State of the art in sustainable biomass recovery technology/supply chain in forest operations

IEA Bioenergy

IEA Bioenergy: Task 43 TR2016:02

Report preparation:

Forest Industries Research Centre (FIRC), Faculty of Arts and Business, University of the Sunshine Coast, Locked Bag 4, Maroochydore DC, Queensland, 4558 Australia, www.usc.edu.au
Project Scientist/Author, Dr Mohammad Reza Ghaffariyan - mghaffar@usc.edu.au
FIRC Director, Professor Mark Brown- mbrown2@usc.edu.au

Funding organisation: International Energy Agency (IEA), Task 43

International participants:
This report was mainly prepared based on the expert's knowledge and information provided by international researchers from different countries. The participation of following scientists in this project is greatly appreciated;
Dr Mauricio Acuna (University of the Sunshine Coast, Australia), Prof. John Sessions (Oregon State University, USA), A/Prof. Tom Gallagher (Auburn University, USA), Prof. Tat Smith (University of Toronto, Canada), Prof. Evelyne Thiffault (University of Laval, Canada), A/Prof. Rien Visser (University of Canterbury, New Zealand), Dr Raffaele Spinelli (IVALSA, Italy), Dr Martin Keuhmaier (BOKU Vienna, Austria), Dr Juha Laitila (LUKE, Finland), Dr Lars Eliasson (Skogforsk, Sweden), Dr Maria Iwarsson Wide (Skogforsk, Sweden), Dr Enrique García (KWF, Spain), A/Prof. Ruben Laina (Polytechnic University of Madrid, Spain), Dr Ger Delvin (University College Dublin, Ireland), Dr Kjell Suadicani (University of Copenhagen, Denmark)

ISBN,

Published by IEA Bioenergy

Table of Contents

1. Short abstract

This report provides an overview of most efficient biomass harvesting technologies and supply chains applied in North America, Europe and Oceania. The productivity and cost of selected efficient technologies have been presented for each country with a brief description about source of the biomass and working method. Expert's opinions on the most successful biomass operations have been also stated briefly for each country. The main conclusions from various international studies have been provided at the end of the report in addition to future requirements for research and development in biomass harvesting operations. Provided information in this report can be useful guide to the industry and academic users.

Chipping operations by a mobile chipper in pine plantation in Victoria (Australia)

2.Introduction

The generation of energy from biomass has a key role in current international strategies to mitigate climate change and enhance energy security. The European Union (EU) should produce 20% of their energy from renewable sources, including bioenergy, by 2020 (Routa et al. 2012). Australia's target for 2030 is 20% while USA has recently announced same target for 2030. EU-28's target for 2030 is 27%. One of the main sources is using forest biomass to help the countries meeting their long term renewable energy targets. Biomass can contribute in stabilizing carbon dioxide concentrations in the atmosphere in two ways, through: (1) biomass production for fossil fuel substitution and (2) carbon dioxide storage in vegetation and soil (Ericson and Nilsson, 2006). More than 16% of the harvesting volume in EU is used for energy production (industrial residues and recovered products). In conventional harvesting, the stem of tree is mostly used which covers only 67.7% of the tree volume (Pine). However the share of tops/branches is 19.7% of tree volume which can be a major source for forest biomass. The remaining share of tree volume is 8% for the roots and one fifth of this share (1.6%) is also harvestable (Karjalainen et al., 2004). Dedicated energy crops are another source of woody biomass for energy (Ghaffariyan, 2010). Harvesting usually occurs in winter and the harvested stems are often converted to chips on the site and then transported to the conversion plant (IEA Bioenergy, 2002). According to the IEA's definition forest biomass supply can be defined as 1) the current production of roundwood for conventional wood products (e.g. sawnwood, pulp and paper, panel), 2) the potential stem wood that could be additionally harvested within the sustainable harvest limit, 3) primary forestry residues, e.g., logging residues, early thinnings and 4) secondary forestry residues, residues from the industrial processing of wood (IEA, 2015). Forest biomass is primarily consumed locally due to its low energy density and high transportation costs. From the 1930s until present time the primary energy use for forest biomass in boreal and temperate regions has been for heat and CHP production integrated with existing industries, mainly the forest industry. This market is only likely to increase by 1% of total bioenergy demand by 2020 (from 15%-16%). Power production is expected to increase highly from about 4.8 EJ in 2010 to 17.3 EJ in 2035. Biomass-powered heating services for buildings are expected to increase from 3.7 EJ to 6.3 EJ over this same time period (IEA, 2015).

3.Study objectives

Considering large amount of forest biomass resources, different types of available woody biomass, difficult terrains and relatively long transport distance between forest areas and mill/energy plants the biomass growers require efficient harvesting machines and proper supply chain management to deliver their biomass products in lowest operating costs with minimum site impacts. To provide a general road map and guideline on sustainable biomass harvesting systems this project aimed to;

1. Identify the most productive and cost effective biomass harvesting machines and supply chains based on local research and development experience in various biomass leading countries.
2. Provide the summary of machine productivity and operating cost of most efficient biomass harvesting technologies in each country.
3. Provide concluding remarks and guidelines on efficient biomass harvesting technologies.
4. Identify future research and development requirements to gain sustainable biomass harvesting operations.

4.Methodology

In this report "sustainability" is defined as harvesting the wood resources in a way which produces the materials with lowest operation cost, highest product quality, lowest environmental impacts and higher social benefits for the communities. This definition has been derived from United Nations' description: "Sustainable forest management as a dynamic and evolving concept aims to maintain and enhance the economic, social and environmental value of all types of forests, for the benefit of present and future generations (UN, 2008)." Considering large scope of the study covering most of the forestry regions, it was decided to focus mainly on the economic aspect of sustainability (productivity and costs of most efficient supply chains and harvesting machines) in this report. The product quality, environmental and social impacts were not available in most of the received information from international studies thus these factors have been excluded to be studied by future projects.

The supply chains were mainly classified as harvesting residues from clear cuts, stump collection, energy wood (or fuel wood referring to plantations established for bioenergy usage) harvested by cut-to-length method or whole tree harvesting method and integrated biomass harvesting (combined biomass and sawlog/pulpwood recovery). To collect the information for this project, a questionnaire was designed and sent to different international forest biomass harvesting researchers. The main question was to identify what is the most sustainable and efficient biomass harvesting supply chain in each country/region. The second question was to know what harvesting technologies are most suitable ones to operate within the supply chain. Due to the large number of available studies, harvesting technologies and supply chains in biomass producing countries, expert's knowledge in each region was used to identify the most appropriate biomass harvesting machines/systems. The answers of each participant have been used to write a summary and concluding remarks on most useful supply chains/technologies in each region/country. The machine productivity data has been listed based on the provided information and local reports/publications sent by participants. The productivity (and cost) of best technologies have been reported mostly as Bone Dry Metric tonnes (BDMt) per Productive Machine Hours (PMH) to keep consistency in this report. However in some case studies that BDMt has not been reported by the participants or has not been available in the literatures, the units of m3 or GMt (Green Metric tonnes) have been used. The costs have been presented in local currency provided by the literatures or participants however all costs have been also presented based on the US Dollar ($) to give same economic base for comparison.

5. Efficient biomass harvesting technologies/supply chains

1. NORTH AMERICA

1.1.1. CANADA

The main sources of woody biomass in Canada are sawmill residues and harvesting residues from clearcut operations. The residues are used to produce pellet for domestic use (e.g. for power production in Ontario) and mostly for export to Europe and Asia (Thiffault et al. 2015). In Eastern Canada, harvesting residues at road side and in cut-over area, unmerchantable trees and round woods from thinnings are main sources of biomass. Because of small trees (average tree size less than 0.2 m3) and flat terrain in Eastern Canada, most of the trees are cut by feller-buncher and extracted by skidder to be processed at the landings which yields significant amount of residues at road side. Chippers (disc or drum chippers) and grinders are applied to process the road side residues into wood chips. Ralevic (2013) developed Biomass Opportunity Supply Model (BiOS-Map) in northeastern Ontario to analyse the cost of different types of biomass comminution. His model suggested that due to technical and operational limits, between 55%-59% and 16%-24% of aboveground biomass was not recovered under roadside residue and whole-tree harvesting respectively. The cost of delivering roadside residues was estimated at 52.32–57.45 CAN$/BDMt (39.24-43.09 $/BDMt), and for whole trees 92.63/t–97.44 CAN$/BDMt (69.47-73.08 $/BDMt). In Western Canada trees are mostly processed at the stump using cut-to-length method so harvesting residues are scattered in cut-over area and too expensive to be collected (Stokes, 1992). Thus application of mobile chippers collecting scattered residues following cut-to-length operations has not been very much applied due to high cost of collection and chipping. Chippers are mostly used as stationary ones operating at road sides or landings. There are also some operations to harvest small trees where trees are felled by feller-buncher and extracted to landing by grapple skidder in bunches to the chipper (MacDonald, 2006). In this case full-tree chipping occurs at the road side using a loader feeding the stationary chipper which blow the chips directly into chipvans (Figure 1).

Figure 1. Full-tree chipping operations in Canada (MacDonald, 2006)

MacDonald (2006) has modelled the cost of road side chipping operation. Road side chipping can allow skidding and chipping operation to be operated separately. This might increase the utilisation rate of both skidder and chippers however the trees need to be stacked into piles at road side to ensure chipper works properly. MacDonald (2006) indicated that this system had the lowest operating cost in comparison with other harvesting systems where the stands had less than 50% of fuelwood (suitable for bioenergy usage). In another study by FPInnovations in Vancouver Island (in British Columbia) the costs of harvesting residues at road side were modelled (MacDonald, 2009). The harvesting system included a grinder and loader to comminute the residues and semi-trailer chipvans were used to transport the chips. The estimated productivity of grinding, as an efficient way to process biomass, was 25.0 BDMt/PHM0 which cost 24.02 CAN$/BDMt (18.01 $/BDMt). Grinder and loader require additional cost to be mobilised between harvesting blocks which depends on the volume of residues and actual moving cost. Difficult and steep terrains slowed the movement of grinder. Also high maintenance and delays occurred by trucks reduced the grinder utilisation to 65%. Some areas allowed using water transport. The barging cost for biomass transport from remote locations cost about CAN$10 ($7.5) per m3 per 100 km. Table 1 presents the summary of machine productivity and cost for two biomass supply chains in Canada.

