHP unit has been caused by improved data on electricity requirements for wetland biomass processing. Surplus heat from the CHP unit has been taken into account which introduces a further counterfactual of avoided GHG emissions. However, this does not completely counterbalance the main decrease in avoided GHG emissions from coal-fired heating displaced by briquette-fired heating. Despite these changes, the net GHG emissions savings of this process are still relatively high at 84.1%.

Table 20: Comparison of Annual Total Greenhouse Gas Emissions for the Process in Phase 1, Phase 2, Phase 3 (Interim) and Phase 3 (Final)

Contribution	**Annual Greenhouse Gas Emissions (kg eq. CO_2/a)**			
	Phase 1	Phase 2	Phase 3 Interim	Phase 3 Final
Transport of Equipment to Wetland Site	302	628	628	362
Harvesting of Rush, Reed and Woody Scrub	11,183	10,572	10,708	18,562
Transportation of Biomass for Processing	12,971	7,861	7,961	3,420
Bale Breaking	(a)	2,944	2,231	12,929
Hydrothermal Washing and Screw Pressing	16	318	407	2,095
Agbaging	(a)	(a)	846	3,862
Bale Chopping	(a)	615	471	(c)
Pyrolysis/Charring	252	2,450	2,497	2,516
AD Unit and CHP Unit	12,275	2,325	2,156	7,403
Imported Grid Electricity	40,265	19,248	18,050	6,448
Biomass Mixing and Briquetting	1,442	1,319	1,252	6,290
Briquette Packaging and Pallet Wrapping	(a)	139	139	2,089
Briquette Distribution	3,020	3,499	2,627	1,939
Briquette Combustion(b)	4,870	8,244	6,189	5,820
Sub-Totals for Emissions	*86,597*	*60,162*	*56,162*	*73,737*
Conventional Wetland Management (harvest counterfactual)	61,285	32,078	39,975	38,457
Coal-fired Heating (briquette counterfactual)	662,035	660,350	495,217	368,612
Grid Electricity (surplus CHP electricity counterfactual)	(a)	17,354	45,799	25,747
Coal-fired Heating (surplus CHP heat counterfactual)	0	0	0	30,707
Artificial Fertiliser (digestate counterfactual)	2	1	1	0
Sub-Totals for Avoided Emissions	*723,322*	*709,784*	*580,991*	*463,523*
Emissions Savings (avoided emissions – emissions)	**636,725**	**649,622**	**524,829**	**389,787**
Net Greenhouse Gas Emissions Savings	**88.0%**	**91.5%**	**90.3%**	**84.1%**

Notes

(a) Not specified.

(b) Seasonal thermal efficiency of a briquette-fired domestic boiler has been taken as 70%.

(c) Process is no longer used

The estimated breakdowns for annual total primary energy inputs in Phase 1, Phase 2, Phase 3 (Interim) and Phase 3 (Final) are shown in Table 21. Between the Interim and Final stages of Phase 3, estimated total annual primary energy inputs have increased and avoided annual primary energy inputs have decreased. The former increase is largely due to updated harvesting data with higher fuel consumption and the introduction of contributions to primary energy inputs of briquette-fired boiler manufacture and maintenance based on revised calculations. The decrease in avoided annual primary energy inputs has principally been caused by a reduction in annual briquette output, due to a lower dry yield of rush and a change to the composition of the mixed biomass in briquettes. Additionally, avoided primary energy inputs for grid electricity have declined due to a reduction in surplus electricity from the CHP unit as a consequence of revised electricity requirements for processing equipment derived from current operations. Again, the introduction of avoided coal-fired heating displaced by surplus heat from the CHP unit does not counteract these other reductions entirely, causing the net primary energy savings to reduce to 83.1% which is still a relatively high value.

Table 21: Comparison of Annual Primary Energy for the Process in Phase 1, Phase 2, Phase 3

Contribution	Annual Primary Energy (MJ/a)			
	Phase 1	Phase 2	Phase 3 (Interim)	Phase 3 (Final)
Transportation of Equipment to Wetland Site	3,982	8,369	8,369	4,662
Harvesting of Rush, Reed and Woody Scrub	143,357	119,302	116,380	242,551
Transportation of Biomass for Processing	168,188	101,564	102,849	43,976
Bale Breaking	(a)	7,898	6,050	165,981
Hydrothermal Washing and Screw Pressing	136	2,678	3,429	17,657
Agbagging	(a)	(a)	14,913	50,602
Bale Chopping	(a)	37,074	27,918	(c)
Pyrolysis/Charring	2,121	42,069	42,919	31,763
AD Unit and CHP Unit	59,242[(b)]	30,177	30,177	38,454
Imported Grid Electricity	740,023	349,928	328,148	117,220
Biomass Mixing and Briquetting	16,572	12,316	11,449	53,664
Briquette Packaging and Pallet Wrapping	(a)	5,082	5,082	76,158
Briquette Distribution	39,043	45,436	34,110	27,552
Briquette-fired Boiler	0	0	0	10,271
Sub-Totals for Inputs	*1,172,664*	*761,893*	*731,793*	*880,511*
Conventional Wetland Management (harvest counterfactual)	769,950	404,481	465,200	481,279
Coal-fired Heating (briquette counterfactual)	7,089,149	7,067,814	5,300,370	3,945,301
Grid Electricity (surplus electricity counterfactual)	(a)	315,491	832,597	468,069
Coal-fired Heating (surplus CHP heat counterfactual)	0	0	0	328,661
Artificial Fertiliser (digestate counterfactual)	15	9	5	3
Sub-Totals for Avoided Inputs	*7,859,114*	*7,787,795*	*6,598,172*	*5,223,314*
Primary Energy Savings (avoided inputs – inputs)	**6,686,450**	**7,025,902**	**5,866,379**	**4,342,803**
Net Primary Energy Savings	**85.1%**	**90.2%**	**88.9%**	**83.1%**

Notes

(a) Not specified.

(b) Correction to original Phase 1 calculation to exclude energy in biogas combustion in the CHP unit.

(c) Process is no longer used

Table 21 compares total net GHG emissions per unit of total energy output for Phase 1 through to Phase 3 (Final) for the process. Estimated total GHG emissions and avoided GHG emissions change from the Interim to the Final stage of Phase 3 due to the reasons explained for the differences present in Table 20. However, the overall impact only alters unit net GHG emissions slightly.

Table 21: Comparison of Unit Greenhouse Gas Emissions of the Process in Phase 1, Phase 2, Phase 3 (Interim) and Phase 3 (Final)

Contribution	Unit Greenhouse Gas Emissions (kg eq. CO_2/MWh)			
	Phase 1	Phase 2	Phase 3 (Interim)	Phase 3 (Final)
Total Emissions	92	44	48	86
Total Avoided Emissions	766	516	493	542
Total Net Emissions	**-674**	**-472**	**-445**	**-456**

Table 22 shows the effect of these changes on estimates of total energy efficiency, which compares annual delivered energy outputs to annual biomass and primary energy inputs. Throughout the Phases, the total efficiency of the process has varied due to changes in details of design configuration and in subsequent values of parameters. However, with data from the Final stage of Phase 3, a relatively high total energy efficiency of 57.4% is estimated for the process.

