[T07-05] Intensive, Integrated, Biomass-based Material and Energy Systems: Swedish Experience

Leif Gustavsson, Roger Sathre*

Ecotechnology, Mid Sweden University, SE-831 25 Östersund, Sweden

**Corresponding email: roger.sathre@miun.se*

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SUMMARY

Sustainable development of the built environment requires the production of increased quantities of construction materials and energy services, produced within the constraints of natural systems. This paper presents recent findings from Sweden on the intensive use of renewable forest resources within integrated material and energy systems. Production of materials for wood-framed construction uses less primary energy than for comparable reinforced concrete construction. Multiple wood-based products can be co-produced from the forest biomass, increasing the efficiency of raw material use. Biomass by-products from the entire wood product chain, including forestry, wood processing, construction and demolition, can be recovered for use as biofuel. The biofuel energy available over the life cycle of a wood-framed building is greater than the primary energy used to produce the materials. Increasing forest management intensity gives greater energy returns on management energy inputs. Intensive production of forest biomass is maintained by closing nutrient cycles through application of wood ash and nitrogen fertiliser.

INTRODUCTION

The realization of sustainable development of the built environment requires the production of increased quantities of construction materials and energy services, produced within the constraints of natural systems. Substantial experience has been accumulated in Sweden regarding the sustainable use of forest resources for both material and energy purposes. Intensive, integrated, biomass-based material and energy systems are being developed and implemented on an increasingly larger scale.

Although it is possible to increase the production rates of forests and plantations through more intensive management, wood resources are nevertheless finite. It is thus necessary that the available wood resources are used wisely and efficiently. Integrated use of biomass for both material and energy purposes, as shown schematically in Figure 1, offers the potential to maximise the contribution of the limited forest resource toward sustainable development.

This paper describes recent state-of-the-art advances in the intensive use of forest biomass to provide integrated material and energy services in Sweden. We describe the goals, methods, and limitations of the integrated use of biomass in Sweden, and make observations on the potentials for similar use in other countries.

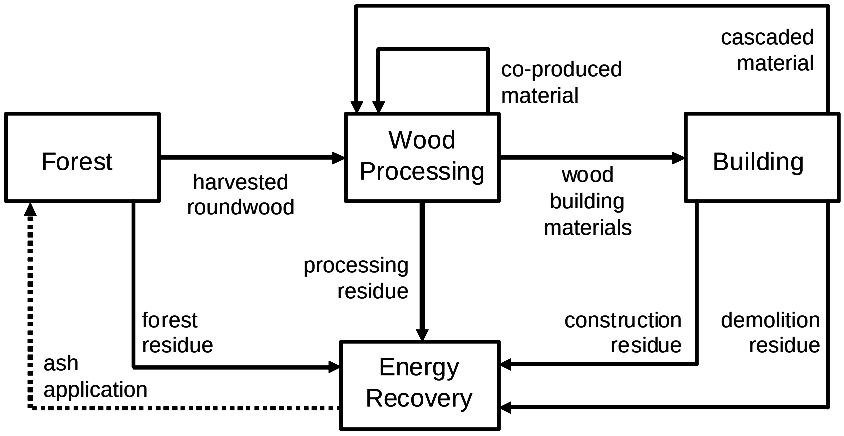

Figure 1. Schematic diagram of intensive, integrated flows of forest biomass for energy and material purposes.

EFFICIENT WOOD PRODUCT MANUFACTURE

Energy for material processing

The manufacture and use of wood products has been shown to have significant lower energy use compared to alternative materials (Gustavsson et al. 2006; Gustavsson and Sathre 2006). The energy balance of the material life cycle is defined as the primary energy expended to extract, process and transport the materials, minus the net energy of biomass by-products that can be recovered and made available for external use throughout the material life cycle. Primary energy use is calculated here as the sum of the fossil fuels used directly for material production and biofuel recovery, the primary energy for electricity used in material production, and sawmill residue used internally for wood processing. Primary fossil fuel use includes inputs for fuel extraction and transportation; electricity supply is based on coal-fired condensing power plant.

