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Subject review

Development of Bioenergy from Forest Biomass – a Case Study of Sweden and Finland

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Abstract

The role of the forest sector in Finland and in Sweden is the starting point for a case study presenting motifs for forest bioenergy in the two countries. Forest bioenergy, evolving in symbiosis with the forest industry, has become important. The successful development builds on piggy-backing conventional forestry, rather than on parallel supply systems.

After thirty years, forest biomass has become the largest energy source in the two countries, contributing almost 1/5 of the energy needs. For developed countries, Sweden and Finland have leading positions in the use of forest fuel, and in related technologies and methods. However, progress has not been simple and drivers for the development have changed over time.

The 1970s »oil crises« put initial focus on energy security and on reducing the dependence on imported fuels. Later, other motifs have become fundamental. Sustainability aspects – especially mitigating climate change – have emerged as key arguments. Fuels from sustainably managed forests cause minor, if any, emissions of carbon dioxide.

The facts that wood-based fuels create rural jobs and improve the trade balance have been ancillary motifs, and the increased net sale of forest products that follows on fuel production will increase the cash flow of the forest owner. However, due to low compensation and high costs compared to the traditional forest products, from the forest owners' perspective, the economic motifs for forest fuel harvesting are not decisive.

For economic use of biomass, heat sinks are important. Combined heat and power, e.g. for district heating plus electricity to the grid or for industrial process heat and power are profitable options. Further refinement is possible but its potential to increase profitability seems limited.

Keywords: bioenergy, forest biomass, forest harvesting residues, climate change, sustainability

1. Introduction

Bioenergy from forest biomass represents one of the oldest ways to utilize forest biomass. It is a prerequisite for man's existence in the boreal parts of the world (James 1989). Also for the large-scale protoindustrial manufacture and for initial stages of the industrial manufacture, wood played an important role both as a material and as a fuel (Sundberg et al. 1994). Despite this, for a long time, utilization of forest biomass for energy attracted only minimal attention. It was considered a primitive, dirty, inefficient and even wasteful way to produce energy that could easily, cleanly and cost-efficiently be replaced by modern and more qualified sources of energy such as electricity from different sources or from fossil fuels, such as coal, oil and gas. In Nordic countries, efforts to modernize the use of forest biomass for energy were done only under the threat of isolation through disturbances to international trade (Fig. 1).

For a number of reasons, this negative view on forest biomass as a fuel changed (Silveira 2001, Hakkila 2006, Björheden 2006). Considerable efforts have been made to reintroduce forest biomass for energy in a large scale. Some of the globally most successful ex-

Fig. 1 In times of disturbances to international trade and threatening isolation, such as the great wars, efforts were made to modernize and intensify the use of forest biomass for energy in the Nordic countries. The picture shows chunking of coniferous branchwood with the manually driven smallwood chunker »Ursus« in a south Swedish forest at the time of the First World War (from Nilsson 2016)

amples of the modernized, large-scale rebirth of forest biomass as a fuel and a source of energy can be found in Sweden and Finland, which have also managed to combine a strong traditional forestry sector with an extensive use of forest biomass for energy.

Forests, the utilization of forests for various goods and services and the functions of the forest sector vary strongly. Some of the reasons behind the large differences depend on differences in ecosystem dynamics between forests of different natural regions such as boreal vs tropical forests (Kuusela 1990, Rudel and Roper 1996), some depend on differences of the forest sector and its demand for raw materials, while other explanations must be attributed to differences in traditions and public/social views on forestry (Parrotta et al. 2006). Universal trends concerning forestry and forest biomass utilization, e. g. for energy, can be identified but, as a result of the heterogeneity of forestry, it is normally necessary to present cases. In this review paper, the universal drivers behind the strong expansion of forest fuel use will be illustrated through case descriptions from Sweden and Finland. The relations between forest energy on the one side and forestry, forest industries and bio-economy on the other will be discussed.