Table 22: Comparison of Total Energy Efficiency for the Process in Phase 1, Phase 2, Phase 3

Contribution	Units	Phase 1	Phase 2	Phase 3 (Interim)	Phase 3 (Final)
Annual Biomass Energy Inputs	MJ/a	6,719,535	7,080,022	7,092,765	4,477,688
Annual Primary Energy Inputs	MJ/a	1,172,664	761,893	731,793	880,511
Annual Delivered Energy Outputs	MJ/a	3,398,907	4,951,316	4,243,005	3,077364
Total Energy Efficiency	**%**	**43.1**	**63.1**	**54.2**	**57.4**

Table 23 summarises estimated annual particulate (PM_{10}) emissions for the process through Phase 1 to Phase 3 (Final), during which there have been significant changes due to process configuration and with basic data on certain emissions factors. The estimates of annual PM_{10} emissions associated with the process and annual avoided PM_{10} emissions for Phase 3 (Final) are distinctly different to the estimates for all preceding Phases. The main contribution to annual PM_{10} emissions associated with the process in Phase 3 (Final) is those from briquette combustion. The most prominent contribution to annual avoided PM_{10} emissions is from the management of wetland woody scrub. The relative magnitudes of these contributions in Phase 3 (Final) depend on a combination of factors. More representative and reliable data on both PM_{10} and oxides of nitrogen (NOx) emissions from the combustion of briquettes became available from testing towards the end of Phase 3. In particular, this increased the combustion emissions for briquettes considerably from 0.020 g PM_{10}/MJ to 0.732 g PM_{10}/MJ. Additionally, the assumed composition of briquettes now includes a higher proportion of wood chip from woody scrub. This amplifies the influence of wetland woody scrub management on estimated annual avoided PM_{10} emissions. This combines with incorporation of PM_{10} emissions from "open field" burning of woody scrub to increase the estimate of annual avoided PM_{10} emissions. These were also affected by corrections to PM_{10} emissions from "open field" burning of reeds as part of conventional wetland management. Since annual PM_{10} emissions associated with the process have increase proportionally more than annual avoided PM_{10} emissions between Phase 3 (Interim) and Phase 3 (Final), net PM_{10} emissions savings have become negative. This means that the process increases PM_{10} emissions relative to those from counterfactual wetland management and conventional heating and electricity supply, as reflected by the estimated net PM_{10} emissions savings of -26.3%.

Table 23: Comparison of Annual Particulate Emissions for the Process in Phase 1, Phase 2, Phase 3 (Interim) and Phase 3 (Final)

Contribution	Annual Particulate Matter Emissions ($g\ PM_{10}/a$)			
	Phase 1	Phase 2	Phase3 (Interim)	Phase 3 (Final)
Annual Emissions	143,251	169,957	133,080	2,889,636
Annual Avoided Emissions	1,627,303	776,830	814,386	2,288,541
Annual Saved Emissions (avoided emissions – emissions)	1,484,052	606,873	681,307	-601,095
Net Emissions Savings	**91.2%**	**78.1%**	**83.7%**	**-26.3%**

Some of these considerations apply to estimated annual oxide of NOx emissions for the process through Phase 1 to Phase 3 (Final) shown in Table 24. The most prominent contributions to annual NOx emissions are briquette combustion, diesel consumption by machinery, equipment and vehicles, and AD biogas combustion. The testing data on briquette combustion which became available towards the end of Phase 3 has reduced this contribution since the emissions factor has decreased slightly from 0.155 to 0.114 g NOx/MJ. Annual NOX emissions from diesel consumption have increased due to updated data for harvesting machinery and processing equipment. However, estimated NOx emissions from biogas combustion in the CHP unit has declined as a consequence of using a more reliable and coherent dataset for emissions from biogas combustion in gas engines which reduced the emissions factor from 0.879 to 0.540 g NOx/MJ. Overall, estimated annual NOx emissions associated with the process have decreased between Phase 3 (Interim) and Phase 3 (Final). At the same time, estimated annual avoided NOx emissions have fallen slightly due to a combination of changes in the mixed biomass composition of briquettes and alteration of NOx emissions from “open field” burning of woody scrub and reed as part of conventional wetland management. Despite such changes in basic data, the overall balance is that the process increases NOx emissions relative to counterfactual wetland management, as indicated by estimated net NOx emissions savings of -22.6%. It will be noted that this estimate is quite similar to the net NOx emissions savings derived for Phase 3 (Interim).

Table 24: Comparison of Annual Oxides of Nitrogen Emissions for the Process in Phase 1, Phase 2, Phase 3 (Interim) and Phase 3 (Final)

Contribution	Annual Oxides of Nitrogen Emissions (g NOx/a)			
	Phase 1	Phase 2	Phase3 (Interim)	Phase 3 (Final)
Annual Emissions	1,918,981	1,157,430	1,876,481	1,398,810
Annual Avoided Emissions	2,767,729	1,461,833	1,480,724	1,141,407
Annual Saved Emissions (avoided emissions – emissions)	848,748	304,403	-395,757	-257,403
Net Emissions Savings	**30.7%**	**20.8%**	**-26.7%**	**-22.6%**

As mentioned previously, all these results are based on data currently available at the end of Phase 3. However, due to ongoing work and development, updated data may become available later. In particular, further data on fuel consumption for harvesting and processing equipment transport and wetland biomass transport would enable modelling of these contributions to primary energy inputs and GHG, PM_{10} and NOx emissions in place of fixed values that are currently incorporated in the LCA workbook, AMW-IBERS Process Phase 3 v10.xlxs. In addition, there are some outstanding uncertainties with data of varying degrees of importance, including:

- Clarification of PM_{10} and NOx emissions from briquette combustion and extension of measured PM_{10} and NOx emissions from combustion of briquettes of different specified mixed biomass compositions,
- Measured or generally–agreed CH_4 and N_2O emissions (probably small) from combustion of briquettes of different specified mixed biomass compositions,
- Unknown CH_4 and N_2O emissions (probably small), and PM_{10} and NOx emissions (possibly more significant) from the pyrolysis of reeds,
- Possible CH_4 leakage from the AD unit (assumed to be zero in Phases 1 to 3 Final),
- Measured or generally-agreed CH_4, N_2O, PM_{10} and NOx emissions from biogas combustion in the CHP unit gas engine, and

More reliable or specific estimates of CH_4, N_2O, PM_{10} and NOx emissions from "open field" burning of woody scrub and reeds during conventional wetland management (based on very generalised data in Phases 1 to 3 Final).

In contrast to uncertainties, there are a number of parameters, some of which are not wholly under the control of the operators of this process,that can affect its LCA performance. Hence, these were explored by means of sensitivity analysis based on a selection of such parameters using the LCA workbook which incorporates necessary functionality. The selected parameters, which are intended to encompass reasonable variations in wetland biomass characteristics and key technological factors, for this sensitivity analysis consisted of the following:

- wetland biomass yield,
- wetland biomass moisture content,
- biogas yield from wetland biomass,
- briquette composition, and
- choice of counterfactual heating fuel.

The sensitivity analysis was performed by varying relevant parameters by specified percentages from a given base case represented by default values within the LCA workbook. The main base case parameters, reflecting current data for the technology operating with wetland biomass at Invertromie Meadows on the Insh Marshes and along the River Tay in Scotland, are summarised in Table 25.

Table 25: Summary of Default Values for Base Case of the Process in Phase 3 (Final)

Parameter	Default Value
Rush Yield	9.85 t/ha at 70% moisture content
Reed Yield	7.06 t/ha/a at 15% moisture content
Woody Scrub Yield	33.5 t/ha at 60% moisture content
Harvesting, Processing Equipment and Wetland Biomass Transport Distances	16.1 km (fixed)
Briquette Composition	65% press cake, 10% charred reed and 25% wood chip
Choice of Counterfactual Heating Fuel	Coal

Figures 57 and 58 demonstrate the sensitivity of net GHG emissions and net primary energy savings, respectively, to wetland biomass yield. As would be expected, both of these net savings increase with wetland biomass yield, with greater sensitivity to declining rather than improving yield. The variations shown in Figures 57 and 58 are largely a consequence of GHG emissions and primary energy inputs of harvesting per unit output, in the form of briquette-fired heating, and surplus electricity and heat from the CHP unit, falling as wetland biomass yield rises.

