Transport economics for short rotation coppice

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1. ABSTRACT

Short rotation coppice willow (*Salix)* has been identified as a potential sustainable energy source but there is no proven, cost-effective system in place for delivering the fuel in the most acceptable form to either small or large scale users. A study was therefore undertaken to ensure the selected concepts for designing an "ideal" willow coppice harvester conform with the optimum system for growing, handling, comminuting, transporting, and storing of the biomass.

To lead the way forward, an efficient and reliable coppice harvesting and handling system needed to be identified. A number of prototype machines exist and have been evaluated over recent years. In addition a series of scientific studies have been conducted on SRC yield production, drying, storage, and transport options. The aim of this study was to bring together all the relevant information, to synthesise it, and then to present a series of concept options to the British biomass industry to determine the optimum harvesting and processing system.

2. INTRODUCTION

Harvesting short rotation coppice (SRC) crops for energy purposes cannot be considered in isolation from the subsequent activities necessary to get the material delivered in the most suitable form at the conversion plant and at minimum cost. In addition the establishment, layout and agronomic management practices of the crop should be determined in part by the harvesting method anticipated. In this case study willow was the chosen crop but similar principles apply for a range of biomass crops. Willow is deciduous and normally harvested during winter after leaf fall. In addition, under British conditions, poor weather at this time can restrict harvesting operations which therefore were assumed to operate for only approximately 50 days each year.

In order to produce a high quality biofuel on a sustainable basis and to minimise the costs in terms of £/GJ of fuel delivered, the whole process therefore needs to be viewed as a **system** for producing a high quality biofuel on a sustainable basis and for optimising the costs in terms of £/GJ delivered. The harvested crop can be quantified in terms of GJ/ha/year, but losses during the harvest, storage and transport operations will reduce the energy available for conversion to heat and power. Minimising these losses needs to be given due consideration during the development of the optimum system.

In the assessment of harvesting options, the assumption was made throughout that there is only a short harvest window of around 10-12 weeks in the winter period but that the fuel will be required over a 12 month period. If electricity production is the main objective, then a 10 to 12 month storage period is inevitable in order to maximise return on investment in the generation plant. The common Swedish bioenergy system of a district heating plant, with bottoming cycle steam turbine to generate some power, and fuelled partly by SRC willow, avoids the major problem of biofuel storage since the winter harvest period for *Salix* closely matches the period of peak heat demand. In addition where wood gasification conversion systems are to be used rather than steam boilers, then dry fuel is essential.

All year round harvesting could serve to partly overcome these storage and drying problems but, although worthy of further investigation, was not considered in this study.

3. CONCEPTS AND SCALE OF OPERATION

A number of broad harvesting categories, based partly on the scale of operation, can be identified. Examples are given below.

- Large scale cut and **chip**, self propelled machine. Chips stored on farm or at conversion plant.
- Large scale cut and **billet**, self propelled machine. Billets transferred to simple on farm storage initially then later comminuted to the form as required at the conversion plant.
- Large scale **stick** harvesters, self propelled machine. Where no indoor storage facilities exist for large volumes of material, which is the case on many farms, sticks can be stored outside in piles, or in tied bundles or as compressed **bales** (Figure 1). Comminution to produce the biomass in a form suited to feeding into the conversion plant could then be undertaken later, either on the farm if for local use or to maximise transport payloads, or at the power station.
- Medium scale machines mounted around conventional self propelled power units for stick, chip, billet or bale production as above.
- Small scale, trailed, stick harvester for grower/contractor use on smaller areas using conventional agricultural tractors as power units (Figure 2).

Depending on the scale, comminution can be accomplished either
- on the farm if the fuelwood is destined for local use; or
- on the farm in order to maximise transport payloads; or
- at the power station if it is cheaper overall to do so and also to provide a consistent fuel quality to suit the conversion plant design in terms of piece size and moisture content.

Until the market develops for fuelwood from SRC willow there will be only a limited demand for harvesting equipment. Therefore it would be impractical and not economically viable for a business to consider manufacturing harvesting equipment to suit all the above categories. In this study only the two extreme categories will be considered:
- a large scale system to supply a 10 MWe power generation plant by harvesting at least 1000ha of SRC per year;
- a small scale system to supply the grower with sufficient fuelwood to be used on site for heating alone or possibly for cogeneration with grid connection to export excess power.