Table 1. Summary of the selected efficient biomass harvesting technologies in Canada (1 CAN$=0.75 US$)

Supply Chain	Machine	Model	Productivity ($BDMt/PMH_0$)	MC (%)	Cost (CAN$/BDMt)	Reference
Residue from clear cut (road side piles chipping)	Track-mounted integrated with grapple	Morbark 50/48 Mountain Goat	20-30	-	21.6-14.4 (16.2-10.8 $/BDMt)	MacDonald (2006)
	Truck	Semi-trailer	-	-	23.4-39.6 (17.5-29.7$/BDMt) **Total**: 45-54 (33.7-40.5$/BDMt)	
Residue from clear cut (road side pile grinding)	Grinder and loader	-	25	-	24.0 (18.0 $/BDMt) Mobilisation cost: 1.5-6 (1.1-4.5$/BDMt)	MacDonald (2006)
	Truck	Semi-tailer	-		27.5 (20.6 $/BDMt) **Total**: 53-57.5 (39.7-43.1 $/BDMt)	

1.1.2. NORTHWEST USA

After timber harvesting, most of the forest residues are piled and burned to clean the areas for replanting, and to reduce fuel loadings, and potential insect and rodent problems (Zamora-Cristales et al. 2013). It is estimated that a total of 127.4 million m3 of logging residues were produced in the United States in 2006 (Smith et al. 2009). There are different systems for processing and transport in the United States. Comminution options include stationary horizontal grinders (electric or diesel), tub grinders, and forwarder-mounted mobile chippers. Short distance in-forest transportation options for unprocessed residues comprise small trucks such as hook-lift trucks, bin trucks, and end-dump trucks. Long distance transportation options include chip vans with different types of tractor-trailer configurations. Trailers vary in length from 9.75 to 16.15 m. They usually contain an extension in the bottom centre of the trailer (drop-centre) to increase the trailer capacity. Different processing and transportation systems include: (1) stationary grinder at centralized landing with bin, dump, or hook-lift trucks; (2) stationary grinder processing at each pile location; (3) mobile chipper processing at each pile and loading set-out trailers; (4) stationary grinder at centralized processing yard with direct discharge into piles; and (5) bundling in forest and grinding or chipping at the bioenergy plant (Zamora-Cristales et al. 2015). Based on the study results, the most cost-effective processing option was the medium-size horizontal grinder (522 kW). A total cost of $53.73/BDMt including transportation was expected using this grinder (Figure 2). The mobile chipper total cost was $67.97/BDMt. Slash-bundler was the most expensive option (total cost of $69.46/BDMt) due to high cost of bundling.

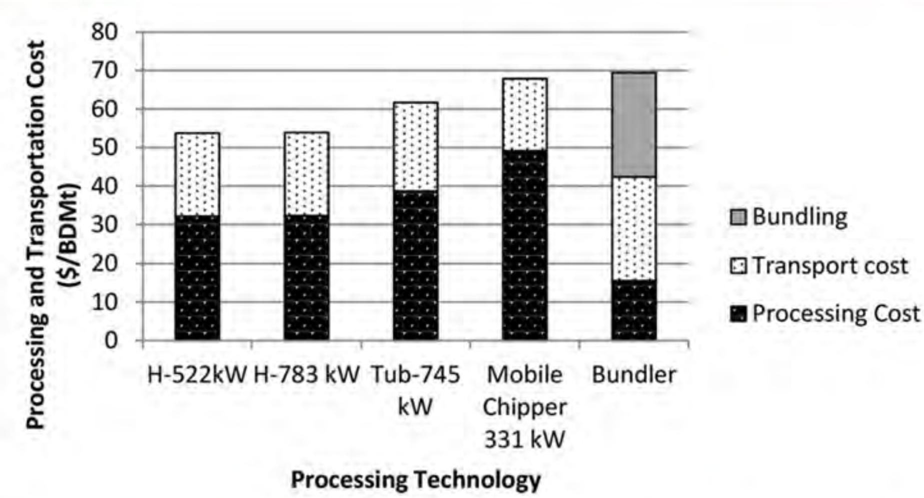

Figure 2. Costs for different biomass operating systems in Oregon, USA (Zamora-Cristales et al. 2015)

The use of a mobile chipper for processing forest residues for energy purposes represents an alternative to the use of stationary grinding machines currently used in the U.S. Pacific Northwest. The advantages of mobile chippers are the mobility to reach different locations within the forest where the forest residue piles remain following harvesting, flexibility to unload the material into different types of containers and a self-feeding system. Also the use of independent containers partially disconnects processing from trucking reducing truck dependence. However productivity is highly sensitive to the size, cleanness and type of harvest residue material, and the number of stages involved in the chipping process (chipping, moving, and dumping into trailers) gives more complexity to this process compared with stationary equipment (Zamora-Cristales et al. 2013). Based on the experience on biomass harvesting in Pacific Northwest, Sessions (2015) described the most efficient biomass systems;

"On steep terrain, whole tree systems that bring biomass to roadside with the sawtimber has the highest economic and lowest environmental impact for recovery of biomass. Point of comminution and transport trailer depend upon a number of factors, but in general grinding at the landing and transporting biomass by chipvan (standard, stinger-steered, or self-steered) directly to the mill. Efficiency of operations depends on truck availability and landing accessibility.

On flatter terrain, whole tree shovel logging is the most common method when yarding distance is less than 150 m. Many branches break off and a following operation by excavator to directly forward biomass to roadside for distances less than 50 m or the use of an excavator to load forwarder(s) for longer distances (Figures 3 and 4). Excavators can load a forwarder much more quickly and much higher volume than the forwarder can load itself.

Figure 3*. Forwarding harvesting residues by a forwarder in Northwest USA (Sessions, 2015)*

Point of comminution and transport trailer depend upon a number of factors, but in general grinding occurs at the landing and transporting biomass is operated by chipvan (standard, stinger-steered, or self-steered) directly to the mill. However, there is one very competitive contractor in northern California that transports all loose material in converted off-highway dump trucks to centralized landings (no storage) with immediate grinding into chipvans that are pulled by 6 x 6 truck tractors to transfer points for highway trucks that pull the trailers to the plant (Sessions, 2015)"

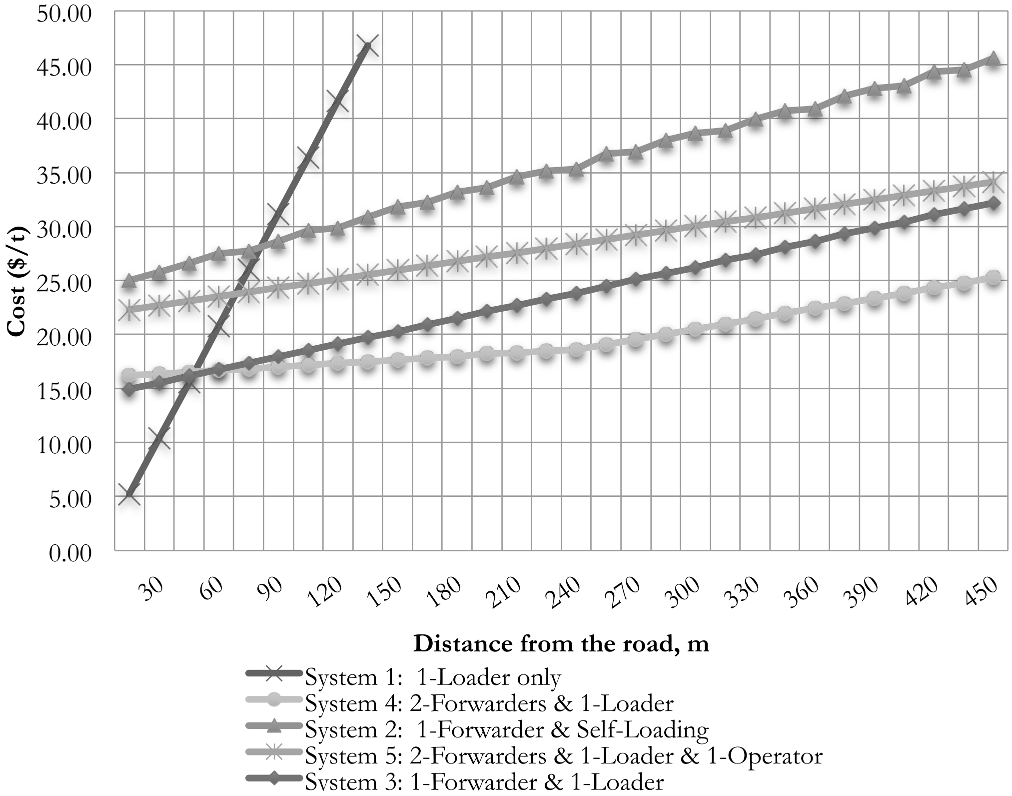

Figure 4. Cost comparison for different harvesting alternatives (Zamora and Sessions, manuscript in review, 2015)

1.1.3. SOUTHERN USA

Most of the timber harvesting activity in Southern USA forests uses ground-based skidding to deliver material from forest to the landing and this method has been used in whole-tree chipping operations. Chipper processes whole trees into uniform chips, which are then hauled to the mills by the chipvans (Johnson et al. 2012). Greene (2013) mentioned that if the green trees are chipped the moisture content can be about 50% and if trees are allowed to be dried in the field after felling the moisture content can drop from 53% to 43% and 39% in 4 and 8 weeks, respectively. This significantly reduced the cost of operations. When the moisture content decreased from 55% to 30% the delivered cost of the biomass decreased by over 50% (Greene, 2013). Whole tree chipping provided the lowest cost option ($14.98 per MWh) at ash content levels less than 1%, and unscreened grinding of clean chip residue produced the least expensive option ($9.79 per MWh) at 5% ash. Clean chipping and roundwood systems were considerably more expensive than whole-tree chipping operations on all tract sizes. Costs declined significantly as truck payload increased and/or haul distance decreased (Greene, 2013).

