Comparison of possible supply chains for forestry derived biomass for bioenergy in New Zealand

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Executive summary

Whilst the need for bioenergy in New Zealand is clear, the best ways to deliver the required or available biomass is less well defined. In many countries residual woody biomass from forest operations is a significant resource. In New Zealand this is also the case, and our forest residue resource is up to 4.1 M green tonnes (1.64M odt) per annum with only a small proportion of this being utilised. Lower quality K grade logs that are exported unprocessed are a further significant potential resource with a long run supply of a further 5.4M green tonnes per annum.

For bioenergy fuel derived from forestry residues to play a greater role in New Zealand's drive to a low carbon future the supply chain for this resource must be optimised, with costs being as low as reasonably possible as a result.

This report covers analysis of forest residue harvesting systems, including the use of aggregation hubs and the effect of screening, storing and drying on the cost of process heat delivered by a biomass fuelled boiler.

The lowest cost fuel and heat energy is that derived from chip logs from a conventional forest via a hub that does storage, drying and chipping ($11.19 per GJ of heat).

The next lowest costs are from residuals produced at landings via a hub that does full processing including hogging ($11.92 per GJ). Next cheapest is landing residues which are taken direct from forest to heat plant and do not go via a hub ($12.93 per GJ).

A suggested system incorporating a hub is one where the material delivered to a hub is subsequently;

- screened to removed fines, dirt and oversize
- stored under cover
- stored on a floor that has passive air inlet pipes
    - upper layer vent pipes could also be considered in high humidity or cooler temperature environments as these may increase the drying rate slightly
- stored for a period of 2 to 3 months, less being preferable

The cost of operating a hub that includes these features was estimated at ~around $6.00 per tonne or $0.67 per GJ assuming the material coming out of the site has reached a moisture content of 40% wet basis (8.9 GJ per tonne) over a storage period of 3 months.

Chip logs direct to the user with chipping at the boiler site is the next lowest cost, followed by material derived from a short rotation forest (16-year rotation) with the material going via a hub that includes chipping. This assumes wood with a moisture content of 54% or can be obtained from these logs.

There are a cluster of supply chains that all have similar costs ($14.90 per GJ to $15.54 per GJ). This cluster includes those supplying material derived from cutover residues.

The use of K grade logs (especially through a hub) would be cheaper than growing miscanthus, SRC or SRF on 12-year rotation or SRF on a 14 or 16-year rotation provided directly.

Putting SRF derived material through a hub is always cheaper than sending the same material directly to a user. In the case of the cheapest SRF options (16-year rotation) the cost difference is $14.90/GJ through a hub and $21 per GJ if sent directly, a difference of 30%.

A further consideration around the use of hubs and sending raw logs and residues to a user's site for hogging is that they may not have the land area required for such a set-up easily available to them.

The cheapest option for delivering harvesting residues was for landing residues that were taken from a landing as they were produced, stored on an adjacent landing, hogged and transported to a hub where they were screened, and stored until required with drying occurring during storage using covered piles with augmented passive air flow.

Cutover residues were typically around $2 per GJ more expensive than landing residues. The cheapest route for cutover residues was to bring the material to roadside with forwarders or skidder+trailer, stockpile at landing or roadside, chip with a truck mounted drum chipper and then take the material to a hub for centralised screening and drying during storage using covered piles with augmented passive air flow. There were only minor differences in cost between the supply chains for material derived from cutover residues.

Based on current long run (3-year average) log prices taking pulp logs to a hub for chipping, upgrading and storage was cheaper than any residue harvesting operation. This is due to the average price for a pulp log being around breakeven with the typical cash cost of production (harvest and transport) excluding growing.

Short rotation forests;

- were more expensive than chip logs and landing residues, similar to cutover residues and, depending on the rotation length, cheaper than SRC and miscanthus. The longer rotations SRF option (16-year rotation) was cheaper than the other SRF options (14-year and 12-year rotations).

Short rotation coppice;

- was cheaper if put through a hub allowing drying, and competitive with material derived from 12-year rotation SRF.

Miscanthus;

- The use of a hub with miscanthus is of limited value as the material is typically dry (15 to 25% MCwb) when harvested and size reduction occurs during the harvesting process. However, due to the seasonal nature of the harvesting storage of up to 9 months may be required.

These results may vary with transport distance and cost – we have assumed an average transport distance of 90 kilometres from forest direct to fuel user and 105 km from forest to fuel user via a hub. These distances can be adjusted within the spreadsheet-based calculator developed for this analysis.

Further work

More development of the Supply Chain Cost Calculator is planned, with more supply chain options being added to the list of options being a focus. A major focus being systems for recovery of residues from steep terrain harvested using cable / hauler systems.

Other additions would be;

- a fuel price adjustment mechanism to allow for repricing of machinery and transport costs based solely on changes in diesel price, which has proved volatile in the last year.
- refining of the calculations on the impact of screening out fines on mass removed and the calorific value of the remaining biomass.
- production of energy (pulp / chip grade) logs from production thinning operations.

Glossary

adt	air dry tonne (MCwb around 15 to 25%)
Access	cost of transporting residue harvesting crew to in-forest operations
Comminution	reducing the size of the raw material (log off-cuts to chip)
Chip logs	logs suitable for chipping and use in pulp / paper / MDF etc. (also called pulp logs).
Chipping	a type of comminution, resulting chips are generally uniform and of higher quality
COR	cutover residues
GJ	gigajoule
g. t.	green tonne
Hogging	A type of comminution, resulting material is often of variable, or lower quality
IFPH	in-forest post-harvest
K grade log	small dimension, knotty (lower quality) saw logs
kWh	kilowatt hour
LR	landing residues
p. a.	per annum
PJ	petajoule
MCwb	moisture content wet basis
odt	oven dry tonne
Overhead’s	office and ancillary costs of in-forest operations
RTFEL	rubber-tyred front-end loader
Stumpage	fee paid to forest owner to access the residues
SRF	short rotation forest
SRC	short rotation coppice

INTRODUCTION

RATIONALE FOR BIOENERGY

The rationale for using bioenergy as a substitute for fossil fuels is its impact on greenhouse gas (GHG) emissions in New Zealand. When used as a heat fuel woody biomass is assumed to have GHG emissions of 1.56 kg per GJ where coal and gas are assumed to emissions of 95.7 and 54.1 kg per GJ respectively (Ministry for the Environment, 2022). The use of wood as a substitute for fossil fuels for industrial process heat is therefore expected to have a significant impact on GHG emissions. New Zealand uses around 60PJ of natural gas and 21 PJ of coal for industrial process heat each year. These equate to approximately 3.2 and 2.1 million tonnes of CO_2-e per annum respectively.

Displacing as much of the fossil fuel demand as possible with biomass is therefore important for ongoing reductions in New Zealand's GHG emissions. New Zealand has a long run supply of around 4.0 million green tonnes per annum of woody biomass derived from in-forest post-harvest residues (Hall, 2022). Not all this material is realistically recoverable, and the likely available volume (long-run) has been estimated at 2.3 million green tonnes per annum (16PJ p.a.). This wood supply is sufficient to displace a significant amount of the coal demand and potentially displace up to 1.5 million tonnes of CO_2-e per annum.

However, the use of wood derived from forest harvesting operations must be cost competitive with coal and gas to make it attractive to the market. The cost of coal delivered to a boiler is likely to cost in the order of $12 to $15 per GJ including the cost of carbon. The cost of carbon (NZU as at 5/12/2022 was $81 per tonne of CO2-e. The whole sale cost of gas is around $9.70 per GJ, with the cost of carbon adding $4.38 per GJ and the fixed charges to connect to the gas grid adding around $3.66 per GJ. Therefore, the cost of gas is around $17.60 per GJ.

Therefore, to be competitive with coal and gas the cost of biomass delivered as a fuel needs to be in the order of $14 to $18 per GJ, depending on the site specifics and the distance to coal mines and gas grid connectivity. It is worth noting that the South Island of NZ has no natural gas grid and therefore the main competitor heat fuel is coal. Very low-cost electricity (overnight) might cost $8 per GJ ($0.03 per kWh) but day-time rates are likely to be at least $17 per GJ (0.06 per kWh).

Residue types

There are two distinct physical locations of in-forest post-harvest (IFPH) residues, those produced at landings from stem to log processing (effectively at roadside) and those on the cutover which are a result of felling and extraction breakage and delimbing.

This analysis involved a literature search for applicable residue harvesting systems and machines for both cutover and landing residues. There are a wide range of potential options that could be used, with a key decision being where the breakdown of the raw residue material takes place; that is do you hog or chip at stump, landing, central processing yard or aggregation hub, or the mill where the residues will be used as fuel?

For cutover residues, those from steep land harvesting (cable / hauler) operations were excluded. The systems described are for flat to rolling terrain harvested using ground-based systems.

Non-residue options

There are some biomass resources which are not logging residues. These include pulp logs (in regions where there is low demand for such logs), prunings, waste thinnings, municipal wood waste and straws. There is also the option of growing biomass for energy from short rotation forestry and short rotation coppice crops such as willow. These materials could also go through a biomass hub, but the focus here is on the materials that could be available in large quantities in the short term (1 to 2 years), these being, landing residues (LR), cutover residues (COR) pulp (chip) logs, K grade logs (low quality saw logs that are small dimension with large knots). Short rotation forests (SRF) short rotation coppice (SRC) and Miscanthus crops are included but would take around 4 to 5 years to establish and get the first harvests for SRC or miscanthus and 12 to 15 years for SRF.

RESIDUE HARVEST SYSTEMS

There are a wide range of residue harvesting systems that can be used for recovery of IFPH residues and one of the options within this range of systems is the use of central processing yards or hubs to aggregate and process a range of biomass feedstocks from a number of primary production sites (forests etc). Worldwide there are many residue harvesting systems that have been tried, described and studied for production rates and costs, some of these are shown in Figure 1 (Andrewartha 2002). Not all these systems will be suitable for use in New Zealand.