Figure 1. Bales of willow sticks formed by Swedish baler under test in UK

Figure 2. Tractor powered stick harvester suitable for small scale harvesting

3.1 Large scale system

This case study was based on a commercial power plant as outlined below buying in the fuel from local growers under contract.

- Combined cycle gas turbine plant.
- Capacity: 10MW$_e$ gross, 8MW$_e$ to be exported.
- Fuel demand: 5 odt/h, @ 8000 h/y (which assumes 91.3% availability) = 40,000 odt/y.
- Fuel storage: need 34,000 odt stored on a hard standing area of > 100,000 m^2 , the other 6,000odt being fed into the plant directly on delivery during the harvest period of 50 days.
  Storage area *filled* over 90 days @ 50 odt/h, and being delivered for 8 h /day.
  Storage area *emptied* over 275 days @ 5odt/h for 24 h / day.

Note: various other options would be feasible such as emptying at 15 odt/h over the 275 days for 10h/day, the choice depending on the optimum time and period for power generation in order to maximise revenue, i.e., to supply base load or peak load.

Alternatively it could be possible to have long term storage off site and only short term storage and drying on site.

3.1.1 Drying. Fuel moisture content of < 20% (w.b.) is required by the gasifier so there is a requirement to deliver the fuel at an acceptable heat value in order to produce quality gas at a level acceptable for firing into the gas turbine.

(a) For chip piles at a drying capacity of 40kg/h/m^2 using air at +28^{o}C above ambient from power plant waste heat (which can be assumed to be free), the floor area needed would be 125 m^2 with a bed depth of 0.4m. A 300kW fan is required to give a constant fan pressure of 1.5 kPa. Energy consumption will be 80kWh/odt which at £0.05/kWh is £4/odt.

(b) Modified grain dryers could be used for drying the fuelwood where available on a farm, (the willow being harvested at a different season to the cereals). This will need:
   - a batch storage / drying system for five days fuel capacity = 720 odt chips.
   - a drying floor of 20 bays of 145 m^2 each and 2 m depth.
   - drying from 50% w.b. at harvest to 15% w.b. in four days using air at 23^o C.

The final desired form of woody biomass feedstock material is determined by the fuel specifications of the conversion plant in terms of acceptable moisture content and particle size ranges. Delivery of fuelwood to the plant site can be in a wide range of forms since the final processing operation can be conducted on site immediately prior to feeding the feedstock into the conversion plant. A wider range of fuel moisture contents may also be acceptable if the desired level can be reached by blending wet biomass with dry, or if the plant has some form of artificial drying facility. However a cost penalty to the grower for supplying wet fuelwood is likely.

3.2 Small scale system

This case study was based on a grid connected, on-farm cogeneration plant where the heat can be usefully used and the fuel is grown by the farmer.

- Gasifier and gas engine operate 5000 - 6000 hours per year.

- Capacity: $100kW_e$, 80% of power exported; heat used for grain drying, space heating of house and buildings, and hot water.
- Fuel demand: 300 odt/y. 30 ha planted in SRC willow; two year rotation; yield of 10 odt/ha/y.
- Storage: Use bulk grain store if empty (i.e. if cereals have been sold off the farm by the time of harvest). If not available piles of chips outside are the alternative, ideally covered with plastic sheets.
- Drying: two stage:
  - using heat from grain drying plant in batch drying at harvest, and
  - using exhaust heat from cogeneration plant immediately prior to delivery to the gasifier.

4. METHODOLOGY

Recent project reports on SRC harvesting and drying were reviewed and a summary table of all characteristics of the harvesters that had been tested and evaluated in the field was compiled.

Informal discussions were held with a wide range of stakeholders in the industry both in the UK and Europe to ascertain their personal concepts for harvesting SRC and priorities for R&D. There was no obvious consensus and many personal preferences were evident. So no opportunity resulted to " pick a winner" from all the harvesting options presented.

Design variables were developed for a SRC harvester. For each specification parameter (i.e., overall machine size and design; work capacity; width of cut; cutting mechanism; comminution; transfer mechanism; transport from field; road transport; storage; drying) the effects each has on the other variables, the limitations imposed by other factors, and a list of options was produced. This summary clearly identified the fairly complex inter-dependencies of any one factor on the others (see Appendix 4.2).

A simple spreadsheet to calculate storage and transport volumes for baled SRC was developed.

Cost comparisons for various systems were made possible by Modelling the various transport options. As a result of this overall process, the preferred concepts for harvesting machines and developing new handling and transport fuel supply systems were identified.