O'Neal and Gallagher (2008) studied a biomass harvesting system (Figure 5) including small tracked feller-buncher, mini-grapple skidder and a small Morbark chipper to supply woody feedstock from small size trees for bioenergy usage. This system could be adopted for Southern Pine and Appalachian hardwood thinning as well. The total system cost was 122.37 $/SMH and average production rate was 10 GMt/ha which was a cost-effective system (unit cost of 12.2 $/GMt) due to application of less expensive machines.

Figure 5. Harvesting system including small feller-buncher, mini-skidder and chipper in South USA (O'Neal and Gallagher, 2008)

For larger tree sizes, in whole tree chipping operations, Johnson et al. (2012) tested similar system but with large feller-buncher, large skidder and medium size chipper. This was most efficient system with the harvesting costs (from stump to road side) of 19.40 $/BDMt and hauling cost of 28.50 $/BDMt. Total system cost averaged at 47.90 $/BDMt.

Gallagher (2015) believed that there are three main sources of biomass in South-East USA. He stated that: *"The first main source of forest biomass is mill residues – very much in use and has been for a long time. Second source is harvesting residues including the tops, limbs and small diameter trees from a harvesting operation. Some operations keep a small chipper on the site and process this material for a market. The last one is small diameter tree harvesting. Some operations have been successful going onto a tract and cutting all the small "junk" from the site and chipping it for biomass. The landowner gets paid a very small amount for his stumpage, but mostly he is happy for the clean site." Gallagher (2015) added that: "The mill residues generally come in the cheapest source to utilise because the mill provides the material to clear the waste from the mill. The operations doing residue harvesting get paid the middle amount and the operations doing small diameter harvesting get paid the most. Who is most and least productive depends on the site and the operation."*

Some of the most efficient biomass harvesting machines operating in North America have been selected and presented in Table 2. From this table, cost of whole tree chipping in small tree sizes was lower than for collecting residues by mobile chipper. Grinder's productivity was much higher than mobile chipper although its cost was about $2 cheaper per BDMt.

Table 2. Summary of the selected efficient biomass harvesting technologies in North America

Supply chain	Machine	Model	Productivity (GMt/PMH$_0$)	MC (%)	Cost ($/BDMt)	Reference
Residue from clear cut	Mobile chipper Truck	Bruks 805.2 mounted on forwarder Single trailer-15.5t	12 -	30 30	37.9 18.1 Total: 56.0	Zamora-Cristales et al. 2013
Residue from clear cut	Grinder	Peterson 5710C	54.4	30	35.7	Zamora-Cristales et al. 2015
Whole tree chipping (large trees)	Large feller-buncher Large skidder Medium chipper Chip van	- - -l®- 120 yd3 with medium chipper	56 13.2 76.2 6.4	50 50 50 50	3.50 10.60 5.30 28.50 Total: 47.90	Johnson et al. 2012

2. EUROPE

2.1.1. AUSTRIA

There are various biomass harvesting systems applied in Austria in flat terrains or mountainous area. Stampfer and Kanzian (2006) described the development of the Austrian wood chips supply chains as following: "Potential woody material sources include thinning and coppice stands as well as harvesting residues. Additional materials can also come from short rotation forests. Chipping in the forest stands is seldom used in mountainous conditions of Austria. In mountainous conditions working space at the road sides is the limited. Loading the truck directly with the chipper requires the machines to be positioned so that enough space is available. One solution is separating the work process, whereby the machines become independent from the other. However, additional costs occur in loading trucks. Another solution is the pre-concentration of material to be chipped at a central landing area. Provision of centralized processing areas close to the forest that can be provided with minimum infrastructure changes makes good sense. Central landings near to the public road infrastructure enable the use of non-specialized means of transportation (e.g. semi-trailer configurations with containers) for the transportation of woody biomass. The additional cost of preparing the centralized processing/storage area can be covered by these positive effects (Stampfer, Kanzian, 2006)".

Keuhmaier (2015) has provided the summary of the most efficient biomass harvesting systems applied in flat or steep terrains of Austria (Table 3 presents three selected systems). He believed that; "There are several biomass harvesting technologies in Austria where each technology has its own strengths depending on terrain, forest type and operating conditions." Thus he has developed a multiple-criteria decision support tool for energy wood supply chain management in Austria to consider various criteria such as economic, environmental and ergonomic factors (Keuhmaier and Stampfer, 2012). Figure 6 illustrates the wood extraction by Wanderfalke tower yarder which is a typical steep terrain harvesting technology in Austrian mountainous forests. Extraction cost by cable yarders are higher than ground-based harvesting equipment (such as forwarders, etc.) mainly due to lower productivity, higher machine cost and considerable cost for installation and take-down.

Table 3. Summary of some selected efficient biomass harvesting technologies in Austria (1€=1.13$)

Supply chain	Machine	Model	Productivity (m^3/PMH_0)	Cost (€/m^3)	Referenc e
Whole tree extraction-steep terrains	Felling with chainsaw, Extraction by yarder, Processing at road side by processor	Wanderfalke tower yarder	4.47	Total system costs: 30.23 (34.16 \$/m^3)	Affenzeller and Stampfer (2007)
Energy-wood chipping	Chipper	MUS MAX Wood Terminator 10	2.80	12.40 (14.01 \$/m^3)	Affenzeller and Stampfer (2007)
Energy-wood harvesting in flat terrains	Feller-buncher Forwarder	Moipu 300ES HSM208	4.00	Total system costs: 28.09 (31.74 \$/m^3)	Elmer et al. 2011

Figure 6. Wanderfalke tower yarder combined with a processor at road side (Austria) (Affenzeller and Stampfer, 2007)

2.1.2. DENMARK

Suadicani (2015) indicated that *"Chipping of whole trees that have been dried during summer period is very well established in Denmark. This operation has low cost especially if the stands are large with large tree sizes. This operation works efficiently on flat terrain and sandy soils with sufficient bearing capacity. This harvesting system consists of a feller-buncher and front-feed chipper mounted on a container attached to a forwarder. If strip roads have been well established/prepared this system can be very productive."* Wood chips are transported to the plant with truck containers where chipping productivity gets as high as 25 to 30 m^3(loose)/PMH0 (Kofman and Kent, 2009; Suadicani, 2004). Silversides and Sundberg (1989) suggested that the greatest advantage may be realized in chipping of multiple stems simultaneously. In this case the chipper is less susceptible to the negative cost-effects of the 'piece-volume-law' (which indicates that increasing piece size typically results in increased production). Figure 7 presents the combination of feller-buncher and chipper in Danish biomass harvesting operations. Table 4 presents the summary of cost and productivity of this system.

Figure 7. Whole tree chipping by combination of feller-buncher and chipper in Denmark (Kofman and Kent, 2009)

Table 4. Summary of some selected efficient biomass harvesting technologies in Denmark (*1€=1.13$*)

Supply chain	Machine	Model	Productivity (m^3/PMH_0)	Cost (€/m^3)	Reference
Whole tree chipping at road side	Feller-buncher Chipper	Silvatec 656 TH Fendt Favorit 614 LSA/TP-960	14-50 25-30	2-7 (2.26-7.91 $/$m^3$) 9.90-11.90 (11.19-13.45 $/$m^3$) **Total cost:** 11.90-18.90 (13.45-21.36 $/$m^3$)	Suadicani (2004); Kofman and Kent (2009)

2.1.3. FINLAND

Finland, as a leader in biomass utilisation, has a target produce 38% of its energy from renewable sources by 2020. The by-products from forest industries (e.g., sawdust, black liquor) have a high degree of utilization. Additional raw materials for energy production include logging residues, stump and root wood, small diameter wood, and other wood not in demand by the traditional forest industries. Biomass supply chains in Finland may be characterized based on the location of comminution into roadside comminution, terminal comminution, or comminution at a plant (Routa et al. 2013). Laitila (2015) has summarised the most efficient Finnish biomass supply chains as following;

*"**a) Multi-tree cutting of thinning wood**: Whole tree harvesting is applied when DBH of the harvested trees is less than 10 cm. Trees are harvested as delimbed, when DBH of the harvested trees is more than 10 cm. Whole trees are chipped at roadside landings and delimbed stems at the terminals or at the plant (the most cost efficient systems). The proper technologies for this supply chains includes medium size harvester-processor (to cut and delim), medium size forwarder (to extract the cut trees), conventional timber truck (to transport the trees to plant) and a chipper at the plant or terminal.*

***b) Logging residues from clear cuts**: The residues can be collected and chipped at landings located at the roadside. The most efficient method is to pile the tops and branches by harvesters along the forwarding trails integrated with the mechanised cutting of round wood. The residues can then be collected and extracted using large or medium size forwarder. Chipping of logging residues will occur at the roadside with truck mounted drum chipper to be transported by a truck-trailer unit to the plant.*

***c) Stumps**: The stumps are excavated in the field (Figure 8) and stumps will be grinded at the plant or at the terminal. Pre-grinding and integrated screening is a feasible way to guarantee the fuel quality expressed as ash content already at roadside landings, but the procurement costs are higher compared to grinding stumps at the plant, when the ash content of ground stumps is 6% or less.*

Figure 8. Excavating stumps (Moffat et al. 2011)

The most efficient working method for this supply chain is to uproot and split the stumps by a tracked excavator (weight about 20 tonnes). Large or medium size forwarder can then extract the stumps to the roadside. Next phase would be transporting harvested stump with a biomass truck for comminution at the plant or pre-grinding and sieving at the landing and final comminution at the end-use facility." Table 5 presents the productivity of some of the selected efficient biomass utilisation technologies applied in Finland.