2. Discussion

2.1 Forestry and agricultural sectors and proportion of renewable energy in the EU

The EU strongly promotes the use of renewable energy sources as important means both for reducing the dependence on foreign energy imports, and for

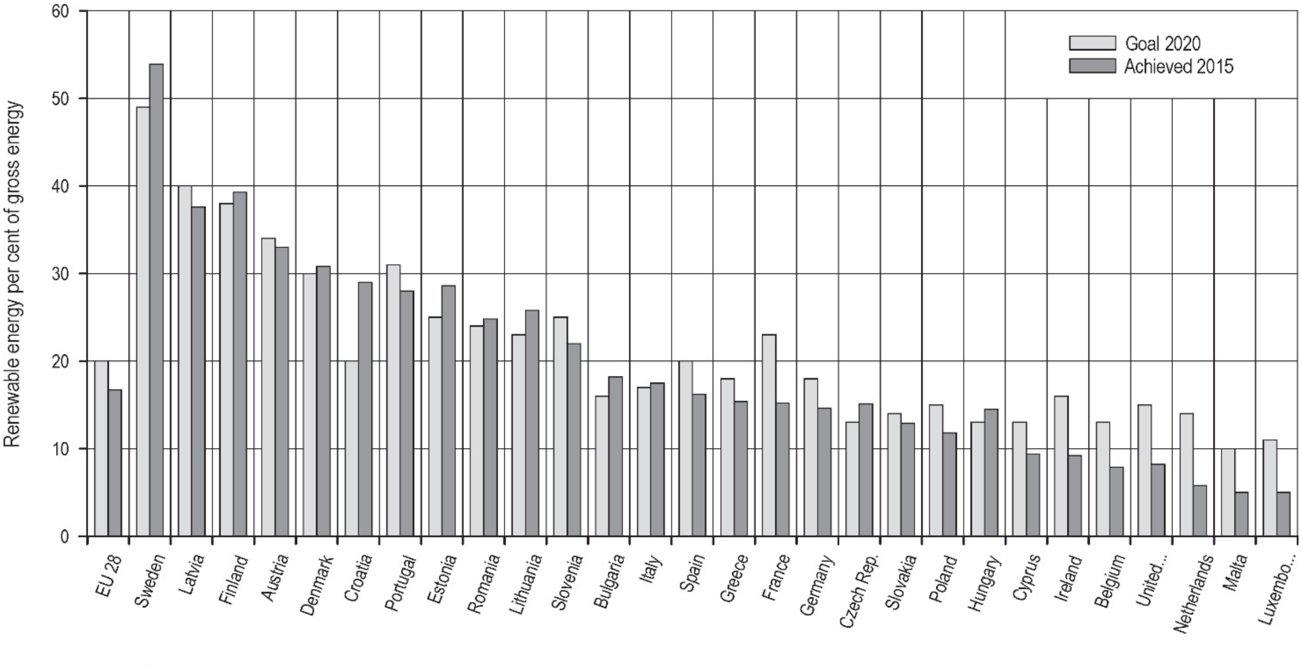

Fig. 2 In 2015 Sweden and Finland, together with 9 other member states, had overshot their goals for the share of renewables in the gross energy consumption 2020 according to RED (Eurostat 2017a). Countries that have prematurely managed to meet the goals often have strong forest sectors

mitigating climate change. In the Renewable Energy Directive 2009/28/EC, RED, (European Council 2009), binding targets are set for all EU member states. By 2020, the Union will reach a 20% share of energy from renewable sources. By 2017, the EU realized a 16.7% share of energy from renewable sources with eleven member states already achieving their goals. The goal for 2020 as well as the current share per member state is shown in Fig. 2.

Biomass, and especially forest biomass, has been identified as an important feedstock for production of renewable fuels and energy. To investigate if a strong forest sector may delimit the growth of renewable energy, a regression was made with the use of renewable energy per capita in each EU member state as the dependent variable and the annual production of roundwood, also per capita, as the independent variable. The per capita production of roundwood was highly significant ($P<0.0001$) and explained 71.4% (adjusted r^2) of the variation in achieved renewable energy share between countries. The hypothesis that a strong forest sector would be an obstacle to bioenergy through competition for biomass was falsified.

A similar regression with »utilised agricultural land per capita« as the independent variable could not explain anything of the variation. A P value over 0.6 further showed that the relative area of agricultural land does not show a strong correlation to the utilization of biomass for energy. All data for the two regressions were accessed on the Eurostat homepage (Eurostat 2017b).

As Fig. 2 shows, the ambition and implementation of RED varies greatly between the member states. The Union is above the target trajectory but some countries are clearly falling behind. Countries with a strong forestry sector and strong national regulation (e.g. Sweden and Finland) have been more successful in reaching their targets than others. Sweden reached its record high 49% renewable energy target eight years ahead of 2020 and was also the first member state to reach the 10 percent renewable transport fuels target. Probable explanations are the implementation of stable, strong national incentives such as a high carbon dioxide tax, an efficient certificate system for renewable electricity and tax deductions in the transport sector.