5. ASSESSMENT OF SRC HARVESTING AND FUEL SUPPLY SYSTEM COSTS

5.1 Assumptions

The standing crop to be harvested and processed was 2 year old willow coppice yielding 40 wet t/ha in a 12 ha field. The harvesting and various supply chain systems were modelled for power station supply from the standing crop through to the power station gate 39.5 km away from the farm gate. Additional costs for loading and chipping/ shredding at the power station were included as a separate cost. In the analysis, the costs presented are for oven dry tonnes (odt) of dry matter delivered to the power station. In the base case, the cost the growers are paid for the standing crop was taken as £20/odt, but this could be modified or excluded from the calculations if desired.

The different harvesting systems result in the coppice being delivered in different forms: as bales, billets, or chips, and as green or partly air dried material. An allowance for dry matter losses in store was made with assumptions of 4% per month loss for chips, 2% for bales and for sticks and 1.5% for billets. The user must decide what value should be put on biomass materials and dry matter losses in each different form to suit the specific case.

The scenarios listed below have been chosen to represent various practical options. The cut and chip harvesters and the Empire 2000 stick harvester have been evaluated in field trials and the performance data is based on these results. The assumptions for capital cost, work rate etc. for each harvester machine used in the model are listed in Table 1.

There is interest in the use of a one-pass cut-and-bale machine for felling and baling coppice material in the field (see Recommendation 1 below). No such machine yet exists so in order to model this option, three scenarios were presented (A, B, C) based on experience from straw baling, one for round bales and two for large square bales. These scenarios illustrate what might be achievable if such a machine were to be built. The concept would be a cutting head attached to the front of a commercial baler such as the Claas Rollant or the Hesston square baler, with the cut sticks being possibly crimped or billeted before being fed into the baler directly. Dropping the cut sticks onto the ground for subsequent collection, possibly after a period to allow some drying to occur, would have some advantages but would be difficult to achieve without high field losses and damage to the stools by the baler pick-up.

6. SYSTEM DESCRIPTIONS AS USED IN THE MODEL

A. *Large round bales.* Based on the Claas Rollant baler with options for net wrapping or twine, the former being faster. A summary of the assumptions used is given in Table 1. The scenario is based on the performance of a round baler for straw with some account taken of the trials on forestry residue bales using the Swedish ‘bala press’. The steps involved in the supply chain are similar to those outlined for well established straw baling and handling systems. Mowing was assumed to cost £36/ha with the mower attached to the baler and a simple crimping or billeting system installed before the baling section. From the 12 ha area used in the analysis, 960 bales of 500kg each can be produced. The bales are dropped in the field for later collection by loader on to a flatbed trailer for delivery to the headland or farm store. A six months average store period was assumed and then the bales are collected and transported by a HGV (heavy goods vehicle). Alternative options would be for the baler to carry the bales directly to the headland for stacking and intermediate storage assuming the HGV could gain access to this point, or for a loader to transfer the bales from field to headland one bale at a time. The HGV is unloaded using a front loader at the power plant and the bales are then fed into the boiler directly.

In this and all other system scenarios (except B and E which are transported directly to the power plant), the transport distance assumptions were:

Travel in field	0.5 km	(8km/h average)
Travel on farm track to farm store	0.5 km	(10km/h average)
Travel from farm store on farm track	0.5 km	(“)
Travel on unclassified roads	9.5 km	(40km/h average)
Travel on single carriageway A/B roads	30 km	(55km/h average)
Total travel distance one-way	41 km	

B. *Large square bales direct to power plant.* This scenario is based on a Hesston high density baler which has become the industry standard for handling straw in Danish power plants and for industrial applications in the UK. It is assumed that these bales are bound with twine.

The steps involved in the supply chain are those broadly used for straw baling systems except it was felt that a self-loading bale carrier would not work satisfactorily amongst coppice stools. So the modified system is:

- mowing, here using a Claas header or similar attached to the baler;
- baling, directly after mowing without dropping the cut material;
- Fastrac tractor and loader to take single bales from the field 0.5 km direct to the HGV.
- 35t gross HGV travels 1km on farm tracks at 10km/h average, 9.5 km on unclassified roads at 40km/h, and 30 kms on single lane A/B roads to the power plant at 55 km/h.
- Unloading by front loader.

600 square bales were produced from the 12 ha field, each weighing 800 kg.