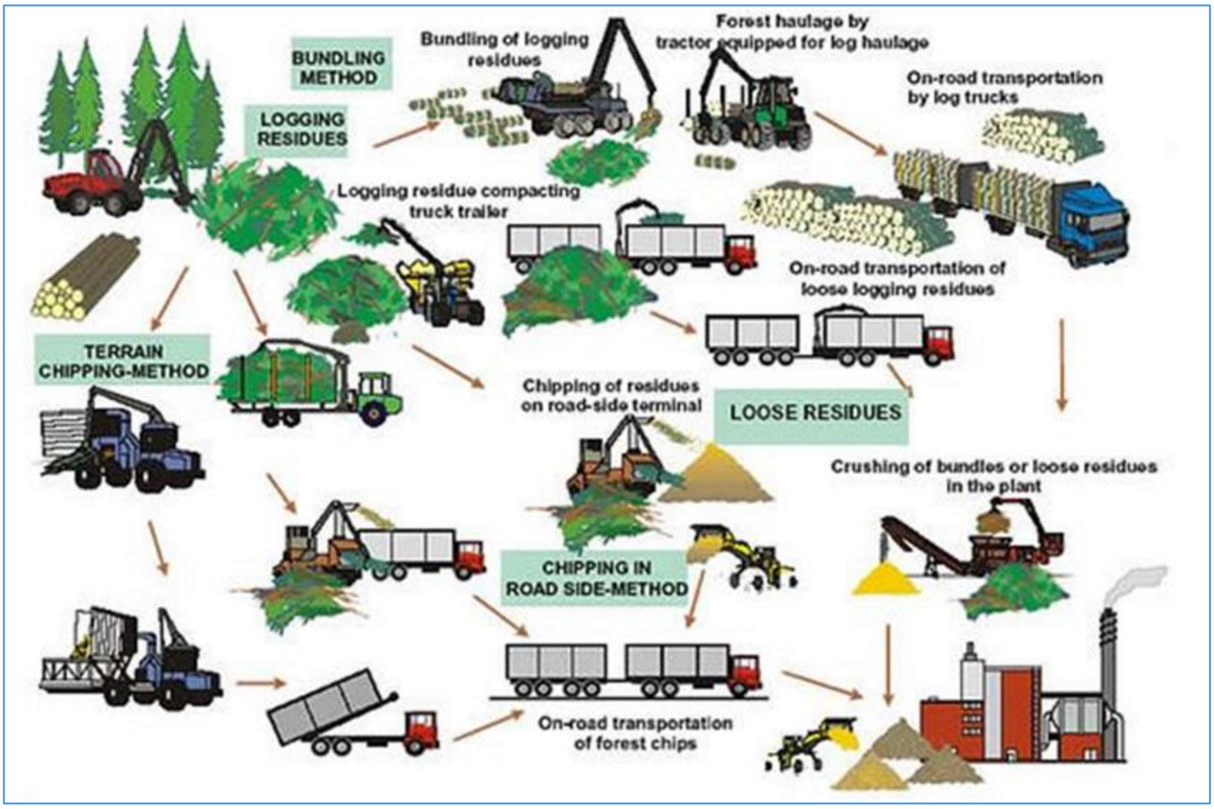


Figure 1 – some possible residue supply chains

Not all these systems are suitable for use in New Zealand.

Some trends in Sweden that are of note (Eliasson, 2000) are;

- Preference for the use of chippers for comminution, as this lowers the risk of dirt contamination in the delivered material (chippers are more susceptible to damage from

dirt and stones and so feedstock providers using chippers take more care in the collection and handling of the raw material). Chippers also reduce the production of slivers.
- A move to larger, more centralised chippers due to the lower cost per tonne of the comminution stage of the supply chain.

The residues produced at landings in New Zealand logging operations are largely comprised of *Pinus radiata* and are a mixture of stem offcuts and branches (Figure 2). Chippers and hoggers need to big (throat size) enough to cope with the larger pieces of stem wood. Machines taking pieces of stem wood which are up to 40cm in diameter and around a metre long are at the larger end of the size range for mobile equipment and will have production rates of around 30m^3 of solid log equivalent per hour (90 m^3 per hour of chip / or hog).

Systems to extract residues from forest in New Zealand have been studied and reported on before (Visser, Hall and Raymond, 2010) but a detailed look at the impacts of hubs where biomass fuels and aggregated, processed, upgraded and stored have not had much attention in New Zealand.

Figure 2 - Landing residues (behind the log pile in foreground) – a mix of stem wood, branches and needles.

The amount of branch material in the landing residues will vary from site to site (Figures 3a and 3b), driven by the crop type and harvesting system. Open grown stands, or small stands with a lot of edge trees will have more branches. Mechanised felling is increasing and with this change there is an increasing proportion of trees that are delimbed at the stump, with lower volumes of branch material brought to the landings. Most (95%) tree stem to log processing is now done with mechanised processors and these tend to produce slightly more volume as stem off-cuts (6% of extracted volume) than the previously predominant motor-manual approach (4%) (Hall 1994 and 1998).

Figure 3a - Pile of stem off-cuts on a landing edge.

Figure 3b – landing residues containing green branches.

These landing residues are typically shoved aside during log making and so contain some dirt / stone contamination. They are piled up around (or over) the edge of the skid site / log making area.

The composition of the landing residues varies with harvesting system and crop, but generally contains a mix of stem wood and branches, with some bark still attached. These stem residues vary in length from 5 to 10 centimetres (e. g., slovens) to several metres (bent or defective stems) and in diameter from 5 to 60cm (Figure 4).

IFPH is likely to be one of the forest resources used for bioenergy as much of it is not currently used for anything and will be comparatively low cost. In some instances, leaving the landing residues in the forests causes environmental issues and incurs management costs in post-harvest operations. There is interest in residue harvesting and the use of aggregation hubs developing with operations in place in the South Island in Southland, Otago, Canterbury and Nelson.

Other resource options that can be considered are pulp logs, K grade logs, and biomass from short rotation forestry (SRF), short rotation coppice (SRC) and miscanthus.

Materials and method

RESIDUE HARVESTING SYSTEMS

This study started with a summary of information on forest residue harvesting systems that have been tried in New Zealand and overseas. From this information we identified a range of systems that could be used in New Zealand.

These systems were derived for two different categories of residues: landing residues and cutover residues. Landing residues are more accessible and tend to be made up of short malformed stem sections (Figures 4). Cutover residues (Figures 5 and 6) need to be extracted to roadside (which involves additional costs) and have a larger component of branch material allied with the stem sections. There will also be some stem material dead at the time of harvest but still sound (wind throw / standing dead). Some of this material may be included in the material collected.

Figure 4 - Hauler landing residues.

Figure 5 - cutover residues

Figure 6 - cutover residues.

On freshly felled cutover the needles are still green and attached to the fine branches. However, over a period of 4 to 6 months as the dead branches and needle dry, the needles turn orange, then brown, and either fall off or become more loosely attached (Hall, 2000, unpublished data).

Therefore, allowing the cutover residues to age and dry causes a significant number of the needles to fall off after log harvest but before or during residue harvest. This is desirable as needles are a poor fuel, with higher ash and nitrogen content than the wood and bark.

Estimates of the residues available from *Pinus radiata* harvest cutover in forests outside of New Zealand suggest that there are volumes of 12 to 34 tonnes per ha (Acuna et al, 2017). This aligns with assumptions used in our estimates for residues available in New Zealand, of around 30 to 50 m^3 per ha (Hall, 1999). The gross level of stem volume left on the cutover after felling and extraction is likely to be around 70m^3 / ha (12% to 15% of the total standing volume) and we expect to harvest around half of this. Leaving some of the residual material on the cutover site is important for maintaining site nutrition.

Changes to forest harvesting equipment such as increased use of feller bunchers on steep slopes where they are assisted by being tethered to a winch base along with a change from dangle head to fixed head felling heads is estimated to reduce felling breakage by a substantial amount, with less trees breaking and the break height increasing (Prebble and Scott, 2019). This could lead to more low-quality wood arriving at hauler landings.

Where machines or systems were identified as having potential in New Zealand, these systems are described, and production rates were derived. Machine and system production rates were obtained from a wide range of sources; literature search, web search, past LIRO / Scion studies (some unpublished data). The systems were costed using New Zealand inputs. Machine capital costs were also obtained from a range of sources, including Informe 2022.

Trucking system productivity and costs were developed using local vehicle weight and dimension limits and costed using New Zealand inputs. Scions in-house transport cost calculator, which was derived from the LIRO business management for logging costing template (Riddle, 1994) was also used.

The LIRO and FFR Business Management for Logging costing system (Riddle 1994, Blackburne 2009) was used to cost systems under New Zealand operating scenario.

Production rates for the machines and systems were derived from literature and manufacturer information. Machine capital costs were obtained from Informe 2022.

The residue harvesting systems with the lowest cost that are likely to deliver the material with an appropriate level of contamination were identified.

Transport costs were derived for a range of systems; including the use of set out bins and hook trailers as well as conventional truck and trailers and semitrailers. Within these options there are also variations on the type of material being carried. One option is to size-reduce the in-forest residues in-forest creating chip or hog fuel prior to transport. The second option is to carry the raw residues to a processing hub or the mill for centralised size reduction. Heavier construction of the bins is required for the trucks carrying unprocessed residues, slightly reducing the trucks payload.

Information on the effect of the screening out of fines on dirt contamination from previous Scion studies (unpublished) was used to estimate the effects of in-forest shaker / trommel screens on dirt contamination.

A study by Anerud et al (2022) looked at the effect of screening out smaller particles on biomass loss in the remaining pile of stored biomass. The differences after 4 to 6 months storage in covered piles were ~1 .2 % loss in the screened pile and ~5.9% in the unscreened pile. It is worth noting that having a consistent particle size can also lead to less combustion emissions as a boiler designed to run on chip size material may not achieve complete combustion in material that has a high proportion of fines leading to higher emissions of PM10, which is why most wood fuel standards have a limit on the proportion of fines in a fuel.

A consequence of doing primary hogging at a yard or mill is that it increases the amount of screened out dirt and fines that will need to be landfilled or composted. If the hogging is done in-forest the discard can be left in-situ and / or spread on the landing. The cost of landfilling, including transport from mill to dump site was estimated at $116 per green tonne of waste fines. However, the proportion of the material screened out is likely to be only 1 to 2% of the total volume after the primary comminution. The cost of the landfilling was spread across each tonne of delivered material and adds between $1.15 and $2.35 per green tonne ($0.17 to $0.33 per GJ) of feedstock, including transport to the landfill.

An option that has been developed in Scandinavia is baling of residues, with a purpose designed machine that can be added to a forwarder base. The bales are then extracted to roadside using a forwarder and can be carried on a log truck (Figures 7 and 8).

Figure 7 - Residue baler and bales ready for forwarding to roadside.

The productivity of residue balers (Figure 7) was found to be in the order of 12 green tonnes per hour (Laitila et al, (2013), which is quite low in comparison with the hourly cost of the machine. The cost of baling residues is likely to be $24 to $29 per green tonne (excluding the cost of extracting to roadside). The densification of the residues achieved by the bundling only justifies its cost over very long transport distances (100km plus).

Production rates for forwarding bales of residues are similar to that for logs in a short wood system, with very similar operating costs. Bale extraction costs were estimated at $11 to $13 per green tonne.

Logging trucks with extended stanchions can reach maximum payloads when carrying green bales made from residues (Figure 8). Bales that have dried will be lighter but will contain a similar amount of energy. Trucking costs are driven by transport distance as well as load type. For a transport distance of 65km costs were estimated at $22 per green tonne, increasing to $27 per tonne at an 85 km haul distance.

Figure 8 - Conventional log truck and trailers can carry residue bales.