We use a case study approach to analyse energy use in material manufacture and use. To illustrate the significance of building material type on the energy use, we make calculations based on two functionally equivalent versions of a building with a wood frame and a reinforced concrete frame. The analysis is based on a case-study 4-story apartment building containing 16 apartments with a usable floor area of 1190 m^2. Figure 2 shows the primary energy for producing the materials in the case-study wood-framed and concrete-framed buildings, broken down by energy carriers. Biofuels shown are those used internally in wood products production for process heat. The results show that less primary energy is needed to produce the wood-framed building (2510 GJ) than the concrete-frame building (3460 GJ). Less fossil fuels and electricity, but more biofuels, are needed to produce the wood-framed building.

Co-production and material cascading

Within forest product industries, the harvested roundwood is processed into a range of products, from structural materials to pulp and paper products. Co-production of multiple products from a single raw material input, for example sawn lumber and particleboard from roundwood, ensures high material efficiency. In the case study buildings analysed in this paper, particleboard is produced from sawmill residue and comprises 18% and 22% by dry weight of all wood products used in the wood-frame and concrete-frame buildings, respectively.

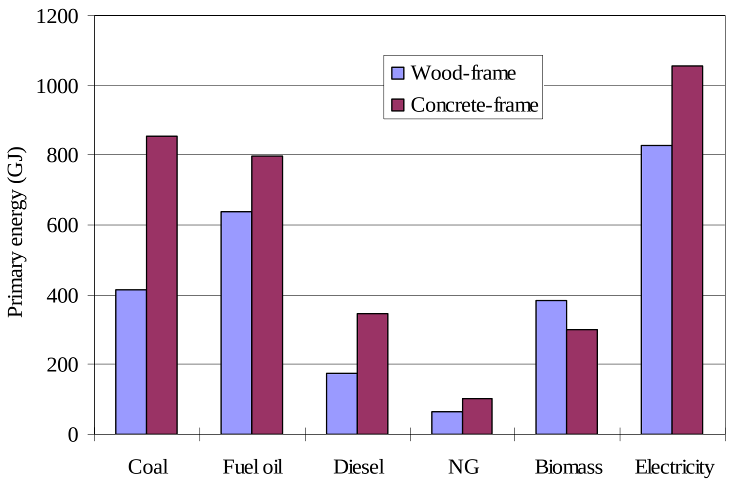

Figure 2. Total primary energy (GJ) for material production for wood-frame and concrete-frame versions of the case study building.

At the end of the building life cycle, wood based materials can be cascaded (reused in applications which demand lower material quality) or can be burned to recover the energy contained (Sathre and Gustavsson 2006). Various alternative uses for recovered wood lumber are possible, including re-use as lumber and re-processing into particleboard or pulp. Such optimisation of end-of-life product recovery and recycling systems are expected to become increasingly important in the future, to gain additional value from the wood as a material, before it is burned to recover its feedstock energy.

SUSTAINABLE INTENSIVE FOREST PRODUCTION

Forest management

Quantities of biomass production depend in large part on the intensity of forest management (Eriksson 2007). This comprehends activities such as species selection, soil preparation, stand establishment, planting density, thinning, fertilisation and rotation period. Forest management can be carried out at varying intensity levels, with more intense management effort resulting in more efficient solar energy capture by the forest stand, resulting in greater biomass energy output. Forest management requires an input of technological energy, but is rewarded by increased solar energy capture in tree biomass. The energy multiplicative effect of different management activities can differ over several orders of magnitude (Mead and Pimentel 2006).

A fundamental basis upon which the modern forest sector depends is that the forest land must be managed sustainably, in such a way that the land use can be continued indefinitely. Essential elements of sustainable land use include the maintenance of levels of soil nutrients and organic matter, the efficient use of available water supplies, and the protection of natural biotic diversity (Reijnders 2006). Intensive use of forest resources for material and energy systems implies the removal of substantial quantities of biomass from forest ecosystems. In the long term, the export of nutrients and organic matter may reduce the resiliency and productive capacity of the forests. Sustainable, intensive forest management may require ash recycling and selective fertilisation to ensure continuing biomass production.