2.2 The role of forests and forestry in the national economy

Both Swedish and Finnish economies are diversified, but the contributions of the respective forest sectors are very important since they produce a significant net surplus in foreign trade, representing as much as 15 per cent of the value of exports in Sweden and almost 40 per cent of the Finnish export earnings. Forest harvesting amounts to around 160 million m^3, from an annual yield of just under 250 million m^3. More than half the land area of the two countries is covered by forests (Anon. 2013, Anon. 2014).

The unusually important position of the forest sector can be explained by history and by the natural geography of the countries. Boreal and sub-boreal softwood forests are, by far, the most common types of ecosystem. Historically, the early industry in both Sweden and Finland was formed largely around raw materials and fuel from the forests. In both countries, the industrial revolution was »powered by wood« and much of the current industry has close ties to the forest sector (Björheden 2006, Hakkila 2006). In short, both countries have a history of high forest use and build their welfare to a large extent on the forest sector. Public acceptance of forestry is traditionally high, and over 60 per cent of the forests are managed by private, non-industrial forest owners as a traditional part of family farms (Anon. 2013, Anon. 2014).

Traditionally, most Swedes and Finns are used to, and accept forestry as a sustainable industry. This fact is of great importance to the efforts in intensifying the use of forest biomass. Ongoing urbanization, however, has led to a growing alienation and an increasing proportion of people questioning the sustainability of intensified forest harvesting. This has become an important issue for Nordic forestry to address (Richardson et al. 2003).

2.3 Initial motifs: secure and cost efficient energy sources

Although both Sweden and Finland have a strong tradition of large scale use of wood for energy, after the Second World War wood fuels were rapidly and almost completely replaced by fossil fuels. In Finland, the cheap oil of the 1960s displaced wood fuels. In the early 1970s, only 14 per cent of the Finnish energy supply was based on wood. In the same period, over 70 per cent of the Swedish energy supply was based on imports of petroleum, mainly from the Arab states (Doherty et al. 2002). Therefore, it was a severe shock to the national economies when, in 1973, the Arab States, proclaimed an oil embargo (Helby 1997). Cheap, abundant oil was no longer guaranteed. In 1979, the oil crisis deepened as oil production fell because of the Iranian revolution. OPEC did not increase production to compensate. The Iraqi invasion of Iran in 1980 made matters worse and it became clear that alternatives had to be found to ensure supply of energy with less susceptibility to turmoil in other parts of the world. An Energy Research Programme aiming at gradual relinquishment of oil/fossil fuels was launched in 1975. It became the second largest sectoral research programme in Sweden. The pursuit of sustainability was identified in the long-term energy policy goal: to base the energy system on »durable, preferably domestic, sources of energy« (Haegermark 2001).

Sweden decided to launch an extensive nuclear energy program, planned to develop more of its potential hydropower, but also looked to forest biomass to decrease vulnerability and dependence on imported oil. The research program »Whole Tree Utilization« (1974 to 1977), which aimed to alleviate a potential shortage of pulpwood through use of fibre from small diameter wood and stumps in conventional industrial processes, was complemented with the goal to investigate if dependency on imported fossil fuels could also be relieved (Anon. 1977). There was an intense public debate challenging the decision to build on nuclear power. In 1979 there was a partial nuclear meltdown at the Three Mile Island Nuclear Generating Station, in Pennsylvania, USA. When, subsequently, in 1980 a Swedish referendum was held to decide the future of nuclear power, distrust prevailed. Nuclear power should be a parenthesis and Sweden should develop its renewable sources of energy and save energy to the extent that the nuclear reactors could be phased out. Public scepticism was strengthened when, in 1986, the Soviet Chernobyl accident triggered downfall of radioactive contaminants in large areas of Sweden (Haegermark 2001) and again by the Fukushima accident in Japan in 2011. So far, three of twelve reactors have been shut down and another three reactors are planned to be closed shortly. A green movement of »river rescuers« halted development of the remaining unharnessed rivers (Doherty et al. 2002). Bioenergy was left as the only sizeable alternative, much to the discontent of leading industrialists who feared that rising energy costs would decrease the competitiveness of Swedish industry (Vedung 2001). In Sweden, with almost two billion SEK, the Oil Replacement Fund 1980–1987 financed rebuilding oil burners to alternative fuels, mainly wood chips, and infrastructural subsidies, e.g. for investment in terminals to simplify the supply of wood for energy purposes (Hillring 1998, Hillring et al. 2001). The key political driver for bioenergy – to replace imported fossil fuels – was strengthened by the public wish to move away from nuclear power. Improved trade balance and increased earnings in rural areas were ancillary arguments for bioenergy in Sweden (Silveira 2001).