The likely productivity of forwarders extracting loose residue (Figure 9) is 19 to 21 green tonnes per hour (Eliasson et al, 2011). Options include a whole bunk compression system that can increase the density of the residues by a factor of 4 (Hoyne and Thomas 2001) or an expanded bunk (Figure 10, Andrewartha 2002). A cost for forwarder extraction of limbs and tops was estimated by Vangansbeke et al (2015) to be in the order of NZ$13 to $15 per green tonne.

Figure 9 - Forwarder with cutover residues.

Figure 10 - Forwarder with bunk extended to allow greater load volume

Forwarders used to extract residues in loose form (Figure 10) require modifications to the load bay (extra stanchions etc.) in order to increase the volume of the load space and retain the random length material within it.

Figure 11 - Chipper forwarder

Chipper forwarders (Figure 11) are estimated to have a production rate of around 12 green tonnes per hour. These machines have been widely used in Scandinavia but are not the only or even dominant form of chipping. Chipper forwarders are estimated to cost $15 to 16 per green tonne of chip delivered to a roadside bin (Figures 12 and 13) or truck. The bins are collected by a truck and trailer unit fitted with a large hydraulic hook for picking up the bins (Figure 14).

Roadside chipping or hogging of forwarded and piled residues is regarded as being a similar or lower cost.

Large centralised hoggers have the lowest hogging costs, but this has to be traded off against the higher cost of transport of unhogged residues or the high cost of baling.

Figure 12 - Chipper forwarder loading set-out bins with chip.

Figure 13 - Set-out bins full of chip

Figure 14 - Truck and trailer unit collecting chip bins

Purpose built chip trucks (Figure 15) can have a load volume of 110 to 115 m^3, more than sufficient to get them to full payload when carrying green chip or hog. Trucks with similar dimensions but using more heavily built bins can be used to carry unhogged residues or bin wood.

Figure 15 - High volume chip trucks and trailers typically used in New Zealand

Self-loading bin trucks in a semi-trailer configuration have been used in several New Zealand residue and bin-wood collection operations (Figure 16). These trucks have a lower volume and a higher tare weight (due to the crane) than a chip truck. However, they can be more suitable for accessing logging landings and the ability to self-load can be an advantage.

Self-loaders can also come in a truck and trailer configuration with the crane mounted on the rear of the truck unit. This option does not allow tip unloading of the truck.

Figure 16 - Bin truck – semi trailer plus self-loader crane

Hook bins can also come in a semi-trailer configuration (Figure 17), whilst having a lower payload than a truck and trailer unit they have a quicker loading time and are suited to shorter hauls (<100km). The dimensions and construction of the bins can be varied to suit the materials (unprocessed residues / bin-wood or chip). The volumes of the semi-trailer bins can be 70 to 80 m^3 – equivalent to around 25 to 26 green tonnes of chip or hog. This is sufficient for the truck to reach its maximum payload. Semi-trailer transport units have a lower maximum allowable gross vehicle mass and therefore lower payload than truck and trailer units.

Figure 17 - Set-out bins – hook semi-trailers

Large mobile wood hoggers (Figure 18) capable of processing larger piece size residues (pulp logs, log ends and whole tree thinnings) can have production rates of up to 60 green tonnes per hour, or more (Anderson et al 2012, Aman et al (2011) depending on the material being processed. They are typically operated by remote control by the loader driver and can discharge direct to a truck or to ground. These machines require a loader to feed them and in the situation being considered here, a screen to remove dirt and fines. Together these machines are estimated to cost $14 to $17 per green tonne. The cost of hogging or chipping with a large central (electric powered) machine is typically lower than when using a mobile unit, in the order of ~45% lower, and less down time due to shifting (Kettunen 2014, Virkkunene 2014).

Figure 18 - Mobile hogger (semi-trailer)

When discharging directly to trucks (Figure 19) truck logistics are critical to maintaining system productivity. Without a steady supply of trucks to discharge into, the hogger or chipper is forced to stop and wait – reducing production and increasing cost per unit. A means to alleviate some of the risk around delayed trucks is the use of an independent mobile surge bin with its own discharge conveyer (see Figure 28, page 27).

Figure 19 - Mobile chipper direct to chip van.

Figure 20 - mobile hogger (track mounted) loading direct to a truck

Mobile hoggers can be trailer mounted (Figures 18 and 19) or self-propelled, mounted on tracks (Figure 20). The tracked units can manoeuvre around and drive to, or along, piles of residues. They are driven by remote control by the loader operator.

The choice of using a chipper or a hogger is an important one. Chippers are likely to be slightly more productive but are only suitable for clean material as they are vulnerable to dirt and stone damage and the associated loss of production (increased cost).

Screens (Figures 21 and 22) are used to reduce the ash content of the hogged wood residues and can have a significant impact on the ash content (Dukes et al, 2013). The production rate of these machines varies with the source material as well as screen size (capacity of the equipment and mesh size of the screen); and production is higher with harvest residues than with recycled wood (Nati et al, 2015). Ash content is highest in the less than 3mm fraction, and this fraction can be 30 to 40% of the total ash content in the raw material collected (Kons et al 2015, Dukes et al, 2013). These machines come in a variety of sizes and configurations and can have multiple screen sizes.

Figure 21 - Mobile trommel screen removing fines from hog fuel

Figure 22 - mobile trommel screen.

When residues are discharged to ground, they are then usually loaded to trucks using rubber tyred front end loaders (RTFELs) (Figure 23) with high volume buckets.

Where hoggers or chippers discharge to ground for later reloading by an RTFEL the cost of this phase (~$3.00 to $3.60 per green tonne) was estimated from a range of sources including Harrill and Han (2011) and Ghaffariyan et al (2017).

Figure 23 - Rubber tyred front end loader (RTFEL) piling hog fuel

Highly mobile chippers / hoggers with the comminution equipment mounted on a truck (Figures 24 and 25) are becoming more common in Scandinavia and are capable of comminuting most residues.

They can move from site to site or along roadsides quickly and so have limited down time when moving. They have their own loaders mounted on the truck. Due to their mobility, their unit cost is lower than for a large semi-trailer mounted hogger. They do however require the material to be well presented and within the reach of the crane boom (~5 metres).

The truck mounted chippers / hoggers in Figures 24, 25 and 26 have production rates of 35 to 45 green tonnes per hour (Ghaffariyan et al, 2012, Spinelli et al, 2015, Mihelic et al, 2018). Costs are estimated to be $6.60 to $7.90 per green tonne (excluding screening).

Figure 24 - Truck mounted drum chipper / loader – discharge to ground

Figure 25 - Truck mounted drum chipper / loader – discharge to truck

Figure 26 - Truck mounted drum chipper to truck.

STORAGE, DRYING AND SCREENING

Logging residues that have not been comminuted (chipped or hogged) will tend to dry slowly over time (Visser et al, 2010) and therefore weigh less and require less drying at the mill. Truck loads will weigh less than if the residues were fresh but will contain the same volume of wood and a similar amount of energy. Dry matter losses are minimal when the biomass is stored in an uncomminuted form. Moisture content could be expected to drop from 56 to 60% wet basis when fresh to around 40 to 45% over a period of 4 to 6 months. The rate and amount of drying will depend on where and how the material is stored. Logs that are in ground contact, or in shady / sheltered areas will not dry much. Residues that have been piled up and are exposed to wind and sun can be expected to have substantial moisture loss (58% to 35% wet basis) over a period of 3 to 4 months (Visser et al, 2010). In dry summer conditions a final moisture content of 30% is possible.

Residues that have been chipped or hogged and stored uncovered may or may not dry during storage depending on the size of the pile;

- small piles that are exposed to rainfall will absorb moisture
- small piles are less likely to have significant self-heating and so will not dry much
- large piles (~6 m in height will tend to shed some of the rain, and whilst the surface of the pile will get wet from rainfall, the inner part of the pile will not be affected by rain
- large piles are more inclined to self-heating and some drying will occur due to this heating, especially in the inner part of the pile.

However, where chipper or hogged residues self-heat they tend to suffer from dry matter losses due to biodegradation (Routa et al, 2018), these losses can be in the order of 1 to 2 % of the original dry matter in the first month in storage, and ~0.5% per month after that. Screening out fines can reduce these losses (Anerud et al, 2022).

The impact of drying on transport payload was included where appropriate. The cost of the inventory and the losses associated with discharging comminuted wood to ground and then reloading later were considered in the system costs.

Handling and storage of biomass at a hub can include some processing such as screening to remove oversize, fines and dirt which will reduce the ash content. The storage at hubs can include covering, venting the upper 2m of the pile and introducing air to the bottom of the pile via perforated pipes either passively or with fans forcing air in through the pipes and up through the pile.

An unpublished report by Hall, Murton and Riley (2022) found that the lowest cost drying of green sawmill chip from ~58 to 54% moisture content was a roofed or covered pile with either underfloor vents with or without forced ambient air directed into the pile. This was estimated to cost around $0.77 to $0.82 per GJ or $5.60 to $6.00 per tonne of chip dried to from 60% to 54% moisture content. The 54% MCwb was the maximum limit set by the fuel buyer in this instance. The implication of this data is that the drying cost $1 per 1% reduction in MCwb per tonne ($0.145 per GJ). The cover must be non-contact. A literature review associated with this study found that putting perforated pipes under a biomass pile and letting the natural heating of the pile draw air into and up through the pile could induce significant drying (Kielder Forest Products, 2021, Randal YouTube accessed, 2022).

Alakoski et al (2016) discuss the mechanisms affecting heat build-up, biomass loss and spontaneous combustion in wood pellets and wood chips. In chips the initial heating is caused by biological activity. The larger and more compact the pile the more it is likely to trap the heat in the pile and have excessive heating which can lead to pile fires. Large piles of chip stored for longer periods (several months) are more at risk. Shorter storage periods and piles that are ventilated (active or passive) will have lower biomass loss and lower risk of spontaneous combustion. This paper also raises the issue of the toxicity of some of the gas emissions (Carbon monoxide) and that oxygen depletion can occur in confined storage spaces. Consequently, it would be prudent for any green chip storage to be well ventilated.

In a study by Saucier and Phillips (1985) uncovered flat, conical and vented conical piles were compared to a covered flat pile. The covered flat top pile was the only option that resulted in chips with a lower moisture content. The vents in the conical pile consisted of 150mm diameter PVC pipe with several 12mm diameter holes in it set into the pile to act as a chimney to allow warm wet air out. The covered pile had the most moisture loss over the storage period (up to 12 months) (Table 4). The vertical pipe vented (similar to a chimney) uncovered conical piles had the next best result; where after 3 months storage the moisture contents had increased slightly, but less than the other uncovered options.