C. *Large square bales to farm store.* As for system B above but with a front loader and tractor/trailer to transport the bales from the field to the farm store since it was assumed a self-loading bale carrier would not work. Unloading at the farm store and collection by HGV after an average period of 6 months. The HGV is a 35t gross articulated low-bodied flatbed trailer which is loaded and unloaded by a front end loader.

D. *Claas forage harvester (cut-and-chip).* Short rotation coppice material is cut and then chipped involving the following steps:

- direct cut and chip blowing into one of two 15 m^3 trailers pulled by 85 kW tractors,
- in-field transport tipped at intermediate store,
- pushed into a heap on hard standing by loader and stored for 6 months on average,
- loader used to fill 38t articulated bulk tipping HGV,
- HGV takes chipped biomass to power plant where it is tipped.

Based on Forestry Commission trials a harvesting rate of 10 odt/h was assumed which is equivalent to 0.5ha /h. Two tractor/trailers were used to convey the chips 1 km on average to the farm store for later collection.

E. *Claas forage harvester with no storage.* This uses the same harvesting machine as system D but the material goes straight from the field to the plant using three 45 m^3 trailers to collect the material direct from the harvester in the field. This illustrates a harvesting operation suitable for dry soils in fields within a reasonable transport distance (40 km) of the plant. It would be the most probable scenario if all year round harvesting was proven to be feasible. Wet chips at around 50% m.c.w.b. are delivered.

The steps involved are :

- direct cut and chip blowing into trailers,
- in-field transport and road transport in trailers pulled by a Fastrac tractor then tipped at the plant.

The 480t of chips delivered would require a storage area of 125 m long, 7 m wide for which land rent is included in the analysis and be piled 3 m high.

F. *Empire 2000 stick harvester.* The costs/ hour and work rates for this system were taken from Forestry Commission calculations. The steps are:

- sticks cut and carted to the headland by the harvester;
- loader loads trailer and tractor;
- on farm storage of sticks after stacking by loader;
- chipped on farm direct into 38t HGV tipping trailer.
- driver and articulated truck arrive to collect the full trailer for delivery to power plant.

A productivity of 7odt/h was assumed which equates to 0.35 ha/h.

G. *Austoft harvester (cut and chip).* As for the Claas chipper system D above but using the Austoft modified sugar cane harvester at the assumed higher cost of £82.81/hour. A productivity rate of 10odt/h was assumed based on Forestry Commission trial results data.

H. *Austoft harvester (cut and billet).* This is the same system with the same steps as for systems D and G above but with the Austoft harvester modified to produce billets rather than chips. The hourly cost is slightly lower as less power is required for billeting than chipping and less knife maintenance is required. This results in lower storage costs but the other input data remains the same. The definition of a billet is a piece size which is bigger than a chip but is small enough to allow the bulk material to be handled by bucket loaders and on belt conveyors. It is large enough to allow air to naturally ventilate in a stack and prevent spontaneous heating. The work rate, machine costs and product bulk density were assumed to be the same for the Austoft harvester in both cut-and-chip and cut-and-billet modes of operation.

models

System	A	B	C	D	E	F	G	H
	Mower/ round baler (farm store)	**Mower/square baler (direct deliver)**	**Mower/ square baler (farm store)**	**Claas harvester (chip & farm store)**	**Class Harvester (direct and store at plant)**	**Empire 2000 (stick, farm store & then chip)**	**Austoft Harvester (chip & farm store)**	**Austoft Harvester (billet & farm store)**
Machine cost £k	?	?	?	182	182	91	190	190
Hourly harvester cost £/h	36.51	78.38	78.38	65.12	65.12	44.75	82.81	80.00
Work rate odt/h	10	16	16	10	10	7	10	10
Road transport payloads (odt)	11.25	12.0	12.0	14.85	14.85	8.7 for sticks 14.68 chips	14.85	13.5
Total loss during storage (%odt)	12	2	12	24	0	9	24	9

Note the dry matter losses during storage vary with time but for the same period (e.g., six months on average) are greater for chips, than for bales, than for billets or sticks. Where the biomass is taken directly to the power plant for immediate use the losses are negligible.

A summary of the analysis is given in Figure 3. Systems E and B show the lowest delivered fuel cost. This is not surprising as for these options there was no intermediate storage, the fuelwood being delivered directly to the plant for immediate use. This option is appropriate in some circumstances, for example in Scandinavian district heating plants where the main heating demand season matches the season for harvesting *Salix* coppice crops. In many other situations (such as for electricity generation or process heat), it is more likely that storage will be needed to provide a plant with fuel supplies all year round. This will increase the costs of supply due to the additional handling operations and storage losses which may result. This confirms the benefits of having a mix of fuels from a range of sources so that the amount of fuel going straight from source to plant can be maximised.