In contrast, Figure 59 indicates that net PM_{10} emissions savings are almost insensitive to wetland biomass yield. Annual PM_{10} emissions are dominated by PM_{10} emissions from briquette combustion whilst annual avoided PM_{10} emissions mainly depend on PM_{10} emissions from the "open field" burning of woody scrub during conventional wetland management. As the yield of wetland woody scrub goes up, the annual production of briquettes rises, thereby increasing annual PM_{10} emissions from briquette combustion, and annual PM_{10} emissions from "open field" burning of woody scrub also increase. In effect, these increases in annual PM_{10} emissions almost entirely cancel each other out, resulting in only a very slight decrease in net PM_{10} emissions savings as wetland biomass yield increases.

A decrease in net NOx emissions savings with increasing wetland biomass yield is more pronounced, as shown in Figure 60. As mentioned previously, annual NOx emissions of the process depend chiefly on diesel fuel consumption in harvesting machinery, vehicles and processing equipment, briquette combustion and biogas combustion in the CHP unit. Given the composition of these particular contributions, only a proportion of these vary with wetland biomass yield with the remainder being fixed with respect to this parameter. Annual avoided NOx emissions are largely influenced by conventional heating, in this case provided by coal-fired boilers, which is displaced by briquette-fired heating. These avoided NOx emissions vary with wetland biomass yield since this determines the annual production of briquettes. Consequently, annual NOx emissions increase relatively less than annual avoided NOx emissions when wetland biomass yield increases. This leads to falling net NOx emissions savings. With all these results for sensitivity with wetland biomass yield, the compressed scales used in Figures 57 to 60 should be noted as these have been adjusted to illustrate comparatively small variations in net savings.

Net GHG emissions savings and net primary energy savings are relatively insensitive to wetland biomass moisture content, as illustrated in Figures 61 and 62. There are very slight reductions in these net savings as wetland biomass moisture content increases. Wetland biomass moisture content exerts comparatively little influence over GHG emissions and primary energy inputs. In general, the impact of wetland biomass moisture content on the outputs of the process, in the form of briquette-fired heating and surplus electricity and heat from the CHP unit, is counterbalanced by its impact on counterfactual wetland management. There are no GHG emission and primary energy input penalties in achieving a fixed moisture content (5%) for briquettes, which determines their net calorific value. This is because, regardless of the original moisture content of wetland biomass, the components of the briquettes are dried to their required levels without the need for using significant or, indeed, any fossil fuels. In particular, agbags are used for natural drying of wood chips to 20% moisture content (from a default value for moisture content of 60% for harvested woody scrub) and press cake to 15% moisture content (from a default value for moisture content of 68% for wet press cake from rush pressing). Pyrolysis, involving only small quantities of diesel fuel (for fan operation), achieves a moisture content of 4% for charred reeds (from a default value for moisture content of 15% for harvested reeds). Regardless of the initial moisture content of the mixed biomass feedstock, drying of briquettes to 5% moisture content is achieved through heat-generating friction during briquetting, without any implications for GHG emissions or primary energy inputs.

In contrast, Figures 63 and 64 show that net PM_{10} emissions savings and net NOx emissions savings, respectively, are much more sensitive to wetland biomass moisture content. In both instances, as the wetland biomass moisture content increases, these savings decrease. These variations are not linear as proportionally larger falls in net savings are apparent with higher values of wetland biomass moisture content. As indicated previously, net PM_{10} emissions savings are mainly influenced by the balance between annual PM_{10} emissions from briquette combustion and annual avoided PM_{10} emissions from wetland scrub management. Wetland biomass moisture content only affects PM_{10} emissions from briquette combustion indirectly via the amount of briquettes produced. However, moisture content has a more direct impact on wetland scrub management since it determines the dry matter content of the woody scrub and, therefore, the PM_{10} emissions from "open field" burning. At higher values of moisture content, the reduction in PM_{10} emissions from the "open field" burning of woody scrub is proportionally much smaller than the decrease in PM_{10} emissions from the combustion of a smaller amount of briquettes. Wetland biomass moisture content exerts a similar influence of annual avoided NOx emissions from wetland scrub management. However, this impact is diluted somewhat by the dominant source of annual avoided NOx emissions which is displaced heating fuel (coal) combustion which only depend on wetland biomass moisture content indirectly via the amount of briquettes produced. The influence of wetland biomass moisture content on annual briquette production also has an indirect impact on the main sources of annual NOx emissions associated with the process; these being briquette combustion, diesel fuel consumption by harvesting, transport and processing equipment, and biogas combustion in the CHP unit. To an extent, these indirect influences moderate the effect wetland biomass moisture content on net NOx emissions savings.

The sensitivities of net GHG emissions savings, net primary energy savings, and net PM_{10} and NOx emissions savings to briquette composition are demonstrated in Figures 65 to 68, respectively. These sensitivities are relatively complex because the briquettes are composed of three components; wood chips, charred reed and press cake. However, there is one trend which is consistent for all types of savings; that is that all net savings increase with the increasing proportion of wood chips in the briquettes. Noting the comparatively compressed scales used in Figures 65 and 66, it can be seen that net GHG emissions and primary energy savings, respectively, decline slightly with the increasing proportion of charred reed.

These outcomes are consequences of quite complex interactions between the harvesting and processing of different types of wetland biomass and their counterfactuals. In general terms, raising the fraction of wood chips in the briquettes increases the annual amount of briquettes produced from a given area because of the higher yield of woody scrub. In turn, a larger amount of briquettes displaces more heating fuel (coal) and, hence, avoids more GHG emissions and primary energy inputs, thereby increasing net GHG emissions and primary energy savings. The most prominent impact of increasing the proportion of charred reed, for any given proportion of wood chips, in the briquettes is to reduce the proportion of press cake. This means that the annual amount of wetland rush harvested and processed is reduced. Rush processing involves generating biogas for use in the CHP unit. Consequently, any reduction in biogas production decreases the amount of surplus electricity and heat provided by the CHP unit. This, in turn, reduces the avoided GHG emissions and primary energy inputs of the surplus electricity and heat markedly. As a result, net GHG emissions and primary energy savings fall with the declining proportion of press cake and, conversely, the rising proportion of charred reeds in the briquettes.

In contrast, Figures 67 and 68 show that net PM_{10} and NOx emissions savings increase with the increasing proportion of charred reeds in briquettes. Again, the complete reasons for this are complex. However, the predominant effect is that increasing the proportion of charred reeds in the briquettes increases the annual avoided PM_{10} and NOx emissions from “open field” burning of reeds. This effect is more pronounced for PM_{10} emissions than NOx emissions. However, for both these types of emissions, it can be seen from Figures 11 and 12 that there are compositions of briquettes for which positive net savings can be achieved as opposed to the negative net savings, representing increases in PM_{10} and NOx emissions, derived for the base case with a briquette composition of 65% press cake, 10% charred reeds and 25% wood chips.

Finally, Figures 69 to 72 illustrate the sensitivities of net GHG emissions savings, net primary energy savings, and net PM_{10} and NOx emissions savings, respectively, to the choice of heating fuel displaced by briquettes and surplus heat from the CHP unit. Figures 69 and 70 show that the highest net GHG emissions and primary energy savings, respectively, are achieved when electric heating is displaced, followed closely by the displacement of coal-fired heating. However, for all choices of displaced heating considered here, positive and substantial net GHG emissions and primary energy savings are estimated. In contrast, Figure 71 indicates that, for the base case, net PM_{10} emissions savings are all negative, representing overall increases in PM_{10} emissions, regardless of the choice of displaced heating fuel. As shown in Figure 72, positive net NOx emissions savings are only possible when electric heating is displaced. For all the other choices of displaced heating fuels, net NOx emissions are negative.