Table 5. Summary of some selected efficient biomass harvesting technologies in Finland

Supply chain	Machine	Model	Productivity (m^3/PMH_0)	Cost	Reference
Multi-tree cutting of thinning wood	Harvester	New Holland Kobelco E135BSRLCD equipped with Naarva EF 28 head	12.80	-	Laitila and Väätäinen (2013)
Energy wood from thinning	Forwarder	Timberjack 810B	11.90 (after mechanized felling) 7.1 (after manual felling)	-	Laitila et al. 2007
Stump utilisation	Crawler excavator (to excavate)	JCB JS 160 L excavator equipped with a "Kantokunkku" extraction-splitting	7.90	-	Laitila et al. 2008
	Forwarder (to extract)	Ponsse Bison S15 B1	7.80	-	

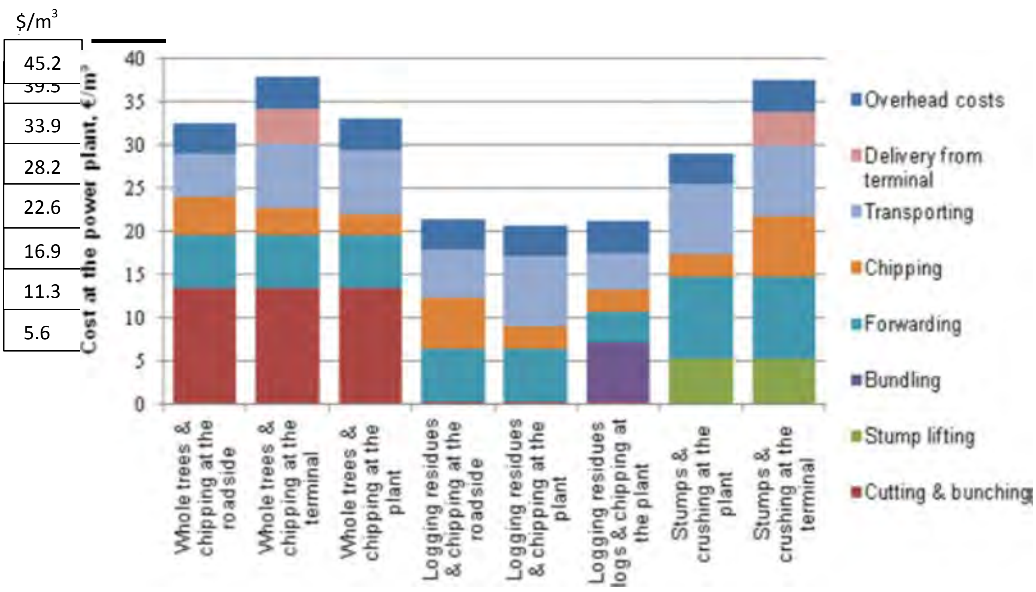

Figure 9. Procurement costs of forest chips with different harvesting systems from different raw materials. The forwarding distance was 250 m and transport distance was 45 km (Routa et al. 2013).

From costing point of view, Routa et al. (2013) indicated that recovering logging residues requires lower costs than whole tree chipping or stump utilisation in Finland and Sweden. Figure 9 (prepared by Routa et al. 2013) illustrates the total costs and cost per each element for different supply chains.

2.1.4. GERMANY

Cremer and Velazquez-Marti (2007) described two harvesting systems to produce biomass chips:

a) Harvesting residues were directly processed in the stand using a mobile chipper mounted on a forwarder, b) Harvesting residues were concentrated with a forwarder in piles along the forest road and then were chipped using a chipper mounted on a truck. Productivity of chipper working at road side was nearly 50% higher in comparison to a chipper working in stand. The higher productivity resulted from the fact that material was very well concentrated. The other reason for higher productivity was that the assortment that could have been utilised for pulpwood was also chipped by road side chipping system which increased the productivity. The other reason was due to larger machine power of road side chipper (442 kW) than chipper working in stands (272 kW). The costs of both systems are comparable: 4.74 €/m^3_{loose} (5.36 $/$m^3_{loose}$) in first system and 5.63 €/m^3_{loose} (6.36 $/$m^3_{loose}$) for second system (Cremer and Velazquez-Marti, 2007). There are also other available biomass harvesting systems in Germany. One system is combination of feller-buncher, forwarder and chipper. In this system, trees are cut by a feller-buncher, and then extracted to the road side by a forwarder to be chipped. Another harvesting system include tree cutting and extraction to road side using a forwarder equipped by felling head. Trees would then be chipped into trucks at the road side (Cremer, 2008). Grosse (2008) reported that short rotation plantations are another source of biomass to produce range of products such as log, bundle and wood chip. The techniques with agricultural reaper-chipper are able to harvest trees up to 12 cm cutting diameter. If cutting diameter is larger, one could use feller-buncher or harvester-chipper. KWF (2012) summarised some efficient energy wood harvesting systems using in-field chipping operation (Table 6) where the system including a harwarder and a chipper (Figure 10) was less costly alternative.

Figure 10. Chipping energy wood by Jenz HEM chipper in Germany (KWF, 2012)

Table 6. Summary of some selected efficient biomass harvesting technologies in Germany (*1€=1.13$*)

Supply chain	Machine	Model	Productivity (m^3/PMH_0)	Cost (€/m^3)	Reference
Energy wood from thinning (spruce)	Harwarder Chipper	- Jenz HEM 420 DL	3.29 22.05	27.96 (31.59 $/$m^3$) 2.72 (3.07 $/$m^3$) **Total:**30.68 (34.67 $/$m^3$)	KWF (2012)
Energy wood from thinning (spruce)	Harvester Forwarder Chipper	- HSM 208 F Jenz HEM 420 DL	4.86 8.10 22.05	24.07 (27.20 $/m3) 9.51 (10.75 $/m3) 2.72 (3.07 $/m3) Total: 36.30 (41.02 $/m3)	KWF (2012)

2.1.5. IRELAND

In 2012, more than 8% of total harvesting volume in Ireland has been used in the firewood sector which indicates the importance of biomass harvesting in this country. Devlin (2016) has described the most efficient biomass operations in Ireland as following;

a) ***Utilisation of standard thinning materials:***

The supply chain includes a harvester to fell and process the trees into standard short logs (3 m length with minimum top diameter of 7 cm). The logs are extracted by forwarder to road side. The logs are chipped into trucks by a tractor-based or truck-based chipper. Woodchips are then transported to power plants using walking floor trucks (Kent et al. 2011, Sosa et al. 2015a, Devlin and Talbot, 2014). Most effective machines includes Silvatec C 856 harvester, Valmet 840 forwarder and MusMax T8 drum chipper based on Valtra tractor (Figure 11).

Figure 11. Thinning operations in Ireland (Delvin, 2015)

b) ***Integrated energy wood from thinning:***

Very similar operations to standard thinning operation except the shortwood (3m) now all becomes energy *wood. The woodchip does obviously not require a minimum diameter. Any material that is not processed for stake or sawlog becomes energy wood (Kent et al. 2011, Sosa et al. 2015a).*

c) ***Woodchip supply from whole tree thinning:***

This operation produces a range of wood products: sawlogs with a minimum diameter of 20 cm, palletwood obtained from the mid-section of the log and has a small end diameter of 14 cm, and pulpwood with a diameter between 14 and 7 cm. In addition to branches, stem material of less than 7 cm in diameter is left on the forest area. Chipping is carried out at the forest roadside by tractor or truck-drawn machines (Kent et al. 2011, Devlin and Talbot, 2014).

d) ***Forest residues after clear cuts (bundling):***

This supply chain is relatively new to Irish operations and still only carried out on specific sites. It was originally trialled in Coillte in 2009 with over 18661 bundles baled by slash bundler over 14 sites. Each was 2.5m long and 60cm diameter (Kent et al. 2011, Sosa et al. 2015b). The bundles were then transported to mill to be chipped there.

Table 7 summarises the productivity and cost of most efficient harvesting systems in Irish conditions (Devlin, 2016)

Table 7. Summary of some selected efficient biomass harvesting technologies in Ireland (1€=1.13$)

Supply chain	Machine	Model	Productivity (m^3/PMH_0)	Cost (€/m^3)	Reference
Energy wood from thinning	Harvester Forwarder Chipper	Silvatec C 856 Valmet 840 MusMax T8 drum chipper	2.57-5.22 3.41-10.25 11-17	**Total:** 38.02-55.45(42.96-62.66 $/$m^3$)	Kent et al. 2011
Integrated energy wood from thinning	Harvester Forwarder Chipper	- - MusMax T8 drum chipper	- 3.63-7.3 7-60	**Total:** 33.43-52.68 (37.78-59.53 $/$m^3$)	*Kent et al. 2011*
Whole tree thinning	Feller-buncher Chipper	- Silvatec Terrain Chipper 878	3-8 12-23	**Total:** 16.85-29.77 (19.04-33.64)	*Kent et al. 2011*

2.1.6. ITALY

Many Italian forest companies produce substantial amounts of wood chips. In most cases, chip is a collateral product obtained from less valuable trees and tree portions. Chipping is one of the most effective way to dispose of the harvesting residue (Spinelli and Hartsough, 2001). Chip production is associated with the type of silviculture regimes. Clear cuts provide the highest contribution. Thinning operations also play an important role in providing substantial amounts of chip. Most of biomass harvesting operations chip the materials in the stands (in-field chipping). When terrain conditions are less favourable, one could use a bulldozer to pull the truck or resort to tractor and trailer units. Chipping at the landing site is also common. It is performed when terrain conditions prevent in-stand truck traffic and when the logger believes that chip shuttling would not be viable option. At the landing, chips can be blown into a truck, a trailer, a container or directly on the ground forming a large heap. In the case of heaps, chips will be reloaded on the trucks. Some loggers prefer to reload the chip from a heap, in an effort to reduce truck waiting time. A loader can fill up a standard truck faster than the average professional chipper (Spinelli and Hartsough, 2001). Harvesting the roots of popular plantations is another source of biomass (Spinelli et al. 2005). Spinelli (2015) described three efficient and common supply chains applied in Italy as below;

a) Harvesting residues from clear cuts in steep terrains:

Whole trees are extracted with cable yarders to road side to be processed into logs. After the cable yarder is removed, a truck-mounted chipper (Figure 12) drives up to the landing and chip the harvesting residues (tops and branches) into chip vans for transportation to the CHP plant.