Where SRC is to be the major fuel source, this study shows the potential cost reductions that could be achieved if the crop were to be harvested all year round. Provisional studies, both in New Zealand on coppice *Eucalyptus* and in the UK on *Salix*, have shown that there is potential for such a management system without loss of yield over a sustained period. The advantages which would result in terms of reduced dry matter losses, together with lower handling and storage costs, justify further research.

Where storage of fuelwood is necessary to provide an all year round energy supply to a plant, the costs will be increased significantly. This confirms the benefits of having a mix of fuels from a range of sources so that the amount of fuel going straight from source to plant can be maximised. For a wood-fired plant such sources might include wood process residues, forest arisings and SRC. In some circumstances it may be appropriate to mix fossil fuels with the biomass to ensure a low cost supply. This reduces the risk associated with obtaining secure supplies of fuelwood for the long term and gives time for confidence to be generated in the supply chain by the plant operators.

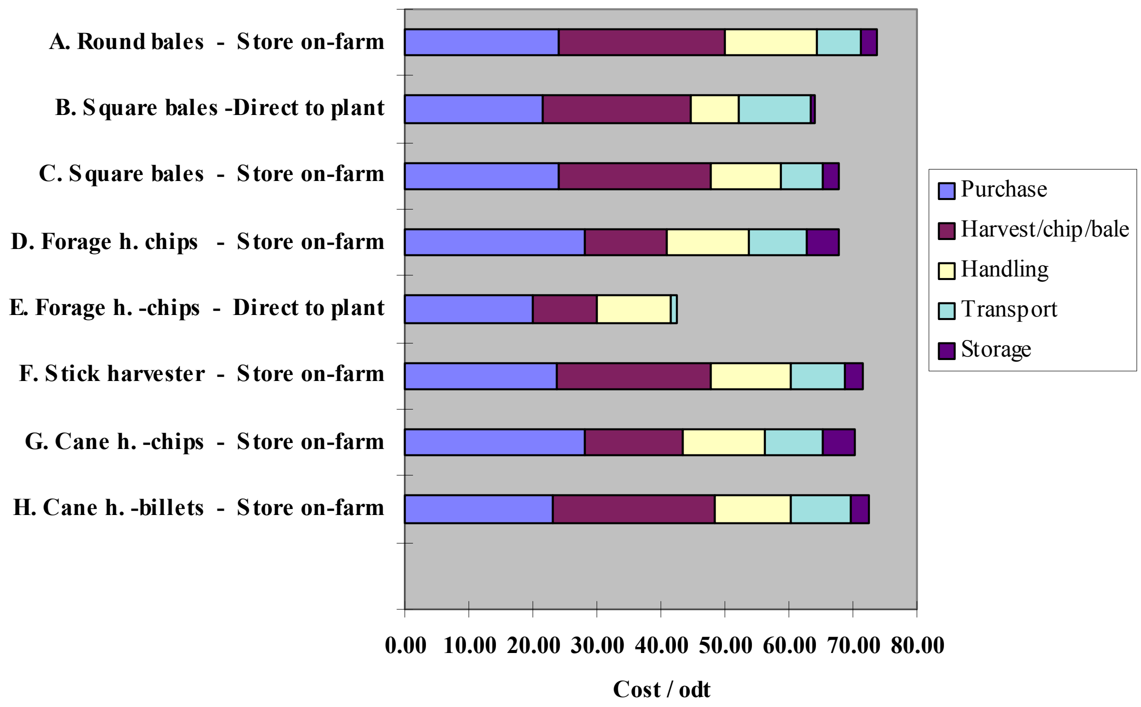

Figure 3. A comparison of delivered costs of a tonne of oven dry fuelwood to the power plant gate (£/odt) for the eight selected system options

In systems where fuel storage is required, the study showed that cut-and-bale or billeting systems could be competitve with chip systems and are worthy of further investigation. The big advantage of billets and bales, which was not fully evaluated in the analysis, is that the fuel delivered to the plant in these forms has a lower moisture content than do chips from the same source and suffers less degradation in store over any given period. However, chipping and screening at the plant to produce a consistent quality fuel will be necessary.