Forest fertilisation

Nitrogen is often the element that limits forest growth. Nitrogen in biomass is released to the atmosphere when biomass is burned, and nitrogen compounds are deposited from the atmosphere to the ground in rainfall. In some areas, atmospheric deposition is excessive, leading to acidification of soils and lakes. In these areas, extraction of forest fuels can beneficial to ecosystem health, by removing excessive nitrogen (Börjesson 2000). In other areas with less atmospheric deposition, intensive forestry can require fertilisation, starting in young coniferous stands and including nutrients supplied throughout the rotation period. This is done by small balanced doses to avoid nutrient leakage. This silvicultural method has been shown to increase the production by 50-300% (Bergh et al. 2005) with minimal negative impact on the environment (Grip 2006).

Table 1 shows the characteristics of two forest management regimes, traditional and fertilised, modelled by Eriksson et al. (2007). Both are Norway spruce (*Picea abies*) stands in central Sweden growing in a typical forest soil type with an average fertility. The energy inputs and outputs associated with the two forest management regimes are shown in Figure 3. The fertilised management requires more energy input, but also results in greater output. Without recovery of forest residues, the traditional management regime uses 1.03 GJ ha^{-1} yr^{-1} energy input to produce an output of 34.8 GJ ha^{-1} yr^{-1}, or a net yield of 33.7 GJ ha^{-1} yr^{-1}. The fertilised management has a higher net yield of 47.9 GJ ha^{-1} yr^{-1} in spite of the relatively large energy requirement to produce fertiliser. Additional biomass output is produced by using energy inputs to recover thinning and harvesting residues. Including the recovery of thinnings, slash and stumps, the net yield becomes 51.8 and 73.3 GJ ha^{-1} yr^{-1} for the traditional and fertilised management, respectively. This type of energy analysis applies to the *heat value* of forest biomass for use as biofuel, but does not adequately describe the varying qualities of forest biomass (e.g. sawlogs, pulpwood, forest residues) that have different *utility values* for the production of forest products (Sathre and Gustavsson 2008).

Table 1. Characteristics of traditional and fertilised forest management regimes.

Characteristic	Traditional regime	Fertilised regime
Total age (yr) of trees at time of thinnings	37, 47, 62	27, 32, 42
Total age (yr) of trees at time of clear-cutting	92	67
Fertiliser applications	none	12 *
Stem volume production per rotation (m^3 ha^{-1})	669	680
Mean volume production (m^3 ha^{-1} yr^{-1})	7.3	10.0
Mean biomass production (t d.w. ha^{-1} yr^{-1})	5.0	7.1

* Fertiliser applications of CAN (125-150 kg N ha^{-1}) and NPK (125-150 kg N ha^{-1})

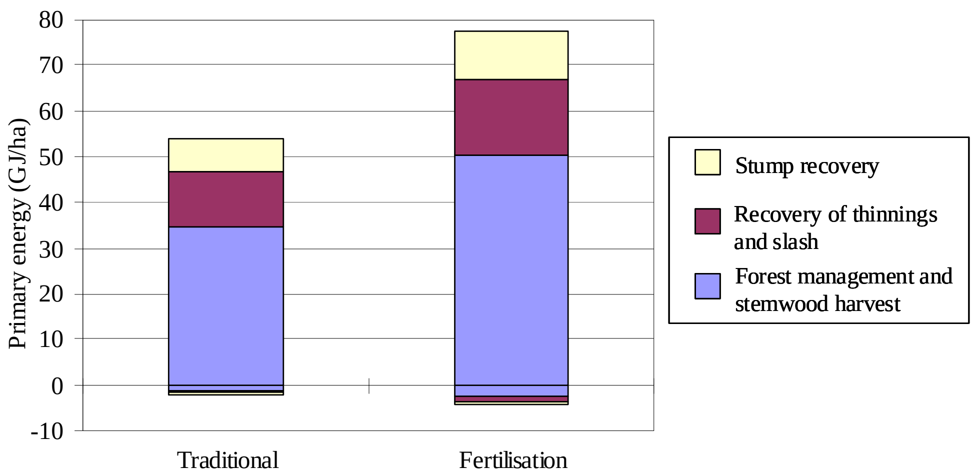

Figure 3. Primary energy inputs (negative values), and heat energy of biomass outputs (positive values), under traditional and fertilised forest management regimes, with different levels of residue recovery.