Figure 12. Truck mounted chipper working at road side in mountainous forests in Italy (Spinelli, 2015)

b) Harvesting residues from poplar plantations:

Poplar plantations are clear cut at age of 12 years (DBH of 35 cm) to produce plywood and sawlog. After industrial wood recovery, the harvesting residues including tops and branches are piled. A self-propelled chipper access the field, chips the residues and blows the chips into trailers towed by farm tractors (Figure 13), which dump the chips on a pad for later reloading and transportation to the CHP plant (Spinelli and Magagnotti, 2011).

Figure 13*.* Chipping poplar residues in Italy (Spinelli, 2015)

c) Energy wood from second thinning:

Pine trees from second thinning operations are harvested at age of 20 years using a combination of feller-buncher, skidder, self-propelled chipper and truck (Figure 14). Whole trees are extracted to road side using skidders. The whole trees are then chipped into trucks (Spinelli et al. 2014). Spinelli (2015) has summarised the productivity and costs of efficient systems in Italy in Table 8. Road side chipping of residues by truck-mounted chipper seems to be slightly more expensive than thinning operations in pine plantations while harvesting residues from poplar plantations is most costly operation.

Figure 14. Harvesting energy wood in Italian pine plantations (Spinelli, 2015)

Table 8. Summary of some selected efficient biomass harvesting technologies in Italy (*1€=1.13$, MC not available*)

Supply chain	Machine	Model	Productivity (GMt/PMH_0)	Cost (€/GMt)	Reference
Residues from clear cut in steep terrain (pine)	Chipper Truck/trailer	Truck-mounted -	15 4	13.3 (15.0 $/GMt) 15.0 (16.9 $/GMt) **Total:** 28.3 (32.0 $/GMt)	Spinelli (2015)
Residues from poplar plantations	Loader Chipper Loader Truck/trailer	- Self-propelled - -	25 20 30 6	2.4 (2.7 $/GMt) 20.0 (22.6 $/GMt) 2.0 (2.3 $/GMt) 10.0 (11.3 $/GMt) **Total:** 34.4 (38.9 $/GMt)	Spinelli (2015)
Energy wood from thinning (pine)	Feller-buncher Skidder chipper Truck/tailer	- - Self-propelled -	32 24 20 6	3.1 (3.5 $/GMt) 2.9 (3.3 $/GMt) 10.0 (11.3 $/GMt) 10.0 (11.3 $/GMt) **Total:** 26.0 (29.4 $/GMt)	Spinelli (2015)

2.1.7. SPAIN

In Mediterranean area, in addition to the forest biomass the agricultural woody biomass productions are important. In Southern Europe permanent crops residues such as olive, vine and orchid pruning are produced in the greatest amount compare to the other parts of Europe (RENEW, 2006). The common biomass harvesting system is combination of a farm tractor, small chipper and trailer (Ghaffariyan, 2010). The collected biomass varies from 1.77 GMt/ha to 4.0 GMt/ha and the efficiency ranges from 0.61 to 24 hours per ha (Pari and Cutini, 2002; Nati et al. 2007; Valazquez-Marti, Fernandez-Gonzalez, 2009). Garcia (2015) and Laina (2015) have summarised the efficient Spanish biomass supply chains;

*"**a) Whole tree chipping operations:** This is applied for commercial pine, oak or beech thinning in moderate to flat terrains (slope less than 30%). This operation includes felling and processing with a harvester (e.g. John Deere 1270), extraction of full tree with forwarder (e.g. Timberjack 1410D) (Figure 15) chipping with a mobile chipper (e.g. Willibald ESU 4800) and stacked in piles along the roadside, loading in the truck with a telescopic crane. Better economic results can be expected with multi-tree harvester but the presence of these machines in Spain is low. On steep terrains (with slope > 30%) or very restrictive conditions for protective function of the forest (east and south of the country) motor-manual felling is applied to fell and process the trees. The expected damage to remaining stand for operation with harvester is medium (5%-20% of the remaining stand can be damaged) while operations using chainsaw has about 14% rate of damaged stands.*

Figure 15*.* Whole tree harvesting using harvester and forwarder in Spain (Laina et al. 2013)

b) Residues from clear cut: *This system is applied for commercial poplar, eucalyptus or pine timber harvesting. Felling and processing are carried out by a harvester (e.g. Ponsee Scorpion). The harvest residues (crown and branches) are left and separated on the site by harvester. Round woods are extracted by a forwarder and the harvest residues are left on the site for a drying period of 3 to 6 months. Extraction of residues will then be carried out by a chipper mounted on a forwarder (e. g Timberjack 1210A with chipper package Erjo 7/65). In large forest areas the most productive system is chipping at the roadside. In eucalyptus plantations, slash-bundlers (e.g. Timberjack 1490D) are also applied to collect the residues".* Table 9 presents the productivity-cost of some of the selected efficient biomass utilisation technologies applied in Spain.

Table 9. Summary of some selected efficient biomass harvesting technologies in Spain (*1€1.13$*)

Supply chain	Machine	Model	Productivity (BDMt/PMH_0)	MC (%)	Cost (€/BDMt)	Reference
Whole tree chipping (pine plantations)	Harvester Forwarder Chipper	Valmet 911 Valmet 910 *Willibald ESU 4800*	6.30 6.50 31.64	- - -	11.34 (12.87 $/BDMt) 8.31 (9.43 $/BDMt) 3.29 (3.73 $/BDMt) **Total:** 22.94 (26.03 $/BDMt)	Garcia (2015)
Residues from clear cut (Eucalypt plantations)	Forwarder (to extract bundles) Chipping	Timberjack 1410D Erjo 7/65	12.5 13.5	- -	4.32 (4.90 $/BDMt) 7.70 (8.74 $/BDMt) **Total:** 12.02 (13.64 $/BDMt)	Garcia (2015)

2.1.8. SWEDEN

Sweden has one of the largest targets on application of bioenergy in Europe. Its target is to produce 49% of the consumed energy from biomass by 2020 (Routa et al. 2013). The consumption of forest chips was 8.4 million m^3 in 2010. Logging residues have been the main source of biomass chips in Sweden (4.3 million m^3) in 2010. Harvesting volume of small diameter wood was 1.3 million m^3, stump and root wood 0.3 million m^3 and roundwood 2.5 million m^3 in 2010 (Routa et al. 2013). Eliasson from Skogforsk (2015) stated that; "*The most efficient and sustainable supply chains in Sweden are: a) utilisation of defect wood from final felling and b) collecting harvesting residues from final felling. Most productive and least costly technologies for defect wood utilisation includes forwarder to extract, log truck to transport and large disc or drum chipper at the yards to chip. The harvesting residues from final felling are best to be collected by a forwarder equipped with special bunk for residues (Figure 16). Then a drum or disc chipper at the landing can chip the residues into containers or chip trucks to be transported to energy plants. The biomass recovery rates averages at 75% to 85%. Site and stand damages by the operations depends on site and weather conditions. In frozen soils there is very low level of damages while in dry conditions the level of damage is low and when the soils are moist during wet season then the high level of damage to the environment can occur".* Iwarsson Wide from Skogforsk (2016) added that multi-tree cutting of small diameter trees and stump are other sources of biomass in Sweden. She stated that: "*The potential in multi-tree handling is greatest in stands with a low mean stem volume (0.02-0.05 m^3) that can increase machine productivity by 15-50 percent. Whole tree harvesting is not that common in Sweden at the moment, but sometimes applied when DBH is less than 7-8 cm and trees shorter 6-7 meters height. Wholes trees are stored at the landing before chipping and transport to the plant. Trees with a DBH over 8-9 cm are harvested as delimbed energy wood with medium or large size harvesters with multi-tree equipment, forwarded with a medium size forwarder and normally chipped at a terminal or plant. In the case of stump utilization because of low forest fuel demand and FSC regulations no stumps are being harvested in Sweden nowadays. Stumps are otherwise excavated in the field, forwarded to landing for storage and then either pre-grinded before transport or transported to the plant for grinding. Comminution at the landing is preferable if the transport distance is more than 70 km."*

Table 10 summarised the productivity of some of the most efficient forwarding and chipping technologies tested by Skogforsk. It seems that most effective method is applying chippers at road side to chip the residue piles directly into truck/trailers which is consistent with the results of chipping productivity model (Ghaffariyan et al. 2013 (b)) due to reducing the time of chipping per each load which leads into higher productivity.

Skogforsk has also studied three alternatives for collecting and transporting harvesting residues including; logging residues comminution at the cutover area, comminution at the landing by chipper/grinder and systems with no moving costs between sites, i.e. direct transport of loose logging residue or by chips comminuted by chipper truck (or chipper link) (Figure 17). Comminution at the cutover is expensive and can only be justified on non-economic grounds. The system with landing-based chippers can compete over longer extraction distances (>100-120 km). On medium-sized to large harvesting sites, large chippers or crushers are preferable. The systems with no moving cost are superior for most of the raw material, particularly on small logging sites and short-medium hauls (Björheden, 2011).