Figure 58: Sensitivity of Net Greenhouse Gas Emissions Savings of the Process to Wetland Biomass Yield

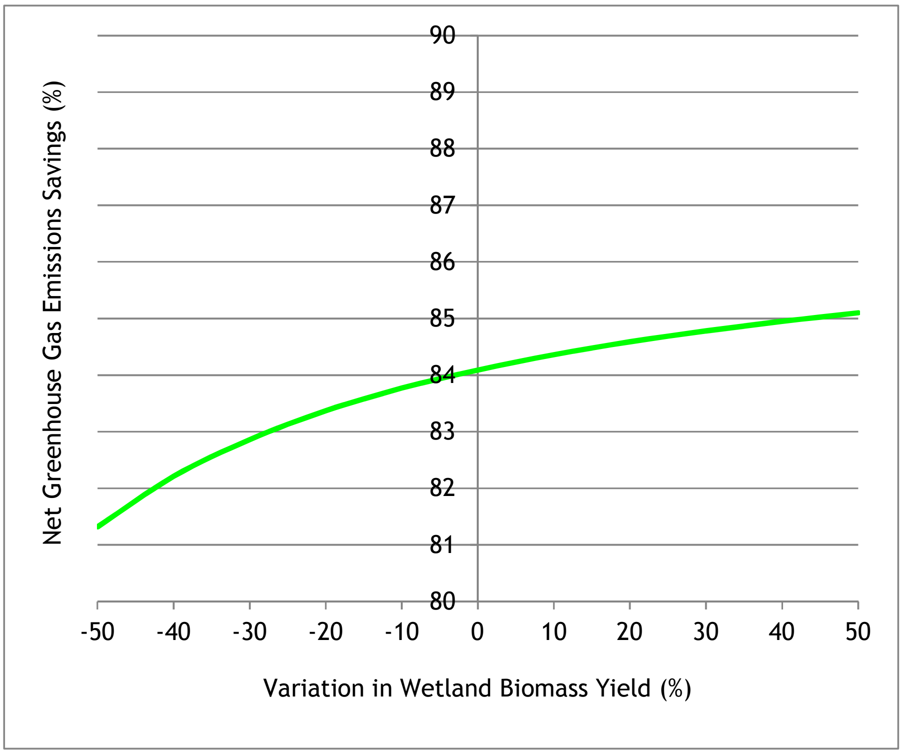


Figure 59: Sensitivity of Net Primary Energy Savings of the Process to Wetland Biomass Yield

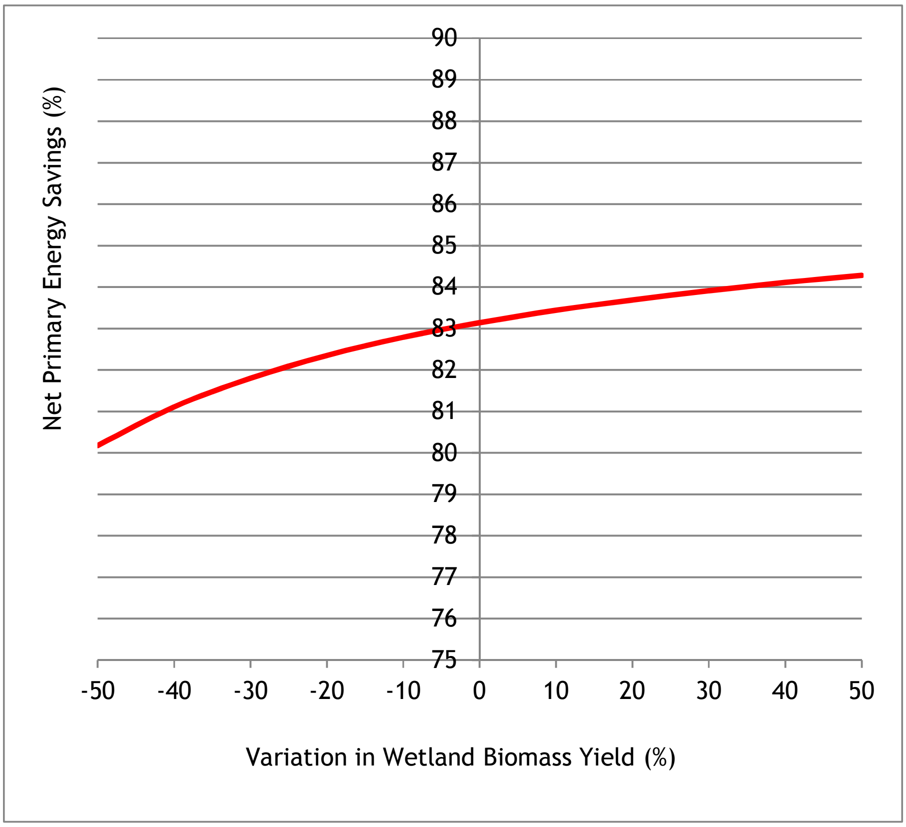


Figure 60: Sensitivity of Net Particulate Emissions Savings of the Process to Wetland Biomass Yield

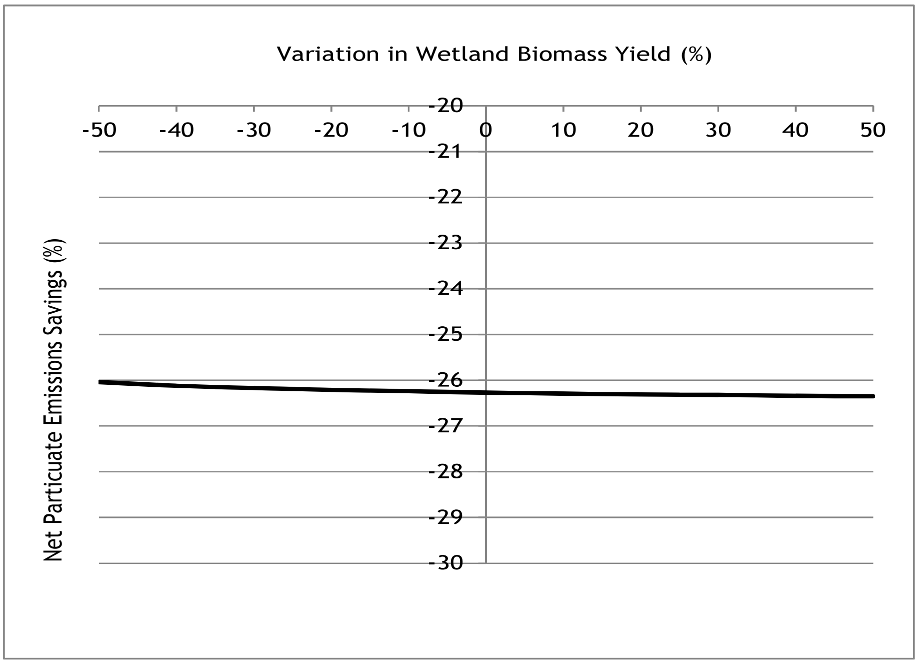


Figure 61: Sensitivity of Net Oxides of Nitrogen Emissions Savings of the Process to Wetland Biomass Yield