BIOFUEL ENERGY RECOVERY

Biomass by-products from the entire wood product chain can be recovered and used as biofuel to replace fossil fuels, leading to a more sustainable energy supply system. Recoverable by-products include thinnings during the forest growth period, harvest residues from the final felling, residues from wood processing and building construction activities, and wood from the demolished building at the end of its life cycle (see Figure 1).

Sources of biofuels

Residues from the harvesting of trees, such as branches and treetops, have commonly been left in the forest, but are increasingly viewed as a valuable energy source. Recovery and utilisation of forest residue is becoming more common in Sweden. In particular, residue from clear-cut areas is increasingly recovered, with efficient logistical systems to collect and transport the residue currently being developed (Gustavsson and Näslund 2008). Recovery of forest thinning residue is less common, due to its dispersed nature making efficient and economic collection more problematic. Recovery of stumps is a potentially significant source of biofuel (Eriksson et al. 2007).

Conversion of harvested logs to finished wood products results in processing by-products such as bark, slabs and sawdust. Traditionally this was regarded as a waste product that was dumped and allowed to decay naturally, or was burned without energy recovery. In Sweden this resource is now commonly used as fuel for sawmill process energy or for other energy purposes such as district heating. Some processing residue is also burned internally in the production facility for kiln-drying of lumber and particleboard process heat. After subtracting processing residue used as raw material for particleboard production and as fuel for internal process heat, there still remains significant additional processing residue available for external use as biofuel.

Wood waste is generated at the construction site when standard-sized boards and panels are cut into smaller sizes required in the building. The amount of construction waste depends on a variety of factors including the design of the building, the characteristics of the materials supplied to the construction site, and the craftsmanship of the construction personnel. Additional waste material can be produced by secondary wood processing industries that provide manufactured wood products to the building site. The recovery of wood-based construction waste for use as biofuel is becoming more widespread, with source separation of different types of construction wastes occurring on many construction sites.

Utilisation of wood-based demolition waste as biofuel has a significant impact on the energy balance of material systems (Gustavsson and Sathre 2006). It is becoming increasingly common and has the potential to increase (Thormark 2001). Policy measures including landfill dumping fees and regulations affect the amount of wood that is recovered from building demolition sites. A high recovery percentage of demolition wood is likely to be achieved in the future as the value of wood as an energy source is more widely recognised, and as more buildings become designed and constructed in ways that facilitate deconstruction to allow greater recycling and reuse of building materials (Kibert 2003).

Quantities of biofuels

The heat value of recovered biomass residues derived from forest harvesting (70% of harvest residues), wood-product manufacture (100%), building construction (100%) and the later demolition (90% of demolition residues) for the case-study buildings is shown in Figure 4.

Net energy values of the biofuels are shown, calculated as the heating value of the biomass minus the fossil energy used for its recovery and transport. More biofuels are available from residues of the wood-framed building materials than from the concrete-framed building materials. The heat values of the processing residues used internally for process heat, and of those used to make particleboard, are also shown. The amount of wood processing residue used internally is small in relation to the total amount of biomass residues recovered. Biomass residues that are available for use externally in the energy supply system are increasingly used in cogeneration plants to produce electricity as well as heat which is distributed in district heating systems, reducing total primary energy use (Joelsson and Gustavsson 2007). Comparison of Figures 2 and 4 shows that the energy available from biomass residues over the life cycle of the wood-framed building is greater than the primary energy used to produce the materials.