Figure 16. Modified bin load of a forwarder to extract residues in Sweden. Note the framework on the bunks and the rearward extension with the two slightly rearward leaning additional rear posts. (Eliasson et al. 2011)

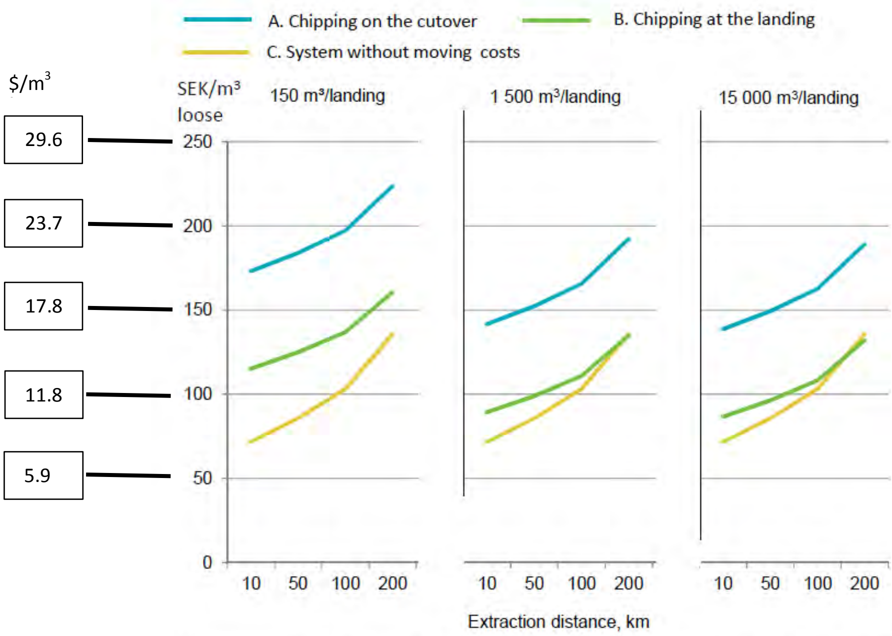

Figure 17. Operating costs for different harvesting residue harvesting systems in Sweden (Björheden, 2011). Note that corresponding cost in $\$/m^3$ loose is added to the figure (*1 SEK=5.93 $*).

Table 10. Summary of some selected efficient biomass harvesting technologies in Sweden (*1€=1.13$*)

Supply chain	Machine	Model	Productivity ($BDMt/PMH_0$)	MC (%)	Cost (€/BDMt)	Reference
Residues from clear cut (pine and spruce)	Forwarder	John Deere 1110D with modified bin load	7.90	40	-	Eliasson et al. 2011
Residues from clear cut (pine and spruce)	Trucked based chipper at road side	Container handling chipper truck (CCT)	10.10	-	-	Eliasson (2011)
Residues from clear cut (spruce)	Truck based chipper at road side	Chipper link (Bruks-Kloeckner 805 CT)	25.84	-	-	Eliasson (2011)
Whole tree harvest	Harvester	Valmet 911, Bracke C16	2.80-5.50	-	-	Iwarsson Wide and Belbo (2009)
Multi-tree cutting of energy wood	Harvester	Eco Log 560C with LogMax 4000B	6.90	-	-	Iwarsson Wide and Fogdestam(2011)
Energy wood	Forwarder	Ponsse Elk	10.45	-	-	Iwarsson Wide and Fogdestam(2011)
Stump utilisation	Excavator	20-25 t	3.80-4.50	-	15.92 *(*18 $/BDMt)	von Hofsten (2011)
	Forwarder	15t	5.70	-	-	Lazdins et al. (2009)

3. OCEANIA

3.1.1. AUSTRALIA

Australia is at an early stage of exploring the use of forest biomass to produce energy. Woody biomass utilisation programs include power stations that cofire wood waste with coal in New South Wales and Queensland. An energy-pelletising plant in Albany (Western Australia) has been recently commissioned to use forest biomass (Ghaffariyan et al. 2011(a)). There are three main sources for biomass including harvesting residues, dedicated plantations and mill residues. The estimated harvesting residues is Australia is more than 3 million tonnes (Ryan et al. 2012). Harvesting technology and working method can significantly impact the level of recovered and retained biomass (Ghaffariyan, 2013). One of the technologies tested to recover harvesting residue from Eucalypt clear cuts was Pinox slash bundler. This slash bundler recovered 65% of the harvesting residues. It was applied under two treatments. Firstly it collected residues from cut over area (average productivity of 4.9 GMt/PMH_0) which costed 65-70 AU$/GMt (45.5-49 $/GMt) to deliver the bundles at road side. Secondly the residues were raked by an excavator then collected by slash-bundler which resulted in higher bundling productivity (10.5 GMt/PMH_0) of 35-40 AU$/GMt (24.5-28 $/GMt) at road side (Ghaffariyan at al. 2011 (b)). The chipping cost needs to be added to the bundling and forwarding cost which will increase the total cost. Given the price of delivered biomass chips at the mill gate around 30-40 AU$/GMt (21-28 $/GMt) in Australia the slash-bundling system does not seems to be economically viable option. The other technology for harvesting residue collection is Bruks mobile chipper mounted on a forwarder (Figure 18) which was tested in Victoria to recover residues from a pine clear felled plantation (Ghaffariyan et al. 2012). This machine was more productive to chip road side residue log piles into trucks rather than collecting residues scattered in cut over area (Ghaffariyan et al. 2014). The recovery rate ranged from 15% to 50%.

Figure 18. Bruks mobile chipper for biomass recovery in Victoria (Australia)

Integrated biomass harvesting was found as an efficient way to harvest residue logs during the sawlog and pulpwood recovery by conventional forwarders in pine plantations (Ghaffariyan et al. 2015). Residue logs (called Fibre plus) that do not meet the minimum length and diameter of a sawlog or pulpwood can be collected and extracted by forwarders during the operations with reasonable operating cost. The recovery rate of this type of operation is about 20% to 25%.

Whole tree chipping has been applied to harvest a low quality and failed Eucalypt plantations in Western Australia. The trees were cut by a tracked feller-buncher, then extracted by a grapple skidder to road side. A Husky Precision chipper was applied to chip whole tree into truck at road side and the wood chips were transported in Albany pelletizing plant. The biomass recovery was very high (90%-95%) due to whole tree extraction which may result in high nutrient removal (Figure 19). Table 9 presents the summary of productivity and cost of efficient biomass harvesting systems in Australia.

Figure 19. Whole tree chipping operations in Eucalypt plantations in Western Australia

Table 11. Summary of efficient biomass harvesting technologies in Australia (*1 AUD=0.70 $*)

Supply chain	Machine	Model	Productivity (GMt/PMH_0)	MC (%)	Cost (AU$/GMt)	Reference
Residues from clear cut (pine)	Mobile chipper	Bruks 805.2 STC mounted on an Ecolog 594C forwarder	43.88 (19.40 BDMt/PMH_0)	55.8	24.2 (16.96 $/GMt = 38.36 $/BDMt)	Ghaffariyan et al. 2012
Integrated biomass operations (pine)	Harvester Forwarder	Cat 541 with a Rosin RD977 processing head Valmet 890.3	88.30 71.20	- -	3.20($2.24) 2.70($1.89) **Total:** 5.90 ($4.13)	Ghaffariyan et al. 2015
Whole tree biomass (Eucalypt)	Feller-buncher Grapple skidder Chipper	Tigercat 845C Tigercat 730C Husky Precision 2366	50.10 44.60 50.70	- -	2.99 ($2.10) 2.69 ($1.88) 7.60 ($5.32) **Total**: 13.28 ($9.30)	Ghaffariyan et al. 2011(a)

3.1.2. NEW ZEALAND

The main source of woody biomass in New Zealand is harvesting residues. The estimated residues produced from harvesting operations at the landings along the forest roads is about 1 million m^3 per year (about 3 to 12% of total harvesting volume). In many regions there is also a diminishing market for lower quality wood for pulp manufacture that could also significantly increase the volume of woody biomass available (Visser, 2010). Visser (2015) who has studied the biomass harvesting operations in New Zealand believed that the most efficient biomass harvesting systems in New Zealand includes;

*"**a) Processing biomass with a tub grinder, transport in a chip truck** (Figure 20): In this system, an*

excavator with a root rake is used to feed the tub grinder to produce hog fuel. A front-end loader is then applied to pile and load the materials into a chip truck. The success of this system depends on the volume of the residues available on the landing. Operating with residues larger than 2000 tonnes in this case study has been recognised as successful operation (Visser, 2010).

b) Picking up 'short logs' residues (>2m) with self-loading truck and taking to commercial mill for chipping / grinding: *Logs with large diameter (length between 2.5 to 4.5 m) can be split by an excavator-splitter into piles to be naturally dried for about 20 weeks prior to be chipped at the landing. The logs to be split are done prior to bucking to length. This is done with an excavator with a mounted ripping tine. Once all logs are split and cut to 1.8m they are carefully stacked on the pallets up to a height of approximately 1.6m (Visser, 2010)".*

Table 12 presents the productivity and cost of the applied harvesting technologies in New Zealand.

Figure 20. Tub grinder and chip truck operating in New Zealand (Visser, 2010)

Table 12. Summary of efficient biomass harvesting technologies in New Zealand (*1 NZD=0.63 $*)

Supply chain	Machine	Model	Productivity (GMt/PMH_0)	MC (%)	Costs (NZ$/GMt)	Reference
Harvesting residues at landing	Excavator Grinder Loader Truck	20 T tracked Diamond Z tub-grinder Hitachi LX200 Chip truck	15-30	55	*Total cost:* 38-46 (23.94-28.98 $/GMt= 53.20-64.40 $/BDMt)	Visser, 2010
Recovering residue logs from landings	Splitter Chipper Transport	Excavator based Truck mounted Log truck	12	25	*Total cost:* 32 (20.16 $/GMt=26.88 $/BDMt)	Visser, 2010

6.Conclusions

Main source of biomass is different in various parts of the world. European countries seem to be utilising the woods from thinning operations as well as harvesting residues (Routa et al. 2013) while in Oceania or Southern USA the main source for bioenergy is harvesting residues (Ghaffariyan, 2013; Gallagher, 2015) although in southern parts of USA logs and stems are also used for bioenergy purposes. This may be mainly due to different bioenergy policies applied in different regions as in Europe growers are subsidized for biomass production while in Australia there is lack of such a federal support resulting in focusing on recovering residues from cut-over or landings. Low price of biomass in some countries has led to application of integrated biomass and conventional wood recovery to reduce the cost (Ghaffariyan et al. 2015, Spinelli and Magagnotti, 2011) while in European countries separate biomass recovery still sounds as an economically viable option. Moisture content of the biomass materials can impact the cost of harvesting and transportation. In some countries the harvesting residues or round woods are dried in the forest (in the cut-over area or at road side) which seems to be effective way to decrease the cost of operations (Garcia, 2015; Visser, 2010) and also might result in leaving needles and leaves on the sites for soil quality purposes. However harvesting and transporting the green materials are still being applied especially in the areas such as Australia where payment is based on green metric tonnes rather than dry tonnes or calorific values per tonne.