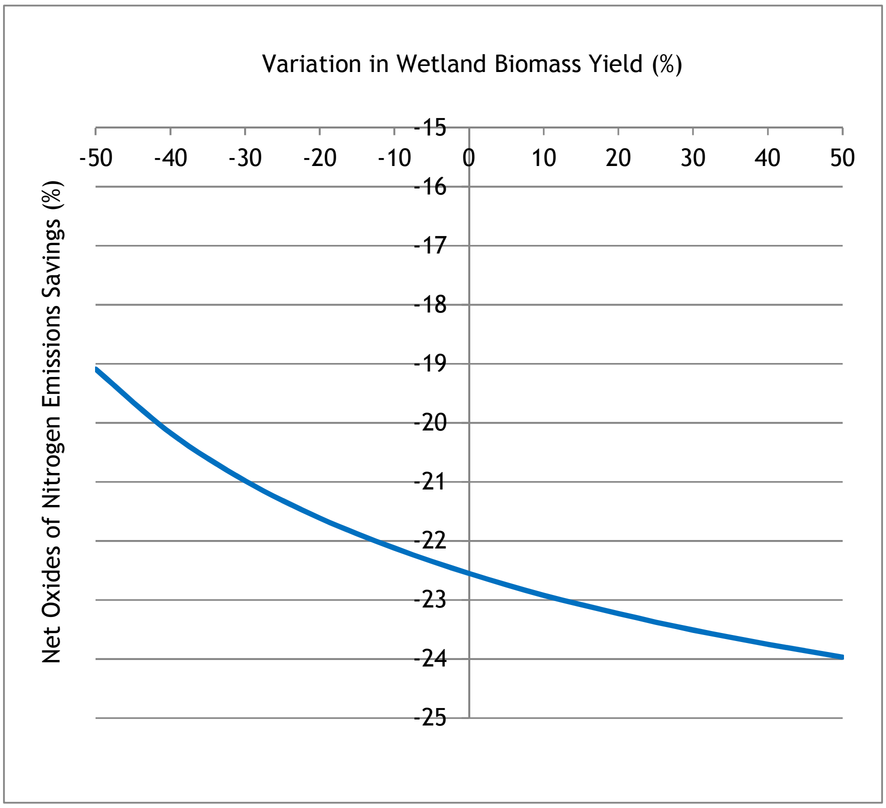


Figure 62: Sensitivity of Net Greenhouse Gas Emissions Savings of the Process to Wetland Biomass Moisture Content

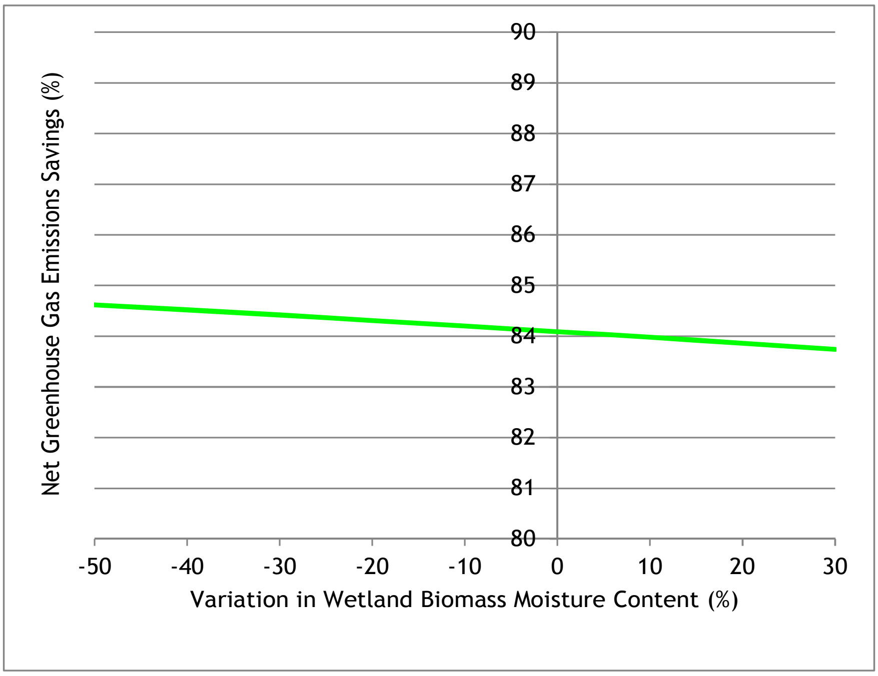


Figure 63: Sensitivity of Net Primary Energy Savings of the Process to Wetland Biomass Moisture Content

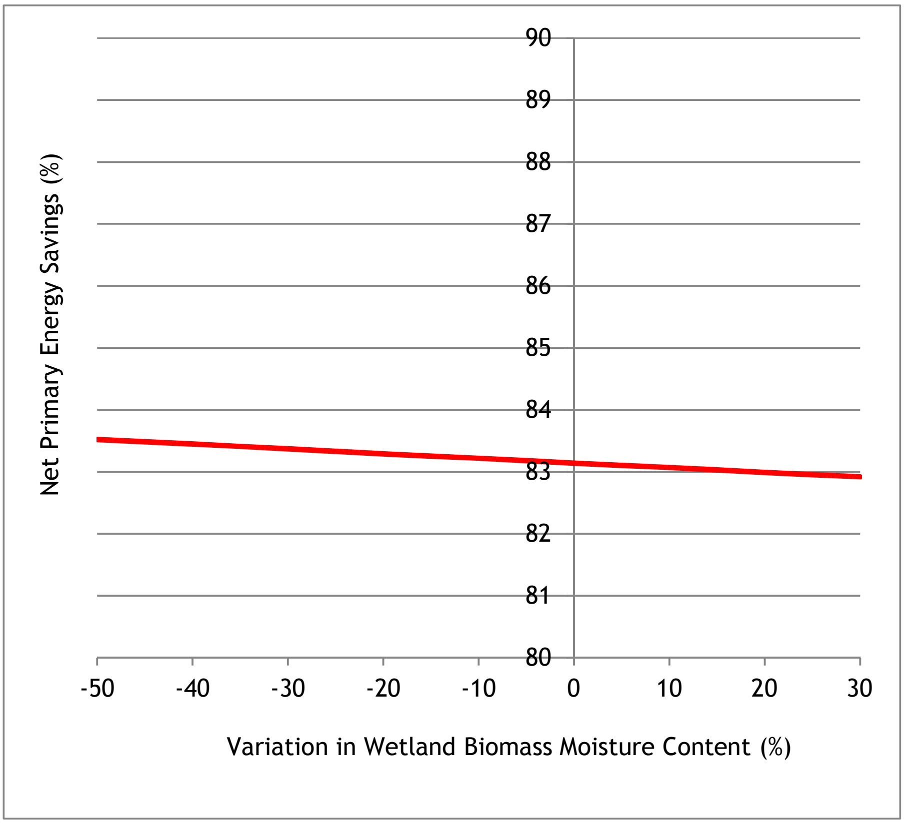


Figure 64: Sensitivity of Net Particulate Emissions Savings of the Process to Wetland Biomass Moisture Content