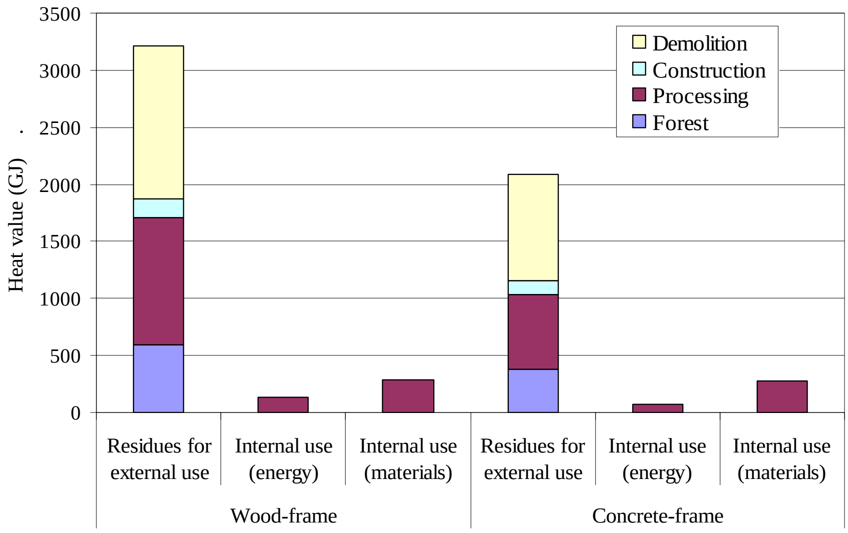

Figure 4. Production and use of biomass residues during the life cycle of the case-study buildings.

Wood ash recycling

Ashes from combusted biomass can be applied to growing forests to ensure that nutrient cycles are closed (Stupak et al. 2007). In the absence of ash recycling, the continued export of nutrients contained in the biomass could lead to nutrient deficiency and reduced forest production. The Swedish National Board of Forestry has published recommendations regarding the appropriate manner in which ash recycling should be done (Swedish National Board of Forestry 2002). The dosage of ash application is calculated in such a way as to balance the removal of nutrients in wood, bark and foliage with the return of nutrients in ash. Quality standards are set out for ashes, including minimum content of Ca, Mg, K and P. To avoid the long-term build-up of heavy metals and other contaminants which can be concentrated in the ash, maximum content of trace elements including several heavy metals is also specified. To avoid the build of radioactive substances, the maximum content of ^{137}Cs is also specified.

Unprocessed ash has a high pH and is quite reactive. Before ashes are applied to the forest, they must be stabilized to slow their dissolution and avoid damage to sensitive flora and fauna. Stabilization takes place both chemically and physically, with the goal that the ashes dissolve slowly over a period of 5 to 25 years in the field. Three methods are currently used to process ash for recycling: self-hardening, compaction, and granulation (Emilsson 2006). In all processes the ashes are first wet with a carefully controlled amount of water, and mixed thoroughly. In the self-hardening method, the wetted ash mixture is spread in layers on a paved surface and compacted by driving over it with a tractor. The ashes are then left for several months for chemical hardening to take place. The dried ash is then broken up with an excavator, crushed, and screened to remove excessively course or fine fractions. In the compaction method, the wetted ash mixture is pressed, for example between rotating cylinders. The ash is then cut into small pieces and allowed to harden for a month. In the granulation method, the wetted ash mixture is rolled in a drum or on a plate to form granules which are dried with heated air. This is the most expensive method due to the drying costs. In all methods, binding agents such as cement can be added to make the final product more stable, and granules can be coated with a surface layer of e.g. lignin or stearate to further slow the dissolution. Ash processing can be done in centralised facilities, or can be done with mobile equipment at the locations where the ash is produced. Ashes can be spread in the forest using ground equipment, such as a converted tractor, or by helicopter. At present, ground application is the most common method in Sweden.

CONCLUSIONS

The Swedish biomass-based material and energy system seeks to adequately fulfil multiple societal needs, by efficiently using natural resources in a sustainable manner. The sustainably-managed forests provide a renewable resource for the production of biomass. Material and energy flows are integrated within the forestry, energy, industry and waste management sectors, providing energetic, economic and environmental advantages. The energy sector is key, and provides heat, fuels and electricity for the other sectors and for society in general. It benefits by using by-products of the forestry and wood industry sector as a fuel, as well as other biomass materials that would otherwise be considered a waste product. The wood industry has the potential to be largely self-sufficient in primary energy terms, and can also provide biofuels and heat to other sectors. The forest sector can also produce liquid biofuels to power forest and transport equipment. The waste management sector, which traditionally has received and disposed of materials such as construction site and demolition waste, is increasingly a source of valuable biofuel to the energy sector. Thus, the closer integration of these different sectors can significantly increase the efficiency of the biomass-based material and energy system. This integration is already underway, and can be further optimised. The recovery and use of wood processing residues is now common in the Swedish forest sector, whereas in times past such material was often disposed of as waste. The recovery of forest harvest residue is now done in parts of Sweden, although stumps and thinning residue are less commonly recovered. Similarly, the recovery and use of wood-based construction and demolition residue takes place in some areas, but still goes unused in other areas. Material cascading of wood biomass is not conducted on a large scale at present. Thus, there is potential for further integration and optimisation of forest biomass flows, to increase the efficiency of primary energy use.