From technological point of view, terrain and availability of the biomass make significant impact on the type of technology to apply and operating costs. Mountainous forests in Central Europe or North-West of USA would require cable yarding systems to extract the woods from steep terrain which may result in higher costs however less impacts on forest soils compared to ground-based harvesting systems like forwarders (Affenzeller and Stampfer, 2007). From New Zealanders' perspective the higher the volume of woody residues available at the landings the more the chance to operate successfully (Visser, 2010). This fact was also proved in Sweden that higher yield per ha will result in lower operating cost as a key factor on biomass supply chain management (Björheden, 2011).

One of the learnt lessons in harvesting residue collection by mobile chippers in Sweden, Canada, Australia and Germany is that although the mobile chippers have been designed to collect the scattered residues on cut over area however to gain higher efficiency of the chipper the best practice is to apply them for road side chipping. The residues can be collected or concentrated into larger piles (using forwarders or any other suitable type of forestry machines) then chipped directly into trucks to reduce operating costs (Desrochers et al. 1993; Björheden, 2011; Ghaffariyan et al. 2012; Ghaffariyan et al. 2014). Other lesson learnt internationally from European, North American and Australian research experience is that using slash-bundlers to collect harvesting residues is one of the most expensive options that may increase operating costs. This is mainly due to high hourly machine cost and relatively low productivity. Transporting bundles (and consecutive chipping at the mill) is relatively expensive, in comparison with chipping whole trees or logs in the forest or at the intermediate chipping terminals.

Size of machine is the other factor influencing the productivity and costs to be considered managing supply chains. Larger machines have larger power which can result in higher productivity however the cost of operation per tonne needs to be taken into consideration as a key decision factor as larger equipment usually have hourly cost. A whole tree chipping of small tree sizes with small feller-buncher, mini skidder and small chipper in Southern USA resulted in productivity of 10 GMt/PMH_0 (total cost of 12.10 $/GMt) (O'Neal and Gallagher, 2008) while same operation in Western Australia (similar tree size to Southern USA case study) was operated by a large feller-buncher, a skidder and a large chipper that yielded lower total costs (9.30 $/GMt) mainly due to higher productivity (50.7 GMt/PMH_0).

7. Future research and development (R&D) requirements

This current review gives the overview of the most efficient biomass supply chains however there are still some needs for future R&D projects to move towards more sustainable of the operations listed as following;

- Application of whole tree extraction (Stokes, 1992) or recovering extra volume of the wood using integrated biomass harvesting after cut-to-length operations may endanger the site sustainability in next rotations due to nutrient removals (Ghaffariyan, 2013). Considerable R&D projects are required to examine the sustainability aspects (nutrient loss, ash recycling, etc.) (Björheden, 2011; Spinelli et al. 2014) and to define the thresholds of maximum allowable biomass recovery in different soils and stands considering the economic and environmental benefits. In short, forest biomass growers will require a practical guideline/tool on how to manage/recover/retain their harvesting residues.

- Follow-up studies may be required to evaluate the share of different harvested volumes (sawlogs, pulpwood and energy wood) in thinning, final felling or selective cutting operations (Sikkema et al. 2014).

- Cost-productivity is very important factor in supply chain management which gives key information to the industry users. However a more comprehensive information will be required to include environmental and social impacts of the biomass technologies.

- The information received from international participants of this project will need to be enriched by collecting more detailed data on environmental, ergonomics and social aspects of supply chains. This may even require carrying out some research projects in different parts of the world where sufficient information are not currently available. Then the completed data base could be used by future research project to develop a decision support tool for international users to identify most sustainable biomass supply chains/machines.

- To estimate the amount of harvesting residues and potential for bioenergy usage in each stand there has been several inventory trials carried out in post-harvest phase however a future study could look at the harvester’s processing head data (e.g. equipped with optimisers) to predict and control the level of harvesting residues prior to tree cut (Brunberg and Eliasson, 2011). More sophisticated study can merge the pre-harvesting inventory data with log scanners identifying the quality of the wood for different products to predict the potential volume for biomass production in addition to sawlog or pulpwood.

- From operation management perspective, the FPinnovations experienced a low utilisation rate for grinders in Canada (MacDonald, 2009) as a result of delays caused by transportation (e.g. trucks not available to be loaded). The same problem has been diagnosed in road side chipping operations in Australia and seems to be occurring in most of the biomass operations in other regions. To solve such operational problem of chipping/grinding (and in deed any in-stand biomass operations) the operation needs to be optimised considering fleet design and trucks productivity and availability. Zamora-Cristales et al. (2013) have developed a model to optimise mobile chipping and transportation in USA and Acuna et al. 2012(a) constructed a tool to optimise the wood transportation (called Fast-truck) and another tool for biomass harvesting (called BIOPLAN) in Australia (Acuna et al. 2012 (b); Ghaffariyan et al. 2013 (a)) however the knowledge can be transferred to other biomass producer regions using Task43 networking mechanism while comprehensive modification to the current optimising tools will be required to each specific operation conditions in different countries through future research projects.

8.References

Acuna, M., Mirowski L., Ghaffariyan, M.R., Brown, M. 2012 (a). Optimising transport efficiency and costs in Australian wood chipping operations. Biomass and Bioenergy 46: 291-300.

Acuna, M., Anttila, P., Sikanen, L., Prinz, R., Asikainen, A. 2012 (b). Predicting and controlling moisture content to optimise forest biomass logistics. Croatan Journal Forest Engineering 33(2): 225-238.

Affenzeller, G., Stampfer, K. 2007. Energieholzmehrmengen bei Seilnutzungen im Baumverfahren. Forschungsbericht, Institut für Forsttechnik, Universität für Bodenkultur Wien, 30 p.

Björheden, R. 2011. Comminution and transport- keys to more efficient forest fuel systems. In: Thorsén, Å., Björheden, R. and Eliasson, L. Efficient forest fuel supply systems. Composite report from a four year R&D programme 2007-2010. Uppsala, Skogforsk sid: 24-26. ISBN: 978-91-977649-4-0

Brunberg, T., Eliasson, L. 2011. Productivity standards for forwarding of logging residues. In: Thorsén, Å., Björheden, R. and Eliasson, L. Efficient forest fuel supply systems. Composite report from a four year R&D programme 2007-2010. Uppsala, Skogforsk sid: 24-26. ISBN: 978-91-977649-4-0

Cremer, T. 2008. Bereitstellung von Holzhackschnitzeln durch die Forstwirtschaft. PhD theis. Albert-Ludwigs University. 199 p.

Cremer, T., Velazquez-Marti, B. 2007. Evaluation of two harvesting systems for the supply of wood-chips in Norway spruce forest affected by bark beetles. Croatian Journal of Forest Engineering 28 (2): 145-155.

Devlin, G. 2016. Background to Irish forest and biomass sector. Draft report. 6 p.

Desrochers, L., Puttock, D., Ryans, M. 1993. The economics of chipping logging residues at roadside: A case study of three systems. Biomass and Bioenergy 5: 401–411.

Devlin, G., Talbot, B. 2014. Deriving cooperative biomass resource transport supply strategies in meeting co-firing energy regulations: A case for peat and wood fibre in Ireland. Applied Energy 113: 1700–1709.

Eliasson, 2015. Personal communications (by completing a questionnaire) in August 2015.

Eliasson, L. 2011. Procurement systems for logging residues. In: Thorsén, Å., Björheden, R. and Eliasson, L. Efficient forest fuel supply systems. Composite report from a four year R&D programme 2007-2010. Uppsala, Skogforsk sid: 24-26. ISBN: 978-91-977649-4-0.

Eliasson, L., Brunberg, T., Lundström, H. 2011. Productivity when forwarding fresh and dried logging residues. FORMEC 2011, October 9-13, 2011, Graz, Austria.

Elmer, G., Rottensteiner, Ch., Stampfer, K. 2011. Energieholzbereitstellung mit Forwarder und Fäller-Sammler Moipu 300ES. Kooperationsplattform Forst-Holz-Papier (FHP), 27 p.

Ericson, K., Nilsson, L. 2006. Assessment of the potential biomass supply in Europe using resource-focused approach. Biomass and Bioenergy 30:1-15.

Gallagher, T. 2015. Personal communications (by completing a questionnaire) in August 2015.

Garcia, E. 2015. Personal communications (by completing a questionnaire) in August 2015.

Ghaffariyan, M.R., 2013. Remaining slash in different harvesting operation sites in Australian plantations. Silva Balcanica 14(1): 83-93.

Ghaffariyan, M.R. 2010. Review of European biomass harvesting technologies. Silva Balcanica 11(1):5-20.

Ghaffariyan, M.R., Andonovski, V., Brown, M. 2011(b). Application of slash-bundler for collecting harvest restudies in Eucalyptus plantation. Forest Science (Sofia) 1-2: 83-89.

Ghaffariyan, M.R., Brown, M., Acuna, M., Sessions, J., Kuehmaier, M., Wiedemann, J. 2011 (a). Biomass harvesting in Eucalyptus plantations in Western Australia. Southern Forests 73(3&4): 149–154.

Ghaffariyan, M.R., Sessions, J., Brown, M. 2012. Evaluating productivity, cost, chip quality and biomass recovery for a mobile chipper in Australian road side chipping operations. Journal of Forest Science 58 (2): 530-535.

Ghaffariyan, M.R., Sessions, J., Brown, M. 2014. Collecting harvesting residues in pine plantations using a mobile chipper in Victoria (Australia). Silva Balcanica 15(2): 81-95.

Ghaffariyan, M.R., Acuna, M., Brown, M. 2013 (a). Analysing the effect of five operational factors on forest residue supply chain costs: A case study in Western Australia. Biomass and Bioenergy 59: 486-493.