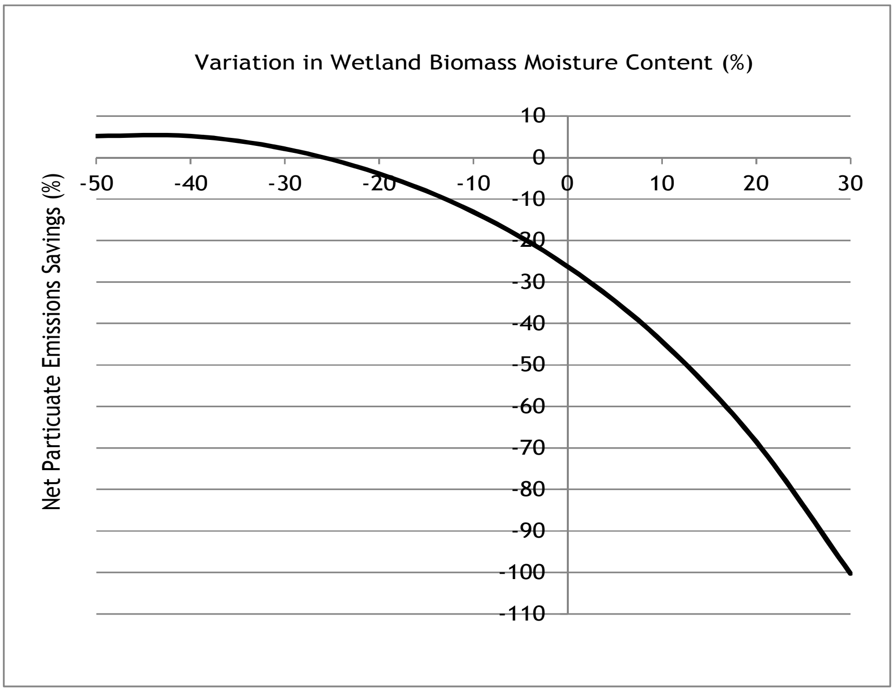


Figure 65: Sensitivity of Net Oxides of Nitrogen Emissions Savings of the Process to Wetland Biomass Moisture Content

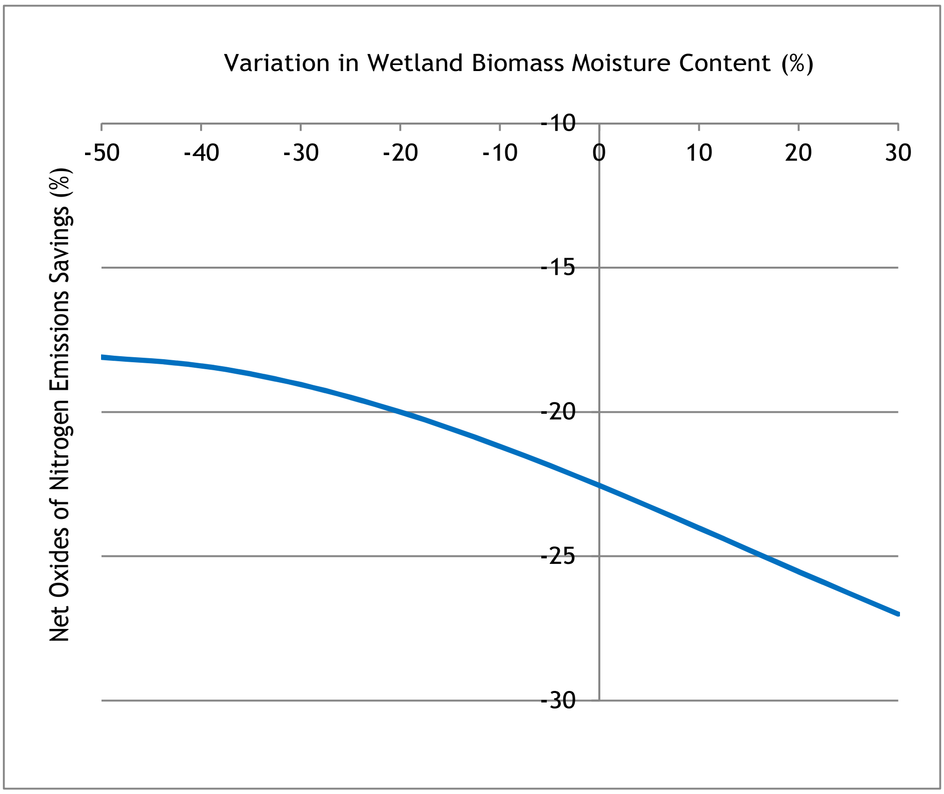


Figure 66: Sensitivity of Net Greenhouse Gas Emissions Savings of the Process to Briquette Composition

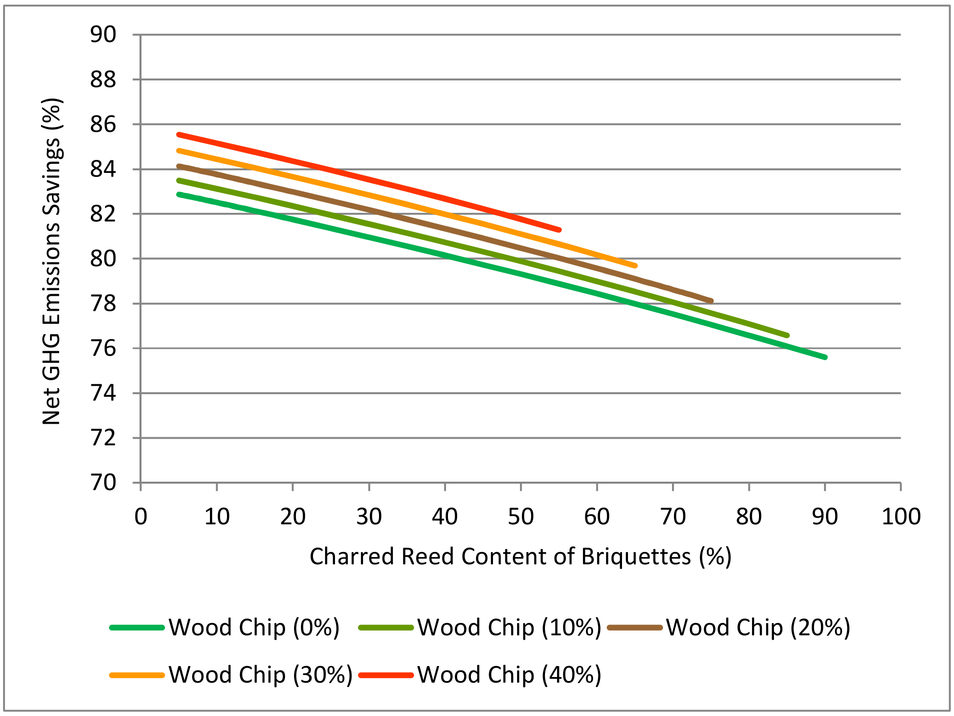


Figure 67: Sensitivity of Net Primary Energy Savings of the Process to Briquette Composition

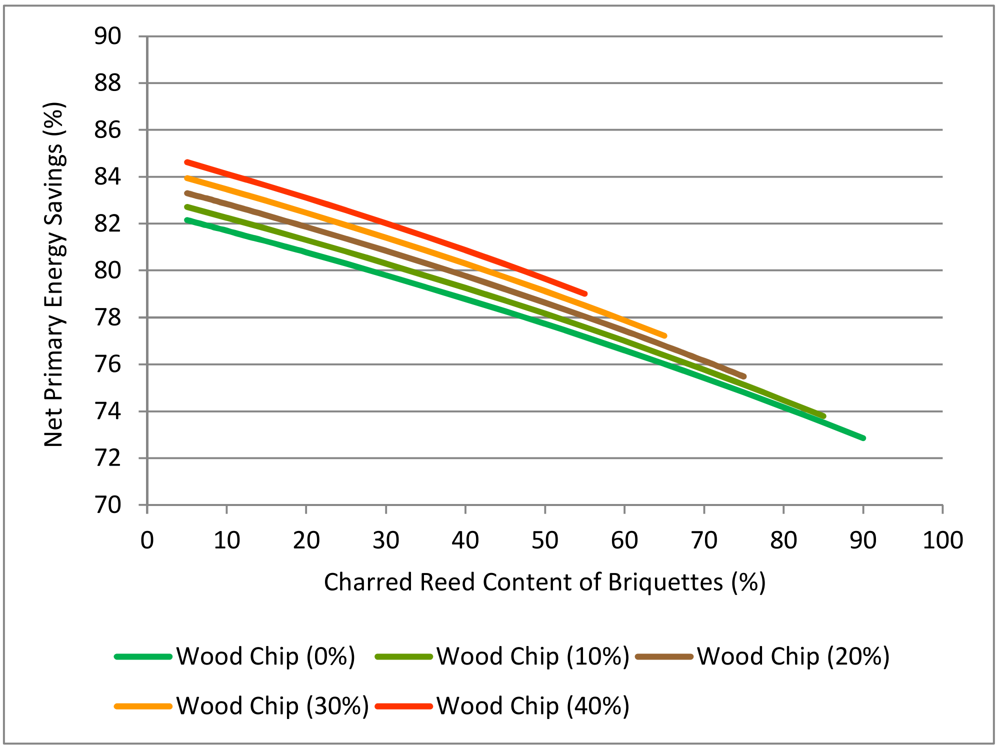


Figure 68: Sensitivity of Net Particulate Emissions Savings of the Process to Briquette Composition