The potential for similar achievements in other countries depends on physical and social factors. Physical factors include climatic and soil conditions that affect forest production potentials. Climatic factors also influence the relative energy use during the construction phase and operation phase of a building, affecting the overall supply and demand for building materials and energy. Social factors include appropriate economic and regulatory frameworks that allow long-term implementation of sustainable practices within the forestry, industrial, energy, and waste management sectors.

REFERENCES

Bergh J., Linder S. and Bergström J. 2005. The potential production for Norway spruce in Sweden. *Forest Ecology and Manangement,* 204(1), 1-10.

Börjesson P. 2000. Economic valuation of the environmental impact of logging residue recovery and nutrient compensation. *Biomass and Bioenergy*, 19(3), 137-152.

Emilsson S. 2006. *International Handbook: From Extraction of Forest Fuels to Ash Recycling*. Swedish Forest Agency. Web-accessed at http://www.recash.info/uploads/documents/handbook.pdf.

Eriksson E., Gillespie A., Gustavsson L., Langvall O., Olsson M., Sathre R. and Stendahl J. 2007. Integrated carbon analysis of forest management practices and wood substitution. *Canadian Journal of Forest Research,* 37(3), 671-681.

Grip H. 2006. Miljöeffekter av intensivodling: Effekter på näringsläckage In: *Slutrapport för Fiberskogsprogrammet*. Institutionsrapport No. 27, Institutionen för Sydsvensk Skogsvetenskap. ISBN 91-576-7161-3. (in Swedish)

Gustavsson L. and Näslund L. 2008. Cost of collection, processing and transportation of forest residues and CO_2 benefits of fossil fuel replacement. Manuscript submitted to *Biomass and Bioenergy*.

Gustavsson L., Pingoud K. and Sathre R. 2006. Carbon dioxide balance of wood substitution: comparing concrete- and wood-framed buildings. *Mitigation and Adaptation Strategies for Global Change*, 11(3), 667-691.

Gustavsson L. and Sathre R. 2006. Variability in energy and carbon dioxide balances of wood and concrete building materials. *Building and Environment*, 41(7), 940-951.

Joelsson A. and Gustavsson L. 2007. District heating and energy conservation in detached houses of differing size and construction. In: *Proceedings of the 3rd International Green Energy Conference,* 18-20 June, Västerås, Sweden.

Kibert C.J. 2003. Deconstruction: the start of a sustainable materials strategy for the built environment. *UNEP Industry and Environment*, 26(2-3), 84-88.

Sathre R. and Gustavsson L. 2006. Energy and carbon balances of wood cascade chains. *Resources, Conservation and Recycling*, 47(4), 332-355.

Sathre R. and Gustavsson L. 2007. Effects of energy and carbon taxes on building material competitiveness. *Energy and Buildings*, 39(4), 488-494.

Sathre R. and Gustavsson L. 2008. Process-based analysis of added value in forest product industries. Manuscript submitted to *Forest Policy and Economics*.

Stupak I., Asikainen A., Jonsell M., et al. 2007. Sustainable utilization of forest biomass for energy—Possibilities and problems: Policy, legislation, certification, and recommendations and guidelines in the Nordic, Baltic, and other European countries. *Biomass and Bioenergy*, 31(10), 666-684.

Swedish National Board of Forestry. 2002. Recommendations for the extraction of forest fuel and compensation fertilizing. Meddelande 3-2002. Web-accessed at http://www.svo.se/forlag/meddelande/1545.pdf.