Table 4 – moisture levels in woodchip plies by pile type over time (Saucier and Phillips, 1985)

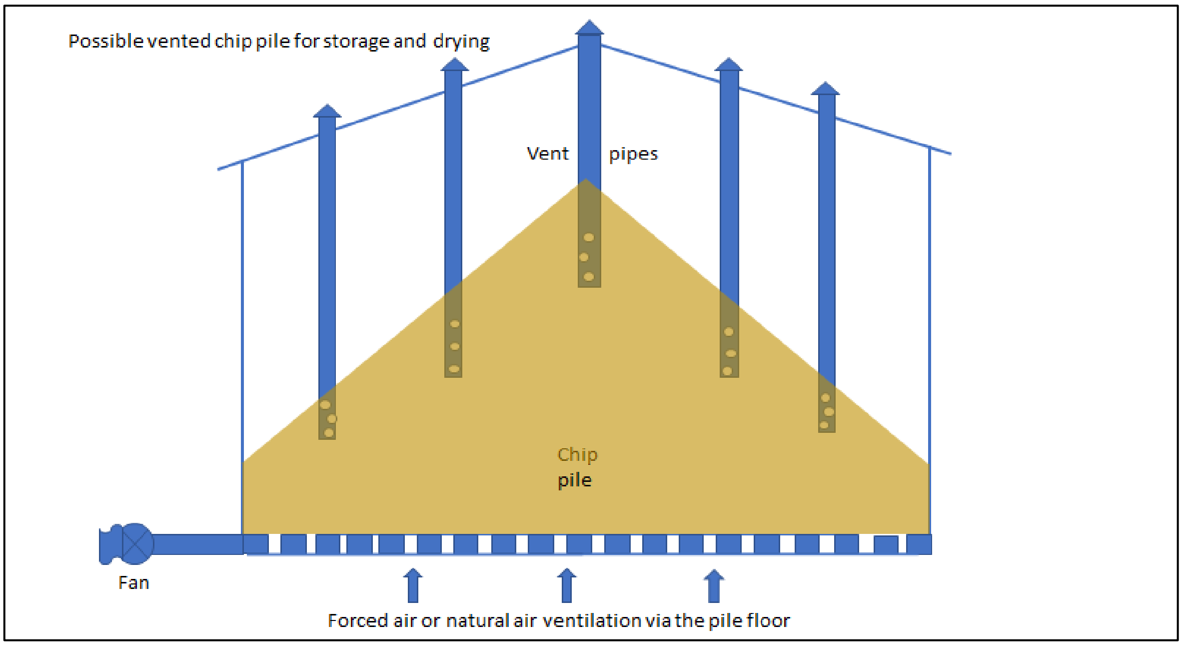
Storage time, months	Uncovered, Flat topped pile	Covered, Flat topped pile	Uncovered Conical pile	Uncovered Vented*, conical pile
0	44	45	42	42
3	55	42	52	49
6	62	40	55	52
12	63	34	54	49

*The vents referred to here are vertical pipes inserted (like a chimney) in the upper layer of the pile to allow moist air to escape

The use of a covered pile, vertical vent pipes and under pile perforated air inlet pipes is expected to give reasonable drying without the need for added heat or fan power.

Based on the report by Saucier and Phillips and the studies on under pile floor ventilation, there is a case to consider the use of vertical pipe vented pile in conjunction with the under-pile vents and / or forced ventilation under pile vents (Figure 27) along with a roof or non-contact cover.

Figure 27 - concept for a chip storage / drying pile with a combination of under pile vents and moist air chimneys



The rate of drying where a combination of a covered pile including the use of upper layer vents and under pile air inlets is not known, as no studies were found where these had been used in combination. However, if the various options are assumed to be used collectively then a drying rate (assuming green chip at 58%MCwb going into the pile) might be in the order of 58% MCwb to 30% MCwb in around a month. Drying rates are higher for wetter material and reduce as the material dries. Depending on the ambient conditions, the use of a fan to force air through the pile may not be necessary, as the heat generated in the pile may be enough to induce sufficient airflow in the pile to get adequate drying in a reasonable time. The key is to have the underfloor vents installed to allow what might be described as augmented passive drying.

Associated with the storage and drying is loss of dry matter. Based on the literature summery in Hall, Murton and Riley (2022) dry matter loss of 2% might be expected in the first month, reducing 0.5 to 1% per month after that. Dry matter losses are reduced by lowering moisture content. Therefore, the ideal system would be a low cost means of storing the material where it will dry quickly.

A suggested system is one where the incoming material to a hub is;

- screened to removed fines, dirt and oversize (oversize being re-sized and reintroduced)
- stored under cover
- stored on a floor that has passive air inlet pipes
    - upper layer vent pipes could be considered in high humidity or cooler temperature environments as these may increase the drying rate slightly
- storage is kept to a minimum; 3 months or less is preferable

The cost of operating a hub that includes these features was estimated at ~around $6.00 per tonne or $0.67 per GJ assuming the material coming out of the site has reached a moisture content of 40% wet basis (8.9 GJ per tonne) over a storage period of 3 months.

HOT AND COLD IN-FOREST RESIDUE RECOVERY SYSTEMS

Hot and cold in-forest residue Residue systems that require an interaction with, or co-operation from, the logging crew are referred to as "hot". Systems that are independent of the logging crew's activities are "cold". All the cutover residue recovery systems are cold systems as the logging crew will have departed the site before these operations commence. In the case of the landing residues some systems (which require the logging crew to load bins or trucks) are hot systems, and the crew will be paid a fee to handle (sort, stack and load trucks) the material.

The lowest cost system for landing residues identified in this analysis is outlined in Table 1. Actual delivered cost may be higher, and a range of cost options were estimated. The minimum cost is estimated at $90 per green tonne. A range of higher costs are possible, and a 20% increase would bring the delivered cost to $108 per green tonne.

Table 1 – landing residue harvesting system description and cost

System Description	Minimum cost; per tonne (per GJ)	Plus 10%	Plus 20%
Stacked as produced, load to dump truck, to CPY, chipped & screened to ground, RTFEL loader to truck, transport to mill	$90 ($13.00)	$99 ($14.26)	$108 (15.56)

For cutover residues from flat to rolling terrain where ground-based harvesting systems were used the costs are higher as the material needs to be extracted to roadside. For these residues the different systems were all similar in total delivered costs; with base costs ranging from $90 to $93 per green tonne.

Table 2 – cutover residue recovery system descriptions and costs

System Description	Minimum cost; $/t ($/GJ)	Plus 10%	Plus 20%
Forwarder / stockpile / mobile chipper / screen / stockpile / RTFEL / truck and trailer / transport	$93 ($13.28)	$102 ($14.57)	$111 ($15.85)
Skidder+trailer / stockpile / excavator to bin truck and trailer / chip at mill	$90 ($12.86)	$98 ($14.00)	$107 ($15.29)

If 20% is added to the base price (as a possible range of likely costs) the delivered costs range from $107 to $111 per green tonne.

These costs include a stumpage fee paid to the forest grower of $25 per green tonne.

The assumed average transport distance used in developing the above costs was 65km, if this increases to 85km the delivered cost rises by around $6 per green tonne.

SYSTEM VARIATIONS

Surge bin with in-forest hoggers / chippers

The first variation is the addition of a surge bin (Figure 28) in any system that is using a mobile chipper or hogger in forest. The current common options are discharge to truck or discharge to ground and reload using an RTFEL. Discharge direct to truck systems are highly reliant on a constant supply of trucks and will suffer production losses (increased cost) if there is a delay in between trucks being available. The discharge to ground system will inevitably have losses as not all the material cannot be picked up by a RTFEL without risk of dirt contamination. These losses are estimated at 5% and this was incorporated in the system costs here that used this approach.

Figure 28 – examples of mobile chip surge bins.

The idea of surge bin is that the chipper or hogger can work at full speed more of the time and discharge into the surge bin which then empties into trucks as they arrive. The size of the bin would dictate how much flexibility would be achieved. A semitrailer type chip bin trailer would have a volume of up to 80m^3, which would be sufficient to take up to ¾ of an hour's production from a large hogger working on landing residues. A surge bin that had a storage capacity of 40 to 50m^3 would give the hogger around 20 minutes of discharge at full capacity, giving some flexibility in truck scheduling.

Based on the costs estimated for the surge bins and the effect on the productivity of the hoggers / chippers this option is at least breakeven, and possibly up to $0.50 per tonne cheaper than the alternatives already analysed and reported above.

Low-cost chip shuttle to follow a chipper forwarder

The second variation is to have a chipper forwarder that has a low-cost tractor-trailer unit working with it that can shuttle the chip from the chipper forwarder to set-out bins at roadside (Figure 29). This leaves the most expensive piece of equipment (chipper forwarder) free to focus on the key role of chipping and leaving the shuttling of the chipped material to a dedicated and much cheaper piece of equipment. The estimated costs (~$12.20 to $14.70 / GJ) for this system are shown in Table 3.

Table 3 – chipper forwarder and shuttle system

System component	Estimated cost	$/t; +10%	$/t. +20%
Stumpage	$25.00	$27.50	$30.00
Chipper forwarder	$14.60	16.10	$17.50
Follow along bin tractor-trailer	$12.42	$13.66	$14.90
Loader	$3.25	$3.60	$3.90
Over heads	$1.00	$1.10	$1.20
Access	$0.46	$0.51	$0.55
Transport	$28.90	$31.79	$34.68
$/t	**$85.63**	**$94.26**	**$102.73**
$/GJ	**$12.23**	**$13.47**	**$14.68**

Figure 29 - Chipper forwarder with chip shuttle (Ag-tractor and tipping trailer)

Bin truck that can piggyback its trailer - NZ developed transport option

The transport of landing residues before they are hogged is sometimes desireable. In many forests in New Zealand getting an empty bin truck and trailer unit to a landing is challenging due to steep terrain and wet conditions. In many instances log trucks "piggy-back" their trailers (Figure 30a) when they are not loaded as this reduces the road user charges and gives the truck greater ability, especially when travelling uphill, to negotiate steep, narrow, wet roads.

The bin truck and trailer design shown in Figure 30b allows for the trailer to fit inside the truck so it cam be carried into the forest when empty.

Figure 30a – empty logging truck piggy-backing its trailer

Figure 30b - bin truck and trailer being loaded with bin wood and the same bin truck and trailer unit shown piggy backing its trailer when empty.

Chilean residue recovery system (Pinus radiata IFPH cutover residues)

An IFPH residue recovery operation used in Chile is composed of an excavator with a slash rake and hydraulic thumb used to make piles of slash on the cutover. A grapple skidder then takes the slash to roadside. A RTFEL is used to make the large piles of residue at the roadside. The material is comminuted direct to truck using an excavator loader / tracked hogger combination. Costs for this operation were estimated if the system was operating under New Zealand conditions (Table 4). The estimated costs of this system were $86 to $103 per green tonne. Truck scheduling was assumed to be giving minimal delays to the hogger.