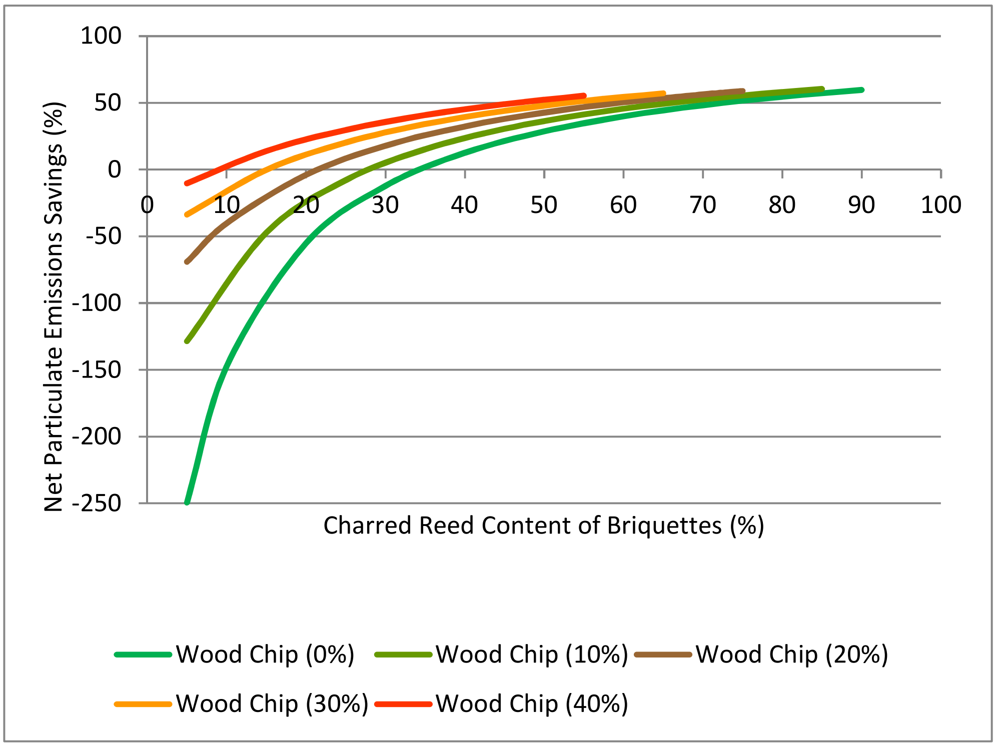


Figure 69: Sensitivity of Net Oxides of Nitrogen Savings of the Process to Briquette Composition

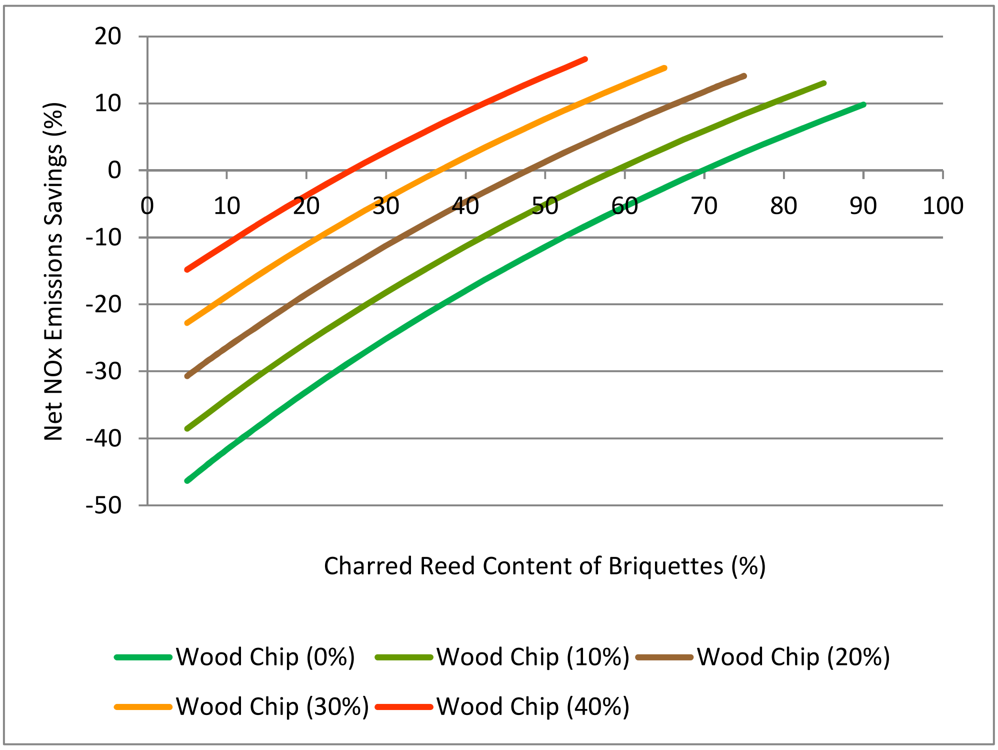


Figure 70: Sensitivity of Net Greenhouse Gas Emissions Savings of the Process to Choice of Displaced Heating Fuel

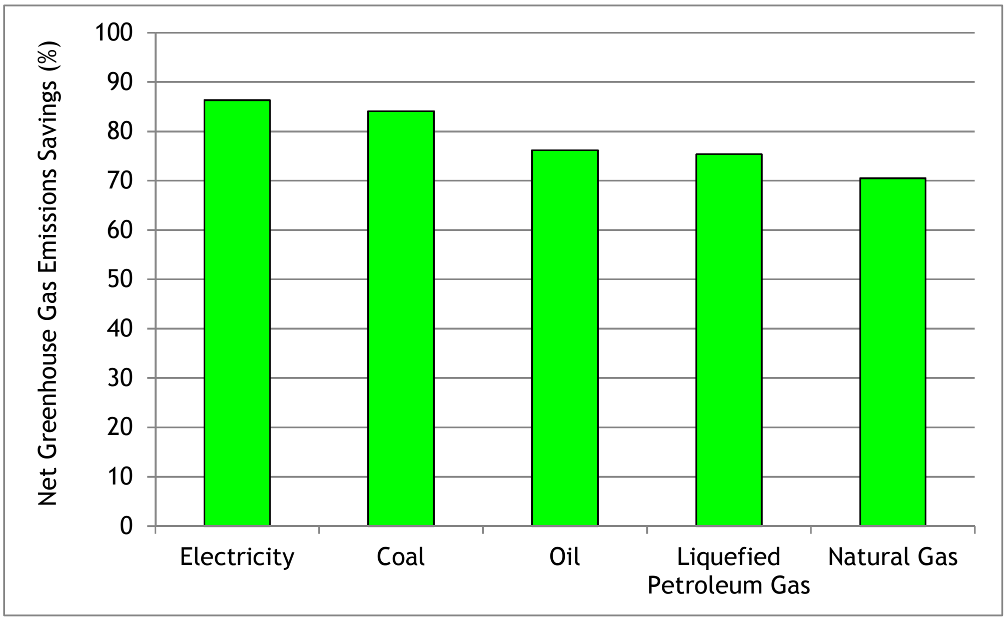


Figure 71: Sensitivity of Net Primary Energy Savings of the Process to Choice of Displaced Heating Fuel