Ghaffariyan, M.R., Spinelli, R., Brown, M. 2013 (b). A model to predict productivity of different chipping operations. Southern Forests 75 (3): 129–136.

Ghaffariyan, M.R., Spinelli, R., Magagnotti, N., Brown, M. 2015. Integrated harvesting for conventional log and energy wood assortments: a case study in a pine plantation in Western Australia. Southern Forests: a Journal of Forest Science (published online 19 June 2015).

Greene, D. 2013. Improving woody biomass feedstock logistics by reducing ash and moisture content. A final report submitted to the Southeastern Sun Grant Centre. University of Georgia. 23 p.

Grosse, W. 2008. Wood energy from plantations: harvesting and supply of wood chips. FORMEC 2008; 41th International symposium in Schmallenberg, Germany. 290 p.

IEA Bioenergy. 2002. Sustainable production of woody biomass for energy. A position paper. 12 p.

IEA Bioenergy. 2015. Mobilizing Sustainable Bioenergy Supply Chains. Strategic Inter-Task study, commissioned by IEA Bioenergy. 170 p.

Iwarsson Wide, M., Belbo, H. 2009. Jämförande studie av olika tekniker för skogsbränsleuttag. Skogforsk, Arbetsrapport nr 679.

Iwarsson Wide, M., Fogdestam, N. 2011. Jämförande studie av olika uttagsmetoder av massaved och skogsbränsle i klen gallring. Skogforsk, Arbetsrapport nr 740.

Johnson, L., Lippke, B., Oneil, E. 2012. Modeling biomass collection and wood processing life-cycle analysis. Forest product journal 62(4): 258-272.

Karjalainen, T., Asikainen, A., Ilasky, J., Zamboni, R., Hotari, K.E., Roeser, D. 2004. Estimation of energy wood potential in Europe. Working papers of Finnish Forest Research Institute 6/2004. 43 p.

Kent, T., Kofman, P.D., Coates, E. 2011. Harvesting wood for energy Cost-effective woodfuel supply chains in Irish forestry, Available at: www.coford.ie.

Keuhmaier, M. 2015. Personal communications (by completing the questionnaire) in August 2015.

Keuhmaier, M., Stampfer, K. 2012. Development of a multi-criteria decision support tool for energy wood. Croatian Journal of Forest Engineering 33: 181–198.

Kofman, P.D., Kent, T. 2009. Whole-tree harvesting of conifer first thinnings for energy wood chip production. COFOR publications series, Harvesting/Transportation No. 13, 6 p.

KWF. 2012. Faszination Forstwirtschaft- Durch Zusammenarbeit gewinnen. 16th KWF Tagung, 13-16 June 2012, Bopfingen, 111 p.

Laina, R. 2015. Personal communications (by completing a questionnaire) in October 2015.

Laina, R., Tolosana, E, Ambrosio, Y. 2013. Productivity and cost of biomass harvesting for energy production in coppice natural stands of Quercus pyrenaica Willd. in central Spain. Biomass and Bioenergy (2013): 221-229.

Laitila, J. 2015. Personal communications (by completing the questionnaire) in August 2015.

Laitila, J., Asikainen, A., Nuutinen, Y. 2007. Forwarding of whole trees after manual and mechanized felling bunching in pre-commercial thinnings. International Journal of Forest Engineering 18(2): 29-39.

Laitila, J., Ranta, T., Asikainen, A. 2008. Productivity of stump harvesting for fuel. International Journal of Forest Engineering 19(2): 37-46.

Laitila, J., Väätäinen, K. 2013. The Cutting Productivity of the Excavator-based Harvester in Integrated Harvesting of Pulpwood and Energy Wood. Baltic Forestry 19(2): 289-300.

Lazdins, A. von Hofsten, H. Dagnija, L. Lasdäns, V. 2009. Productivity and costs of stump harvesting for bioenergy - Production in Latvian conditions. Engineering for Rural Development. Conference documentation, May 28-29 2009.

MacDonald, A.J. 2009. Assessment of economically accessible biomass. FPinnovations technical report. 18 p.

MacDonald, A.J. 2006. Estimated costs for harvesting, comminuting, and transporting Bettle-killed pine in the Quesnel/Nazko area of Central British Columbia. FERIC Advantage repot 7(16): 46 p.

Moffat, A., Nisbet, T., Nicoll, B. 2011. Environmental effects of stump and root harvesting. FCRN009/FC-GB 12 p.

Nati, C., Spinelli, R., Magagnotti, N., Verani, S. 2007. Dalle potature di olivo biomassa per usi energetici. L'Informatore Agrario 2/2007.

O'Neal, B., Gallagher, T. 2008. Evaluating Productivity and Costs of a Biomass Harvesting System in the Southern United States. COFE Conference Proceedings: "Addressing Forest Engineering Challenges for the Future" Charleston, June 22-25, USA.

Pari, L., Cutini, M. 2002. La raccoglitrinciatrice sposa l'olivo. Olivo eolio 7: 22–26.

Ralevic, P. 2013. Evaluating the greenhouse gas mitigation potential and cost-competitiveness of forest bioenergy systems in Northeastern Ontario. PhD thesis, Faculty of Forestry (Graduate Faculty), University of Toronto. 281 p.

RENEW, 2006. Review on existing studies and definitions of biomass provision chains, 42 p.

Routa, J., Asikainen, A., Björheden, R., Laitila, J., Röser, D. 2013. Forest energy procurement - state of the art in Finland and Sweden. WIREs Energy and Environment 2(6): 602-613.

Ryan, M.F., Spencer, R.D., Keenan, R.J. 2002. Private native forests in Australia: what did we learn from the Regional Forest Agreement program. Australian Forestry 65(3) 141–152.

Sessions, J. 2015. Personal communications (by completing the questionnaire) in August 2015.

Sikkema, R., Faaij, A.P.C., Ranta, T., Heinimo, J., Gerasimov, Y.Y., Karjalainen, T., Nabuurs, G.J. 2014. Mobilization of biomass for energy from boreal forests in Finland and Russia under present SFM certification and new sustainability requirements for solid biofuels. Biomass and Bioenergy 71: 23-36.

Silversides, C. R., Sundberg, U. 1989. Operational efficiency in forestry practice 2:1–169.

Sosa, A., Acuna, M., McDonnell, K., Devlin, G. 2015(a). Managing the moisture content of wood biomass for the optimisation of Ireland's transport supply strategy to bioenergy markets and competing industries. Energy 86: 354–368.

Sosa, A., McDonnel, K., Devlin, G. 2015(b). Analysing performance characteristics of biomass haulage in Ireland for bioenergy markets with GPS, GIS and fuel diagnostic tools. Energies 8: 12004–12019.

Spinelli, R. 2015. Personal communications (by completing the questionnaire) in September 2015.

Spinelli, R., Hartsough, B. 2001. A survey of Italian chipping operations. CNR - Consiglio Nazionale delle Ricerche, 112 p.

Spinelli, R., Lombardini, C., Magagnotti, N. 2014. The effect of mechanization level and harvesting system on the thinning cost of Mediterranean softwood plantations. Silva Fennica 48(1): article id 1003. 15 p.

Spinelli, R., Magagnotti, N. 2011. Strategies for the processing of tree tops from hybrid poplar plantations. Baltic Forestry 17(1): 50-57.

Spinelli, R., Nati, C., Magagnotti, N. 2005. Harvesting and transport of root biomass from fast-growing poplar plantations. Silva Fennica 39(4): 539-548.

Stampfer, K., Kanzian, Ch. 2006. Current state and development possibilities of wood chip supply chains in Austria. 27(2): 135-145.

Stokes, B. J. 1992. Harvesting small trees and forest residues. Biomass and Bioenergy 2 (1-6): 131-147.

Saudicani, K. 2015. Personal communications (by completing the questionnaire) in November 2015.

Saudicani, K. 2004. Industrial Round-Wood or Fuel-Chips in Medium-Aged Norway Spruce. International Journal of Forest Engineering 15(2): 95-101.

Thiffault, E., Asikainen, A., Devlin, G. 2015. Comparison of forest biomass supply chains from the boreal and temperate biomes. Draft report, 28 p.

UN (United Nations). 2008. Resolution adopted by the General Assembly 62/98: Non-legally binding instruments on all types of forests. Accessed at: http://daccessdds.un.org/doc/UNDOC/GEN/N07/469/65/PDF/N0746965.pdf?OpenElement.

Velázquez-Marti, B., Fenández-González, E. 2009. Analysis of the process of biomass harvesting with collecting-chippers fed by pick up headers in plantations of olive trees. Biosesystems Engineering 104: 184-190.

Visser, R. 2010. Trial and evaluation of in-forest landing residue recovery operations. Final report prepared for EECA. 76 p.

Visser, R. 2015. Personal communications (by completing the questionnaire) in August 2015.

von Hofsten, H. 2011. Skörd av stubbar – nuläge och utvecklingsbehov. Skogforsk, Arbetsrapport 703.

Zamora, R., Sessions, J., Murphy, G., Boston, K. 2013. Economic impact of truck-machine interference in forest biomass recovery operations on steep terrain. Forest Products Journal 63(56):162-173. Published online

October 2013. (doi: 10.13073/FPJ-D-13-00031)

Zamora-Cristales, R., Boston, K., Sessions, J., Murphy, G. 2013. Stochastic simulation and optimization of mobile chipping and transport of forest biomass from harvest residues. Silva Fennica 47(5). Article id: 937. 22 p.

Zamora-Cristales, R., Sessions, J., Boston, K., Murphy, G. 2015. Economic Optimization of Forest Biomass Processing and Transport. Forest Science 61(2):220-234. Published on line 2014 http://dx.doi.org/10.5849/forsci.13-158

Zamora-Cristales, R., Sessions, J. 2015. Cost comparison for different biomass harvesting alternatives. Draft manuscript.

IEA Bioenergy

Further Information

IEA Bioenergy Website
www.ieabioenergy.com

IEA Bioenergy Task 43 Website
www.ieabioenergytask43.com

Contact us:
www.ieabioenergy.com/contact-us/