Table 4 – estimated cost of Chilean IFPH residue harvesting system in NZ terms

System component	**$/t**	**$/t; +10%**	**$/t; +20%**
Stumpage Fee	$25.00	$27.50	$30.00
Excavator pile	$11.00	$12.10	$13.20
Grapple skidder	$6.00	$6.60	$7.20
RTFEL or Excavator pile	$5.00	$5.50	$6.00
Hogger (excavator fed) direct to truck / surge bin	$8.00	$8.80	$9.60
Chip truck and trailer to mill	$31.00	$34.10	$37.20
Total cost; $/t	**$86.00**	**$94.60**	**$103.2**
Total cost; $ per GJ	**$12.29**	**$13.51**	**$14.74**

Impact of Hubs

The use of hubs is of interest when looking at biomass supply chains. They will have a number of impacts which may add cost but also improve the operation of the supply chain overall. Finding the right system with the best outcome is a goal, but the analysis includes several factors.

1. **Increased handling**

   The use of a biomass hub will increase handling costs as the material will need to be, at minimum, reloaded after storage. There may well be other handling costs as the material is moved around the hub as it is screened and dried.

2. **Increased transport distance**

   The use of hubs can increase the total transport distance from forest to user as the transport route that needs to be used to get from forest to hub to user may not be as direct as that from forest to user. In many instances this increase in distance will be modest and assumed to be 17% in this analysis.

3. **Increased inventory**

   The holding of the material at the hub will mean there is an extra inventory cost.

4. **Aggregation operation costs**

   Whilst the use of the hub may give advantages thorough aggregation and product quality improvement, it will have costs as there will have to be some basic infrastructure (land, sheds, conveyers, screens and loaders)

5. Drying

Many wood-fired boilers have a maximum moisture content limit of 55% MCwb and much prefer to run on material that is closer to 40% MCwb. The drying at a hub can reasonably be achieved through passive methods such as covering and adding air vents into and out of the pile. The moisture content of the biomass can be reduced from 55 to 60% MCwb to 35 to 40% MCwb in a period of a month or two depending on the ambient conditions (air temperature and relative humidity). As the biomass dries the weight of material (per unit of volume) drops and the calorific value per tonne rises. Overall, the energy content on a volume basis (m^3 of solid wood equivalent) rises slightly as the material dries (Figure 31). Drying the material from 60% MCwb to 30% MCwb gives an increase in GJ per m^3 of around 16%.

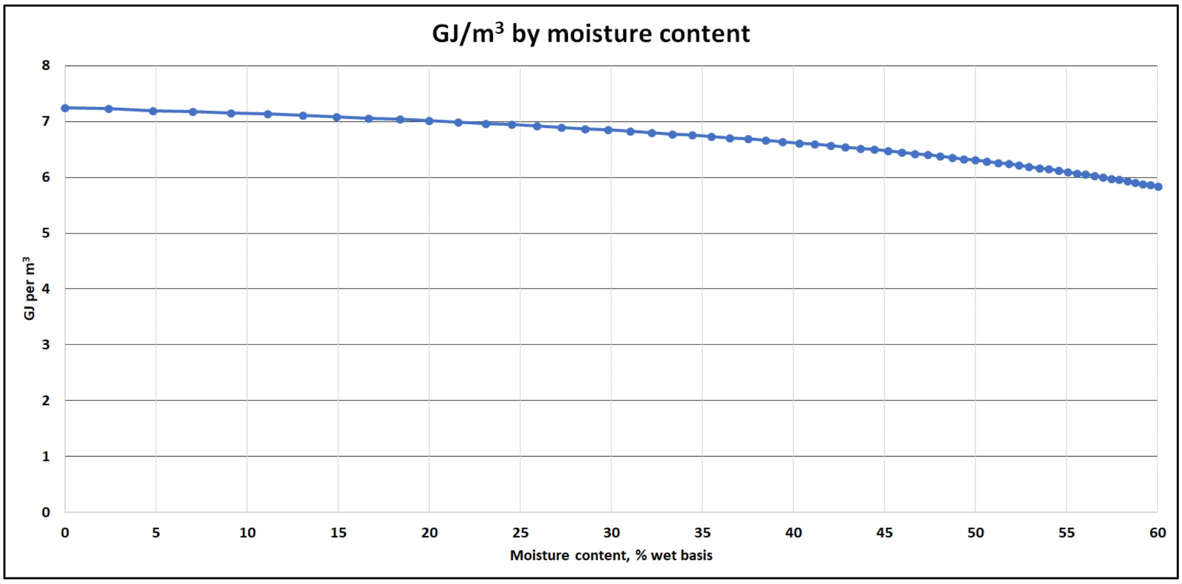


Figure 31 - energy content of wood on a volumetric basis by moisture content

6. Screening

Screening is suggested as a useful thing to do at a biomass hub that is dealing with forest residues. The screening will improve the quality of the fuel as it will remove fines, dirt and stones. These will reduce the ash content and biomass losses whilst in storage. This will improve the calorific value of the fuel and increase the ratio of energy out to energy in.

Impact of moisture content on boiler efficiency

Drying of biomass not only increases the net energy content of the biomass, but it improves the efficiency of the boiler where the efficiency is defined as the % of the net energy content of the biomass that is converted to heat output from the boiler. Large industrial boilers generally require biomass at no more the 55% MCwb and preferably much lower (40% MCwb). The impact of change in moisture content on the boiler efficiency depends on the design of the boiler, but assuming it has heat exchangers taking temperature from the flue gas to be used in preheating the feedwater then the boiler efficiency can improve by around 2% as the material is dried from 55% to 40% MCwb (Figure 32, derived from Dzurenda and Banski, 2017).

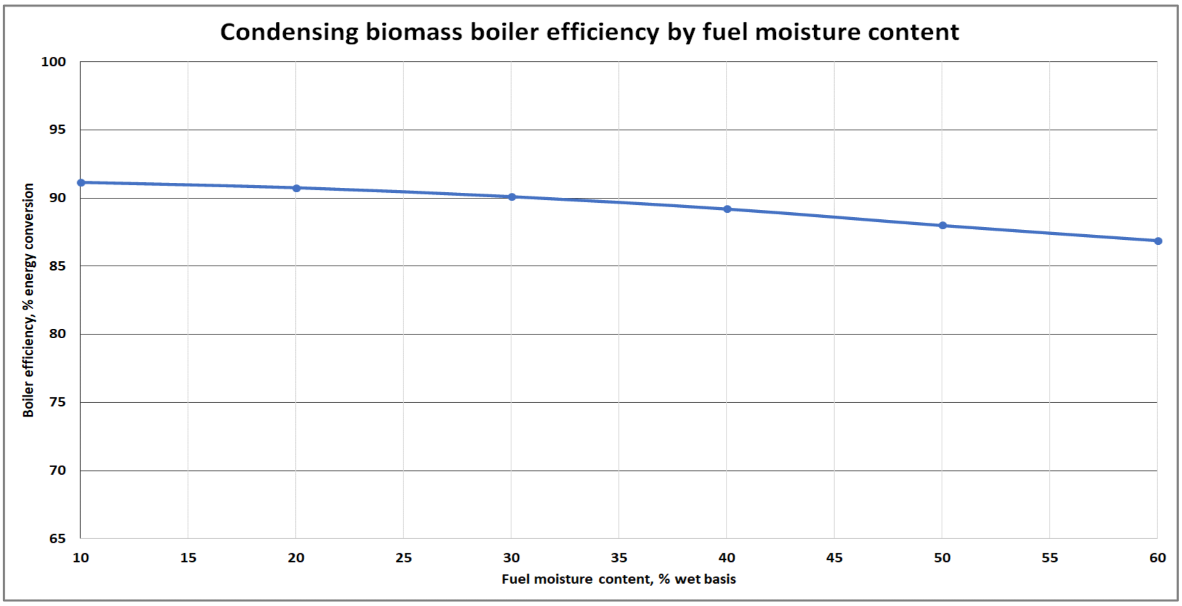


Figure 32 – impact of biomass fuel moisture content on boiler efficiency (derived from Dzurenda and Banski, 2017).

Cost of non-residual biomass

Cost of growing the SRF, SRC and Miscanthus crops were derived using spreadsheet-based calculators developed by Scion. The yields of the various crops were derived from a Pinus radiata specific growth model (PradCalc V4, Knowles & Kimberley, 2014) for the SRF and from NZ specific literature and industry data for the SRC (Snowden et al, 2013) and Miscanthus (Suckling et al, 2018). Examples of the costing templates used are shown in Appendix A. Critical to the growing cost is the assumed cost of land and the impact of this on the total cost of the material produced. For example, land used to grow SRC and Miscanthus must be no more than gently rolling contour (<15 degrees maximum slope) in order to be harvested using the typical modified maize harvesters. Land of this kind is in high demand for either arable or dairy farming and can cost in excess of $50,000 per ha depending on the region. In this analysis we have used a land price of $30,000 per ha for land growing these crops. SRF can be grown on much steeper land as cable logging systems, which are widely used in New Zealand, can be used on land with slopes of up to 35-40 degrees. This steep land is still productive growing trees but less valuable for grazing and unusable for cropping. In this analysis we have used a land price of $8,500 per ha for land growing SRF.

The price of chip and K grade logs coming out of the existing plantation forest estate are set by the market. The price of pulp logs has changed very little in the last 3 years and was set at $56 per green tonne delivered. K grade log prices are higher and much more variable. These were set at $88 per green tonne (24-month average). Log prices were derived from AgriHQ monthly log price reports.

Twenty different supply chain options were assessed in this analysis, covering in forest residues from landings, cutover, chip / pulp grade logs, K grade logs and material derived from SRF, SRC and miscanthus plantations (Table 5). Two different hub options were considered. One does size reduction (hogging), storage and drying (HSD) and one assumes the incoming material is already hogged or chipped and the hub only does storage and drying (SDO). Some of the supply chains excluded the use of the hubs.

For the SRC crops the assumptions are that the first cut will occur after 4 years and then subsequently every three 3 years for a total of 5 harvests over 16 years before the SRC needs to be cleared and re-established. For Miscanthus it was assumed to last for 8 crop harvests over 10 years, with the first taking place after 3 years and then annually.

Table 5 – Supply chain options (#20)

No.	Route	Feedstock	Source
1	Direct	Residuals, L	Conventional forest
1a	Hub HSD	Residuals, L	Conventional forest
1b	Hub SDO	Residuals, L	Conventional forest
2	Direct	Residuals, CO	Conventional forest
2a	Hub HSD	Residuals, CO	Conventional forest
2b	Hub SDO	Residuals, CO	Conventional forest
3	Direct	Chip logs, chip	Conventional forest
3a	Hub	Chip logs, chip	Conventional forest
4	Direct	Logs, K	Conventional forest
4a	Hub	Logs, K	Conventional forest
5	Direct	SRF forest	12-year rotation
5a	Hub	SRF forest	12-year rotation
6	Direct	SRF forest	14-year rotation
6a	Hub	SRF forest	14-year rotation
7	Direct	SRF forest	16-year rotation
7a	Hub	SRF forest	16-year rotation
8	Direct	SRC 4/3/3/3/3	Multi rotation
8a	Hub	SRC 4/3/3/3/3	Multi rotation
9	Direct	Miscanthus 3/1/1/1>	Multi rotation
9a	Hub	Miscanthus 3/1/1/1>	Multi rotation

Results and discussion

The results of the analysis of the various supply chains are shown in Figure 33 and Table 6. There are two sets of figures presented. The cost of the fuel delivered to the boiler and the cost of the heat delivered from the boiler. The order of the ranking does not change with the different measures. The cost of the heat out of the boiler is always higher than the cost of the fuel in due to the efficiency losses associated with the boiler.