Recommendation 1. Bale the cut SRC sticks or chunks into large round or square bales using existing agricultural baling machines mounted on a tractor/mower to give a one-pass machine with either:

- **bales dropped on ground for subsequent collection by tractor/front loader and transport to trailer or truck;**
- **or bales carried to headland on baler for later collection by truck.**

It can be assumed that large scale wood-fired power stations in the UK will probably use a mix of existing forest arisings and wood process residues as their main fuels, together with fuelwood from SRC. Therefore delivering the range of biomass material in a standard form is essential for cheaper and easier handling at the plant. If one truck load delivers biomass in the form of bales and the next as chips, it would be more difficult to handle and process than if all trucks delivered bales or all delivered chips. It must be borne in mind that for larger plants there may be one truck arriving every 5–10 minutes so there is little time to handle the material. Hence having a standard from of delivery is essential.

Bales could be an ideal method of densifying the material to provide transport economies in terms of maximising truck payloads. The costs of baling are however likely to remain uneconomic unless higher throughputs can be achieved than at present and the balers can be used for other crops or purposes during the year in order to spread the fixed costs of ownership.

Since it would be extremely difficult to design a machine to pick up harvested sticks dropped on to the ground after cutting without damaging the remaining cut stems, a mower/baler machine combination seems a desirable design goal. The German company Deutz-Fahr have designed and tested just such a self-propelled prototype machine based on using either a Claas round baler or Heeston square baler. The concept was tested on willow biomass material in the field and by feeding in cut material in a test laboratory. The machine has not yet been made commercially available. An evaluation and cost analysis of this option is given in Systems A, B and C of the cost analysis.

Baling of SRC would also be suitable for the small grower supplying the power plant if a contractor in the locality could be hired or if the baler could be supplied by the owners of the plant for hire by the growers.

This bale system could possibly be used by a small farmer growing SRC to supply heat demand on farm or nearby if the bales could possibly be fed into a whole bale burner as developed for straw bales in Denmark. However if a small gasifier is preferred, a small uniform piece size is desirable so the bale would first need comminuting. This would then require specialist and costly equipment.

Costs. The biomass transport model was used to quantify baling costs for three scenarios, systems A, B, and C (Figure 1). Costs ranged from £65 – 75/odt delivered and were no better than most other options. Mass production of the mower/baler to bring the unit price down would be needed to have a significant affect on costs.

Recommendation 2. Develop a billet system around the Austoft sugar cane harvester or a chain cutter/stick harvester with a billeter mounted on the chassis. Either would need a conveyor with support trailer running alongside, or a mounted bin to carry billets to the end of the row for unloading hydraulically

The advantages of this system are as follows.

- Uses existing equipment, the base machine being also available for chipping as well as for billeting but with some modifications required.
- Harvesting costs of around £10/odt is cheaper than using whole stick harvesters.
- Work rate of around 0.25ha/h will require 16 x 10 hour harvest days to complete 15 ha of 10odt/ha crops, so the harvester could be shared with 4-5 other growers on a syndicate basis if 50 harvesting days are available during the season.
- Acceptable soil compaction even on wet sites due to half-tracks.
- At a work rate of 0.4ha/h and assuming 50 x 20 hour working days, the large scale plant would need 3 similar harvesters to harvest 1000ha/year.
- Harvesting costs for billets delivered to the power plant would probably be similar to chips at approximately £70/odt, but storage of billets rather than chips over long periods provides an overall advantage as a result of less dry matter losses whilst in store, lower energy inputs, and cheaper drying. (Note: Use of the Austoft sugar cane billet machine was modelled using the transport programme and is reported as System H, Figure 1).

As mentioned earlier, year round harvesting, if agronomically feasible under UK conditions, would have a significant effect on harvesting costs and storage systems.

Recommendation 3. For small scale systems on farms with existing grain drying facilities, a manual chainsaw or simple tractor mounted single disc saw blade used for older single stem trees and the trees later manually fed into a mobile chipper

After cutting with a chainsaw or tractor mounted sawblade, a simple harvesting system could be envisaged at this scale with a front-mounted chipper on a farm tractor with trailer towed behind. Feeding the chipper would be manually which would limit the size of tree that couold be harvested. However after being left to dry for some weeks, the tree weight would be less due to moisture loss. Trailer transfer when full would occur at the headlands. The commercial availability of such systems and the potential market for them needs to be identified but they would use mainly existing equipment. The proposed drying system would also need to be fully tested analysed to ensure it works with this chipped biomass material.

This concept has been well researched and developed, but now needs to be commercially proven.

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