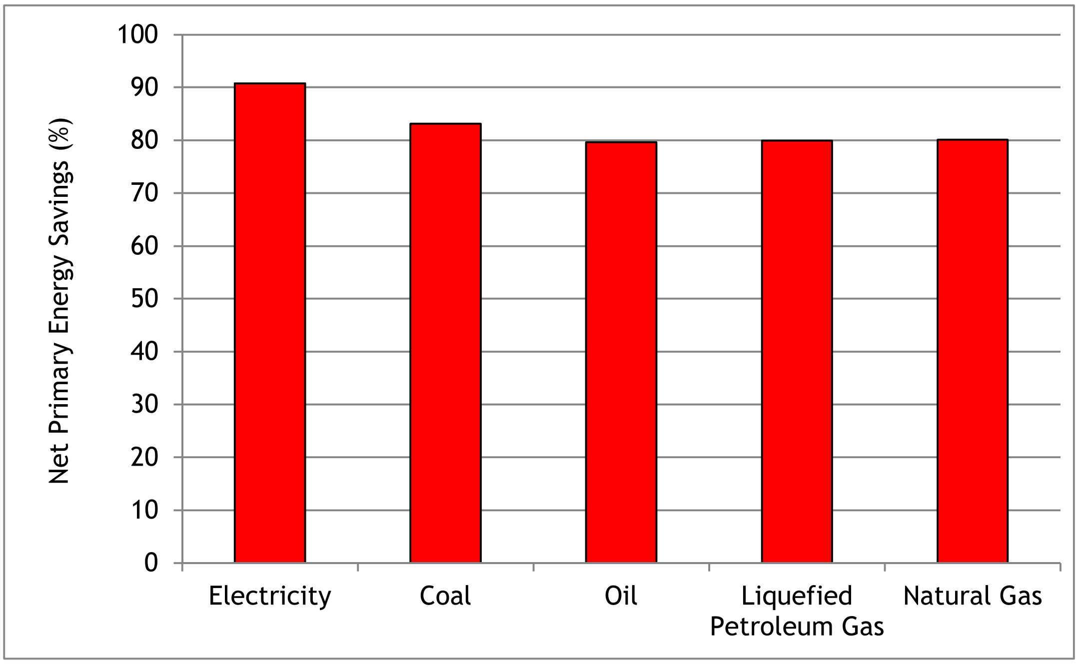


Figure 72: Sensitivity of Net Particulate Emissions Savings of the Process to Choice of Displaced Heating Fuel

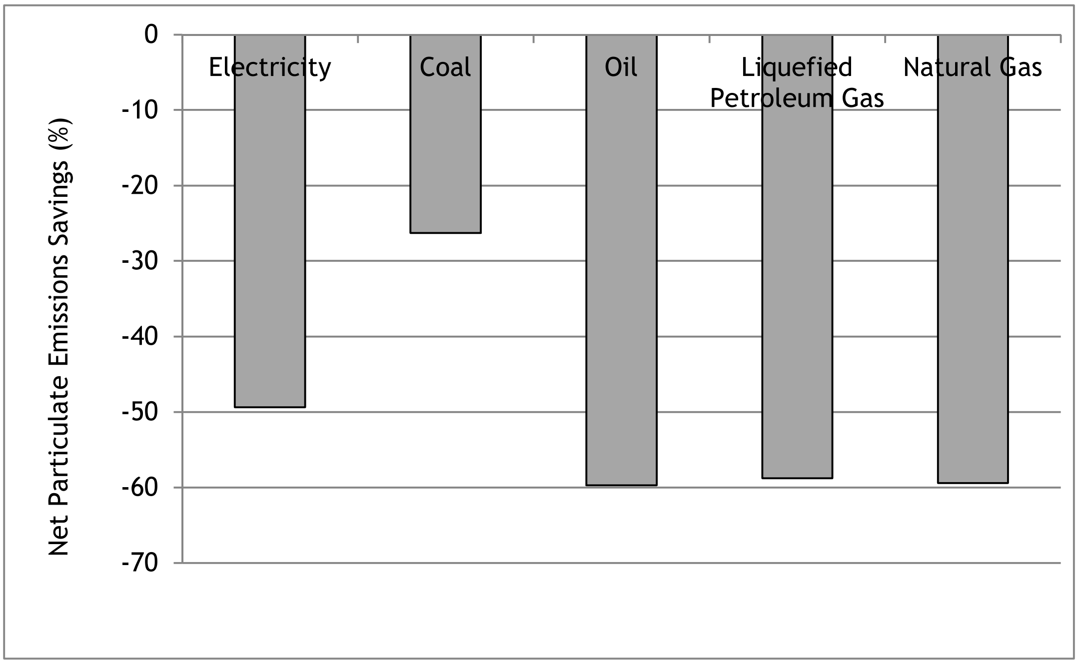
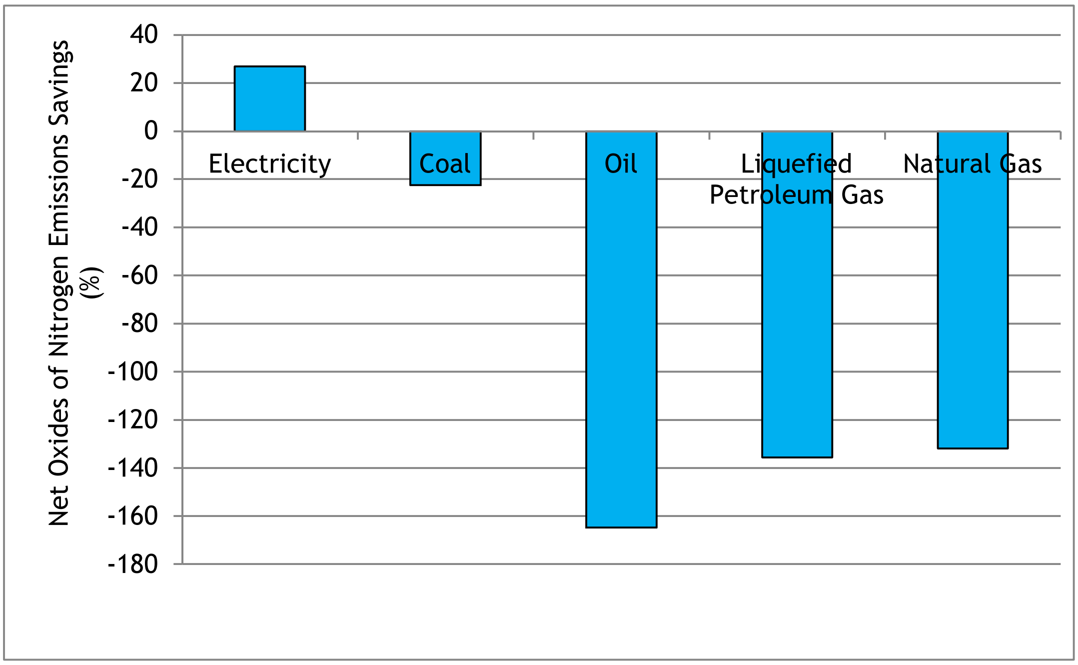


Figure 73: Sensitivity of Net Oxides of Nitrogen Emissions Savings of the Process to Choice of Displaced Heating Fuel



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