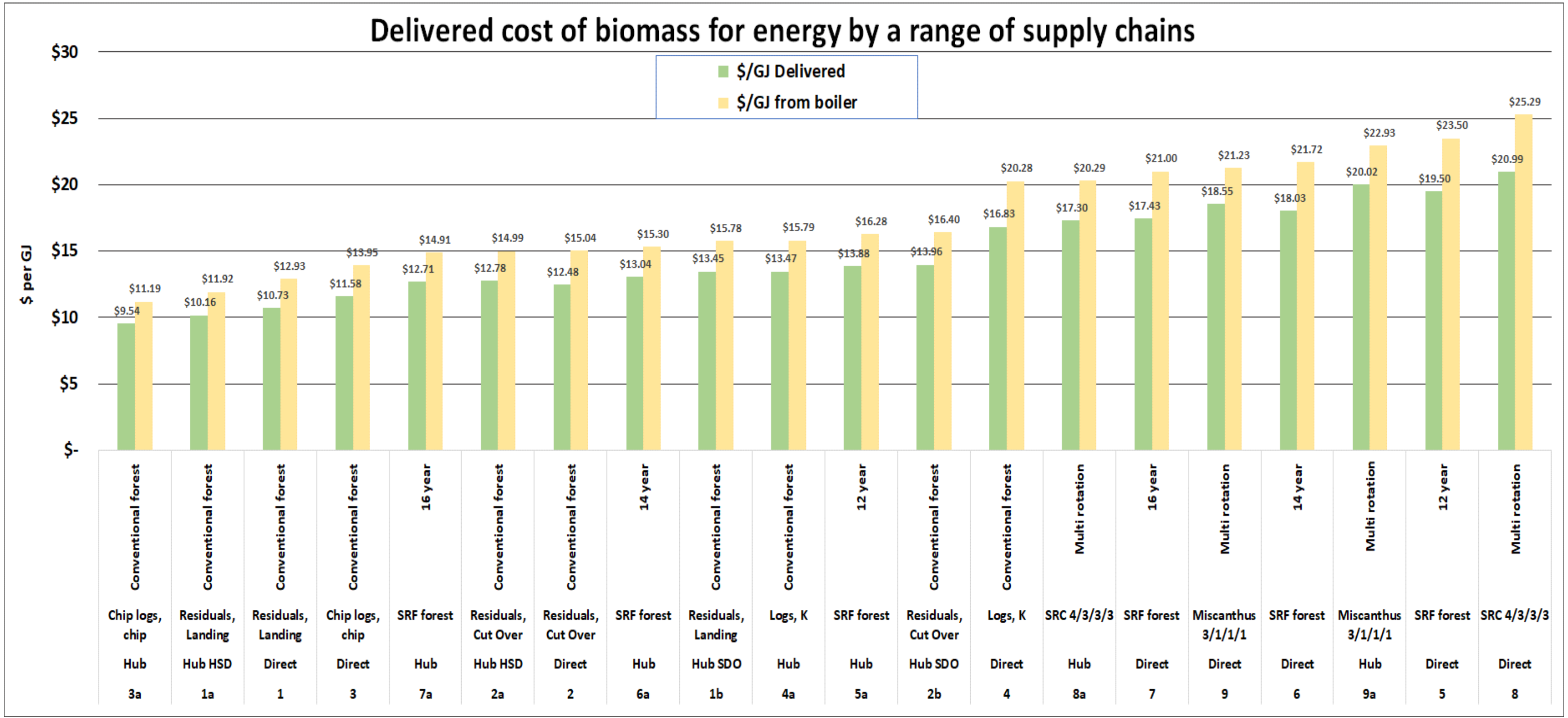


Figure 33 – Results from the supply chain analysis

Table 6 – results from the supply chain analysis

System number	Hub type or direct	Resource	Resource Origin	$/GJ Delivered	$/GJ from boiler
3a	Hub	Chip logs, chip	Conventional forest	$9.54	$11.19
1a	Hub HSD	Residuals, Landing	Conventional forest	$10.16	$11.92
1	Direct	Residuals, Landing	Conventional forest	$10.73	$12.93
3	Direct	Chip logs, chip	Conventional forest	$11.58	$13.95
7a	Hub	SRF forest	16 year	$12.71	$14.91
2a	Hub HSD	Residuals, Cut Over	Conventional forest	$12.78	$14.99
2	Direct	Residuals, Cut Over	Conventional forest	$12.48	$15.04
6a	Hub	SRF forest	14 year	$13.04	$15.30
1b	Hub SDO	Residuals, Landing	Conventional forest	$13.45	$15.78
4a	Hub	Logs, K	Conventional forest	$13.47	$15.79
5a	Hub	SRF forest	12 year	$13.88	$16.28
2b	Hub SDO	Residuals, Cut Over	Conventional forest	$13.96	$16.40
4	Direct	Logs, K	Conventional forest	$16.83	$20.28
8a	Hub	SRC 4/3/3/3	Multi rotation	$17.30	$20.29
7	Direct	SRF forest	16 year	$17.43	$21.00
9	Direct	Miscanthus 3/1/1/1	Multi rotation	$18.55	$21.23
6	Direct	SRF forest	14 year	$18.03	$21.72
9a	Hub	Miscanthus 3/1/1/1	Multi rotation	$20.02	$22.93
5	Direct	SRF forest	12-year	$19.50	$23.50
8	Direct	SRC 4/3/3/3	Multi rotation	$20.99	$25.29

The summary sheet from the calculator used in this study is provided in Appendix B.

The lowest cost fuel and heat energy is that derived from chip logs from a conventional forest via a hub that does storage, drying and chipping ($11.19 per GJ of heat).

The next lowest costs are from residuals produced at landings via a hub that does full processing including hogging ($11.92). Next cheapest is landing residues which are taken direct from forest to heat plant and do not go via a hub ($12.93).

Chip logs direct to the user with chipping at the boiler site is the next lowest cost. followed by material derived from a short rotation forest (16-year rotation) with the material going via a hub that includes chipping.

There are a cluster of supply chains that all have similar costs ($14.90 per GJ to $15.54 per GJ). This cluster includes those supply material derived from cutover residues.

The most expensive material is that derived from SRC going direct from field to mill provided through a hub. It is slightly more expensive than Miscanthus via a hub and 12-year rotation SRF provided directly.

The use of K grade logs (especially through a hub) would be cheaper than growing miscanthus, SCR or SRF on 12-year rotation or SRF on a 14 or 16-year rotation provided directly.

Putting SRF derived material through a hub is always cheaper than sending the same material directly. In the case of the cheapest SRF options (16-year rotation the cost difference is ~$6.00 per GJ ($14.90/GJ through a hub and $21 per GJ if sent directly), a difference of 30%.

A further consideration around the use of hubs and sending raw logs and residues to a user's site for hogging is that the user site may not have the land area required for such a set-up easily available to them.

The cheapest option for delivering harvesting residues was for landing residues that were taken from a landing as they were produced, stored on an adjacent landing, hogged and transported to a hub where they were screened, and stored until required with drying occurring during storage using covered piles with augmented passive air flow.

Cutover residues were typically around $2 per GJ more expensive than landing residues. The cheapest route for cutover residues was to bring the material to roadside with forwarders or skidder+trailer, stockpile, chip with a truck mounted drum chipper and then take the material to a hub for centralised screening and drying during storage using covered piles with augmented passive air flow. There were only minor differences in cost between the supply chains for material derived from cutover residues.

Low grade logs (pulp and K grade)

- Pulp logs were the cheapest option when supplied via a hub that did chipping, storage and drying
- K grade logs were mid-range in terms of costs

Short rotation forests

- Which proved to be more expensive than chip logs and landing residues, similar to cutover residues and, depending on the rotation length, cheaper than SRC and miscanthus. The longer SRF options (16-year rotation) was cheaper than the other SRF options (14-year and 12-year rotations.

Short rotation coppice

- Was cheaper if put through a hub allowing drying and competitive with material derived from 12-year rotation SRF.

These results may vary with transport distance and cost – we have assumed an average transport distance of 90 kilometres from forest direct to fuel user and 105km from forest to fuel user via a hub. These distances can be adjusted within the calculator developed for this analysis.

The cost of the chip and K grade logs was based on the current market price for these logs – not the estimated cost of growing them as was used in the case of SRF, SRC and miscanthus. There is no established market price for SRF, SRC and Miscanthus in New Zealand as there is little or no production or trading of these materials.

The availability of chip logs will depend on the local market. That is, is there a dominant buyer (pulp mill / MDF mill) taking the bulk of the pulp logs. If there is an established buyer, despite the log price being low the material may not be available at that price in the short term as there may be long term supply contracts (with price adjustment clause) in place.

K grade logs are largely exported, are a substantial potential resource, and should be available to those who are prepared to pay the market (export / delivered to wharf gate) price.

CONCLUSIONS

New Zealand has significant currently unused or potentially available biomass resources in the form of in-forest post-harvest residues and other forest derived products.

Getting this material into the energy market at a cost competitive price will require the refinement of fledgling biomass supply chains. For forestry derived biomass to play a greater role in New Zealand's drive to a low carbon future the supply chain for this resource must be optimised with costs being as low as reasonably possible as a result.

The lowest cost fuel and heat energy found in this analysis is that derived from chip logs from a conventional forest via a hub that does chipping, storage and drying ($11.19 per GJ of heat).

The next lowest cost materials are from residuals produced at landings via a hub that does full processing including hogging ($11.92). Next cheapest is landing residues which are taken direct from forest to heat plant and do not go via a hub ($12.93).

The use of hubs can reduce the cost of fuel and heat. Hubs can provide a place to store and improve fuel quality via a system where the biomass is screened, sized and dried. The value of the use of hubs is affected by the specifics of each resource and the site specifics of the demand being met, including transport distance from where the biomass is produced to where it is finally used.

A suggested system incorporating a hub is one where the material delivered to a hub is subsequently;

- screened to removed fines, dirt and oversize
- stored under cover
- stored on a floor that has passive air inlet pipes
    - upper layer vent pipes could be considered in high humidity or cooler temperature environments as these may increase the drying rate slightly
- stored for a period of 2 to 3 months, less being preferable

The cost of operating a hub that includes these features was estimated at ~around $6.00 per tonne or $0.67 per GJ assuming the material coming out of the site has reached a moisture content of 40% wet basis (8.9 GJ per tonne) over a storage period of 3 months.

Chip logs direct to the user with chipping at the boiler site is the next lowest cost. followed by material derived from a short rotation forest (16-year rotation) with the material going via a hub that includes chipping.

There are a cluster of supply chains that all have similar costs ($14.90 per GJ to $15.54 per GJ). This cluster includes those supply material derived from cutover residues.

The use of K grade logs (especially through a hub) would be cheaper than growing miscanthus, SCR or SRF on 12-year rotation or SRF on a 14 or 16-year rotation provided directly.

Putting SRF derived material through a hub is always cheaper than sending the same material directly. In the case of the cheapest SRF options (16-year rotation) the cost difference is $14.90/GJ through a hub and $21 per GJ if sent directly, a difference of 30%.

A further consideration around the use of hubs and sending raw logs and residues to a user's site for hogging is that they may not have the land area required for such a set-up easily available to them.

Short rotation forests;

- were more expensive than chip logs and landing residues, similar to cutover residues and, depending on the rotation length, cheaper than SRC and miscanthus. The longer SRF options (16-year rotation) was cheaper than the other SRF options (14-year and 12-year rotations.

Short rotation coppice;

- was cheaper if put through a hub allowing drying and competitive with material derived from 12-year rotation SRF.

All costs results are dependent on the transport distances assumed in the calculations.

FURTHER WORK

More development of the Biomass Supply Chain Cost Comparison Calculator is planned, with more supply chain options being added to the list of options being a focus. The current analysis does not include residue recovery from steep slope cutovers. Around 40 to 43% of New Zealand's plantation forest is on land that is more than 20º slope requiring cable-based (hauler / yarder) logging. Systems for recovering this material will be described and costed.

Other additions would be;

- a fuel price adjustment mechanism to allow for repricing of machinery and transport costs based solely on changes on diesel price, which have proved volatile in the last year.
- refining of the calculations on the impact of screening out fines on mass removed and the calorific value of the remaining biomass.

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Appendix A - crop growing costing templates

SRF costing template

Growing costs		833 no thin								**Management costs (insurance, rates supervision, planning etc)**										
16 year rotation										**$100 per ha per year**										
		Per ha	**Per ha**			**Interest compound**		0.06		**Andrew Clarke P. F. Olsens August 2019**										
Year		**Operate**	**Manage**	**Land rent**	**Total**					Use $80 /ha / p. a.								**Without Carbon**		**With Carbon**
1	Land + Establish	$ 2,068	80	$ 590	$ 2,738		2738.036							2738.04	-$ 2,738.0			-$ 2,738	$450.00	-$ 2,288.04
2	Release	$ 350	80	$ 590	$ 1,020	$ 3,922	$ 1,184							1184.28	-$ 1,184.3			-$ 1,184	$450.00	-$ 734.28
3	Release	$ 350	80	$ 590	$ 1,020	$ 5,178	$ 1,255							1255.34	-$ 1,255.3			-$ 1,255	$450.00	-$ 805.34
4		0	80	$ 590	$ 670	$ 6,158	$ 981				**Carbon Price**	$70		980.66	-$ 980.7			-$ 981	$450.00	-$ 530.66
5		0	80	$ 590	$ 670	$ 7,198	$ 1,039				**Carbon average volume**	180		1039.50	-$ 1,039.5			-$ 1,039	$450.00	-$ 589.50
6		0	80	$ 590	$ 670	$ 8,300	$ 1,102				**Carbon value**	$12,600		1101.87	-$ 1,101.9			-$ 1,102	$450.00	-$ 651.87
7	Dothi	5	80	$ 590	$ 675	$ 9,473	$ 1,173				**Carbon per annum**	$450.00		1172.98	-$ 1,173.0			-$ 1,173	$450.00	-$ 722.98
8		0	80	$ 590	$ 670	$ 10,711	$ 1,238							1238.36	-$ 1,238.4			-$ 1,238	$450.00	-$ 788.36
9		0	80	$ 590	$ 670	$ 12,024	$ 1,313							1312.66	-$ 1,312.7			-$ 1,313	$450.00	-$ 862.66
10		0	80	$ 590	$ 670	$ 13,415	$ 1,391							1391.42	-$ 1,391.4			-$ 1,391	$450.00	-$ 941.42
11		0	80	$ 590	$ 670	$ 14,890	$ 1,475							1474.91	-$ 1,474.9			-$ 1,475	$450.00	-$ 1,024.91
12		0	80	$ 590	$ 670	$ 16,453	$ 1,563							1563.40	-$ 1,563.4			-$ 1,563	$450.00	-$ 1,113.40
13		0	80	$ 590	$ 670	$ 18,111	$ 1,657							1657.20	-$ 1,657.2			-$ 1,657	$450.00	-$ 1,207.20
14		0	80	$ 590	$ 670	$ 19,867	$ 1,757							1756.64	-$ 1,756.6			-$ 1,757	$450.00	-$ 1,306.64
15	Road	3125	80	$ 590	$ 3,795	$ 22,992	$ 4,882							4881.64	-$ 4,881.6		$/t	-$ 4,882	$450.00	-$ 4,431.64
16	Log	0	80	$ 590	$ 670	$ 25,042	$ 2,050							2049.54	-$ 2,812.0		90	-$ 762	$450.00	-$ 762.43
						$ 26,544		0.06	**Profit**						$ 54,720.0			$ 54,720		$ 54,720.00
					Vol/ha	608								**IRR**	**8.5%**		**IRR**	**#NUM!**		**12.61%**
						$ 43.66		0	**Log $/t**	Comminute	0			**NPV**	**$3,936.98**		**NPV**	**$4,744**		**$9,114**
	Transport	1	1.254			$ 1.25		$ 90.00	Sale price											
	Chip / Hog	$0.00	/ m3			$0.00		$54,720.00	total sale											
		$/m,3 cost to grow and deliver				**$ 44.91**														
	Road build $/km	50,000																		
	ha of logging / km of road	16																		
	Roading $/ha	3125				Grow	$ 36.31	82.9	%											
						Road	$ 6.24	14.2	%											
						Log	$ -	0.0	%											
						Comminut	$ -	0.0	%											
	Land and establishment cost composition					Transport	$ 1.25	2.9	%											
	Land	$ 510	8500			**Total**	**$ 43.81**	100	%											
	Prep spray	$ 320						100.0												
	Mech Prep	$ 45		Stock cost $/1000		Stocking														
	Planting stock	$ 458		550		833														
	Planting Labour	$ 285		342	38	0.833														
	Release 1	$ 350																		
	Misc	$ 100	$ 2,068																	

Miscanthus costing template

Growing costs																						
			Land cost +												Management costs (insurance, rates supervision, planning etc)							
		Per ha	Per ha		Interest compound		0.06								$100 per ha per year							
Year		Operate	Manage	Total											Andrew Clarke P. F. Olsens August 2019							
1	Land + Establish	$ 10,169	$ 1,880	$ 12,049	$ 12,049										Use $80 /ha / p. a.							
2	Release cut / fert	460	$ 1,880	$ 2,340	$ 15,112																	
3	Harvest	3120	$ 1,880	$ 5,000	$ 17,593													ODT / ha	ADT / ha			
					$ 23,648		0.06	Profit							1	$ 12,049	$ 12,049					
				Vol/ha	30	odt									2	$ 2,340	$ 14,931			Grow		Delivered
					$ 788.27		104	Log $/t							3	$ 1,880	$ 17,483	13	15.29	$ 1,143	H1	$ 1,278
															4	$ 1,880	$ 1,880	13	15.29	$ 122.92	H2	$ 257.52
	Transport	90	0.34		$ 30.60										5	$ 1,880	$ 1,880	13	15.29	$ 122.92	H3	$ 257.52
					$0.00					45	odt / ha harvest				6	$ 1,880	$ 1,880	13	15.29	$ 122.92	H4	$ 257.52
															7	$ 1,880	$ 1,880	13	15.29	$ 122.92	H5	$ 257.52
		$/m,3 cost to grow and deliver			$ 818.87						Yield = 10 to 14 odt/ha/year in CNI				8	$ 1,880	$ 1,880	13	15.29	$ 122.92	H6	$ 257.52
											OJI pulp / paper				9	$ 1,880	$ 1,880	13	15.29	$ 122.92	H7	$ 257.52
	Road build $/km	1									20 Peter Brown				10	$ 1,880	$ 1,880	13	15.29	$ 122.92	H8	$ 257.52
ha of logging / km of road		35																				
	Roading $/ha	$ 0.03			Grow	$ 684.27	84 %			-$ 12,049.20												
	Roading / odt	$ 0.00			Road	$ 0.00	0 %			-$ 2,340.00									$/adt	$ 250.45		$ 385.05
	Roading / g. t.	$ 0.00			Harvest	$ 104.00	13 %		$/t	-$ 7,700.00									$/GJ	$ 15.09		$ 23.20
	Land and establishment cost composition				Transport	$ 30.60	4 %		$ 90.00	$ 2,700.00												
	Land	$ 1,800	$ 30,000.00		Total	$ 818.87	100 %		IRR	-71%												
	Prep spray	$ 300							NPV	-$19,389.20							$ 57,624	$ 104	554.0764			
	Mech Prep	$ 650																	36.93842			
	Planting stock	$ 7,440		12,000	$ 0.62																	
	Planting Labour	$ 1,459		38.4	$ 38.00																	
	Release 1	$ 300																				
	Misc	$ 20																				
	Total	$ 10,169																				

SRC willow costing template

Growing costs		SRC											
			Land cost +										
		Per ha	Per ha		Interest compound		0.06						
Year		Operate	Manage	Total									
1	Land + Establish	$ 9,620	$ 1,880	$ 11,500.00									
2	Release cut / fert	460	$ 1,880	$ 2,340.00	$ 14,530								
3	Grow on	20	$ 1,820	$ 1,840.00	$ 17,242								
4	Harvest	1575	$ 1,880	$ 3,455.00	$ 21,731								
					$ 26,490		0.06	Profit					
				Vol/ha	75	g/t							
					$ 353.20		21	Log $/t					
	Transport	90	0.31		$ 27.90								
					$0.00					30	odt / ha harvest		
										Yield = 10 to 12 odt/ha/year in CNI			
		$/m,3 cost to grow and deliver			$ 381.10						Snowdon, McIvor & Nicholas		
	Road build $/km	5,000											
	ha of logging / km of road	60											
	Roading $/ha	83.33333			Grow	$ 113.39	69 %			-$ 11,500.00			
	Roading, $/g.t.	$ 1.11			Road	$ 1.11	1 %			-$ 2,340.00			
					Harvest	$ 21.00	13 %		$/t	-$ 10,205.00			
	Land and establishment cost composition				Transport	$ 27.90	17 %		$90.00	$ 6,750.00			
	Land	$ 1,800	$ 30,000.00		Total	$ 163.40	100 %		IRR	-52%			
	Prep spray	$ 320							NPV	-$17,295.00			
	Mech Prep	$ 650											
	Planting stock	$ 7,440		12000	0.62								
	Planting Labour	$ 760		$ 38.00	20								
	Release 1	$ 350											
	Misc	$ 100											
	Total	$ 9,620											

Management costs (insurance, rates supervision, planning etc)						
$100 per ha per year						
Andrew Clarke P. F. Olsens August 2019						
Use $80 /ha / p. a.						
			Harvest	Harvest	Grow	Delivered
Year			odt/ha	g. t. / ha	$ / g. t.	$ / g. t.
1	$ 11,500.00	$ 11,500				
2	$ 2,340.00	$ 14,358				
3	$ 1,840.00	$ 16,844				
4	$ 1,820.00	$ 19,422	30	75	$ 258.95	$ 308.97
5	$ 1,820.00	$ 1,880				
6	$ 1,820.00	$ 3,785				
7	$ 1,820.00	$ 5,775	30	75	$ 77.00	$ 127.01
8	$ 1,820.00	$ 1,880				
9	$ 1,820.00	$ 3,785				
10	$ 1,820.00	$ 5,775	30	75	$ 77.00	$ 127.01
11	$ 1,820.00	$ 1,880				
12	$ 1,820.00	$ 3,785				
13	$ 1,820.00	$ 5,775	30	75	$ 77.00	$ 127.01
14	$ 1,820.00	$ 1,880				
15	$ 1,820.00	$ 3,785				
16	$ 1,820.00	$ 5,775	30	75	$ 77.00	$ 127.01
					$ 113.39	$ 163.40
					$/g.t	$/g.t

Appendix B – summary output from the biomass supply chain comparison

Supply Chain Comparison Calculations (SCCC)	For woody biomass to a heat user, including moisture content effects on boiler efficiency																			
	1	1a	1b	2	2a	2b	3	3a	4	4a	5	5a	6	6a	7	7a	8	8a	9	9a
Direct forest to mill or via a hub	Direct	Hub HSD	Hub SDO	Direct	Hub HSD	Hub SDO	Direct	Hub	Direct	Hub	Direct	Hub	Direct	Hub	Direct	Hub	Direct	Hub	Direct	Hub
Raw material source	Residuals, Landing	Residuals, Landing	Residuals, Landing	Residuals, Cut Over	Residuals, Cut Over	Residuals, Cut Over	Chip logs, chip	Chip logs, chip	Logs, K	Logs, K	SRF Logs	SRF Logs	SRF Logs	SRF Logs	SRF Logs	SRF Logs	SRC / Wood chip / purpose grown	SRC / Wood chip / purpose grown	Miscanthus chipped	Miscanthus chipped
Origin	Conventional forest	Conventional forest	Conventional forest	Conventional forest	Conventional forest	Conventional forest	Conventional forest	Conventional forest	Conventional forest	Conventional forest	SRF forest	SRF forest	SRF forest	SRF forest	SRF forest	SRF forest	SRC 4/3/3/3	SRC 4/3/3/3	Miscanthus 3/1/1/1	Miscanthus 3/1/1/1
	Post-harvest residues (L)	Post-harvest residues (L)	Post-harvest residues (L)	Post-harvest residues (CO)	Post-harvest residues (CO)	Post-harvest residues (CO)	Pulp logs	Pulp logs	K grade logs	K grade logs	12 year	12 year	14 year	14 year	16 year	16 year	Multi rotation	Multi rotation	Multi rotation	Multi rotation
Regime	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1111 / 12	1111 / 12	833 / 14	833 / 14	667 / 16	667 / 16	10,000 /4/3/3/3	10,000 /4/3/3/3	10,000 /3/1/1/1	10,000 /3/1/1/1
Land value	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	$ 8,500	$ 8,500	$ 8,500	$ 8,500	$ 8,500	$ 8,500	$ 30,000	$ 30,000	$ 30,000	$ 30,000
Rental (% of LV, p.a.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Land Rental ($ p. a.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	$ 510.00	$ 510.00	$ 510.00	$ 510.00	$ 510.00	$ 510.00	$ 1,800.00	$ 1,800.00	$ 1,800.00	$ 1,800.00
Yield / g.t. per ha	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	441	441	550	550	608	608	75	75	12	12
Stumpage or growing costs; $/m³	$ 25.00	$ 25.00	$ 25.00	$ 25.00	$ 25.00	$ 25.00	n.a.	n.a.	n.a.	n.a.	$ 35.6	$ 35.6	$ 34.4	$ 34.4	$ 36.3	$ 36.3	$ 112.0	$ 112.0	$ 250.0	$ 250.0
Roading costs; $/m³	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	$ 8.4	$ 8.4	$ 6.7	$ 6.7	$ 6.2	$ 6.2	$ 1.0	$ 1.0	$ 1.0	$ 1.0
Harvest (gather material to landing to or Roadside)	$ 11.75	$ 11.75	$ 11.75	$ 33.34	$ 33.34	$ 33.34	n.a.	n.a.	n.a.	n.a.	$ 60.0	$ 60.0	$ 54.0	$ 54.0	$ 49.0	$ 49.0	$ 26.0	$ 26.0	$ 30.0	$ 30.0
Process (load comminutor Plus, comminute and then load out / stockpile)	$ 16.21	n. a.	$ 27.96	$ 8.33	n. a.	$ 8.33	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Log price (delivered)							$ 56.00	$ 56.00	$ 88.00	$ 88.00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Log Price (on Truck)	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	$ 104.0	$ 104.0	$ 95.1	$ 95.1	$ 91.5	$ 91.5	$ 139.0	$ 139.0	$ 281.0	$ 281.0
In-forest	$ 52.96	$ 36.75	$ 64.71	$ 66.68	$ 58.34	$ 66.68	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
To consumer or hub transport distance	90	65	65	90	65	65	n.a.	75	n.a.	90	90	65	90	65	90	65	0	65	0	65
To Hub Transport cost	n. a.	$ 24.00	$ 24.00	n. a.	$ 24.00	$ 24.00	n.a.	n.a.	n.a.	n.a.	$ 27.93	$ 21.56	$ 27.93	$ 21.56	$ 27.93	$ 21.56	n.a.	$ 24.00	n.a.	$ 26.40
At Hub Price	n. a.	$ 60.75	$ 88.71	n. a.	$ 82.35	$ 90.68	n. a.	$ 56.00	n. a.	$ 88.00	$ 131.93	$ 125.56	$ 123.03	$ 116.66	$ 119.43	$ 113.06	n.a.	$ 163.00	n.a.	$ 307.40
Hub Costs	n. a.	$ 6.73	$ 5.96	n. a.	$ 6.73	$ 5.96	n. a.	$ 6.73	n. a.	$ 6.73	n. a.	$ 6.73	n. a.	$ 6.73	n. a.	$ 6.73	n.a.	$ 5.96	n.a.	$ 5.96
Distance (km) Hub to Consumer	n. a.	40	40	n. a.	40	40	n. a.	40	n. a.	40	n. a.	40	n. a.	40	n. a.	40	70	40	70	40
Transport to consumer	$ 31.09	$ 16.32	$ 16.32	$ 31.09	$ 16.32	$ 16.32	n. a.	$ 16.32	n. a.	$ 16.32	n. a.	$ 16.32	n. a.	$ 16.32	n. a.	$ 16.32	$ 25.46	$ 16.32	$ 25.46	$ 16.32
Consumer hogging costs ($/tonne)	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	$ 13.52	n. a.	$ 13.52	n. a.	$ 13.52	n. a.	$ 13.52	n. a.	$ 13.52	n. a.	n. a.	n. a.	n. a.	n. a.
Consumer storage costs ($/tonne)	$ 0.385	$ 0.768	$ 0.963	$ 0.448	$ 0.966	$ 0.981	$ 0.64	$ 0.36	$ 0.47	$ 1.02	$ 0.67	$ 1.36	$ 0.63	$ 1.28	$ 0.61	$ 1.25	$ 0.75	$ 1.70	$ 1.40	$ 2.73
Delivered to boiler costs ($/tonne)	$ 84.43	$ 109.83	$ 145.39	$ 98.21	$ 138.13	$ 147.97	$ 91.12	$ 103.13	$ 132.45	$ 145.54	$ 153.49	$ 149.97	$ 141.88	$ 140.99	$ 137.19	$ 137.36	$ 165.21	$ 186.98	$ 307.86	$ 332.41
Delivered to boiler costs ($/GJ)	$ 10.73	$ 10.16	$ 13.45	$ 12.48	$ 12.78	$ 13.96	$ 11.58	$ 9.54	$ 16.83	$ 13.47	$ 19.50	$ 13.88	$ 18.03	$ 13.04	$ 17.43	$ 12.71	$ 20.99	$ 17.30	$ 18.55	$ 20.02
MC	54	40	40	54	40	41	54	40	54	40	54	40	54	40	54	40	54	40	20	20
GJ/t	7.87	10.81	10.81	7.87	10.81	10.60	7.87	10.81	7.87	10.81	7.87	10.81	7.87	10.81	7.87	10.81	7.87	10.81	16.60	16.60
Conversion Efficiency percent	83.0	85.3	85.3	83.0	85.3	85.1	83.0	85.3	83.0	85.3	83.0	85.3	83.0	85.3	83.0	85.3	83.0	85.3	87.3	87.3
Energy out / GJ per t in	6.53	9.21	9.21	6.53	9.21	9.02	6.53	9.21	6.53	9.21	6.53	9.21	6.53	9.21	6.53	9.21	6.53	9.21	14.50	14.50
$ per GJ out	$ 12.93	$ 11.92	$ 15.78	$ 15.04	$ 14.99	$ 16.40	$ 13.95	$ 11.19	$ 20.28	$ 15.79	$ 23.50	$ 16.28	$ 21.72	$ 15.30	$ 21.00	$ 14.91	$ 25.29	$ 20.29	$ 21.23	$ 22.93
$/tonne at delivered MC	$ 84.43	$ 109.83	$ 145.39	$ 98.21	$ 138.13	$ 147.97	$ 91.12	$ 103.13	$ 132.45	$ 145.54	$ 153.49	$ 149.97	$ 141.88	$ 140.99	$ 137.19	$ 137.36	$ 165.21	$ 186.98	$ 307.86	$ 332.41
$/GJ delivered	$ 10.73	$ 10.16	$ 13.45	$ 12.48	$ 12.78	$ 13.96	$ 11.58	$ 9.54	$ 16.83	$ 13.47	$ 19.50	$ 13.88	$ 18.03	$ 13.04	$ 17.43	$ 12.71	$ 20.99	$ 17.30	$ 18.55	$ 20.02
$/GJ out of boiler	$ 12.93	$ 11.92	$ 15.78	$ 15.04	$ 14.99	$ 16.40	$ 13.95	$ 11.19	$ 20.28	$ 15.79	$ 23.50	$ 16.28	$ 21.72	$ 15.30	$ 21.00	$ 14.91	$ 25.29	$ 20.29	$ 21.23	$ 22.93