Driven by the same concerns of vulnerability and rising oil prices the Finnish government began to promote wood energy in the mid-1970s, also with complementary goals concerning rural employment and intensified thinning of young forests. However, in contrast to the Swedish development, when oil prices fell and availability was again ensured, »Finnish promotion of wood for energy more or less terminated« (Hakkila 2006). In contrast to Sweden, Finland assumed a reserved, or at least, cautious stance towards forest bioenergy.

2.4 Sustainability and climate change become powerful international drivers

The Finnish scepticism to forest bioenergy changed radically when in the early 1990s Finland signed the UN Climate Convention in Rio de Janeiro. By this time, sustainability and greenhouse gas management to reduce the extent of climate change, had become the main drivers for bioenergy (Anon. 2012). All EU member states must reduce greenhouse gas emissions and Finland and Sweden are faced with extraordinarily ambitious goals. A Finnish national Action Plan for Renewable Energy Sources was adapted (Anon 2000b). In Sweden, a milestone decision came in 1991, when carbon dioxide emissions from fossil fuels were taxed, making bioenergy an economic choice. In Finland, bioenergy was promoted through specific subsidies, especially focussing on supporting small-tree fuel from young stands (Aguilar 2014). This explains why the fractions of additionally harvested forest biomass differ strongly between the two countries with a higher proportion of small trees specifically mobilised by the Finnish KEMERA support (Tanttu and Sirén 2004) and a larger share of logging residues, integrated with conventional harvesting, being the most economical in Sweden (Petty and Kärhä 2011).

2.5 The supply of forest biomass for energy conversion

The ten years of development that had been »lost« in Finland, compared to Sweden, was quickly caught up – forestry conditions are very similar, so technology and methods developed in Sweden could easily be used in Finland. Within a few years, the two countries complemented each other and prospered from joint research cooperation and mutual development. During the 1990s, the technologies and methods for harvesting and converting forest biomass for energy matured in the two countries. Biofuels became an important part of the energy budget of both countries (Anon. 2000a, Hakkila 2006). The build-up of district heating provided an excellent heat sink for large parts of the year and through deliberate concentration on Combined Heat and Power production almost one

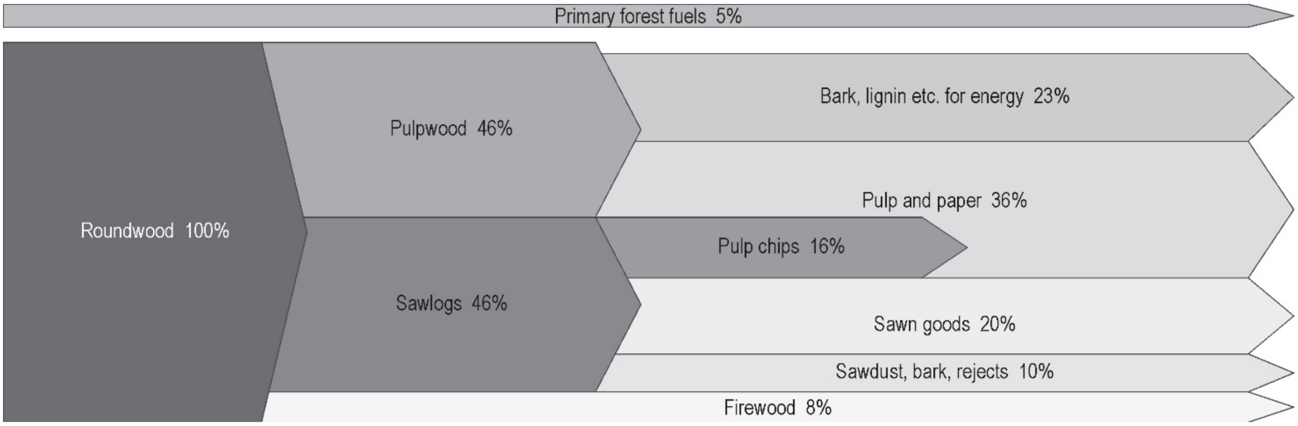

Fig. 3 Proportional wood flows in Sweden 2012. The additional biomass in primary forest fuels such as logging residues, small trees and stumps only contribute to around 5% extra biomass for energy, while the sum of energy fractions of roundwood represent 42% of the annual roundwood harvest (Anon. 2014)

third of the bioenergy was produced in the form of high value electricity. The current use of primary forest fuel in Sweden and Finland corresponds to around 10 million m^3 biomass solid or some 20 TWh (Dìaz-Yáñez et al. 2013), which is more than double that of any other country. Even so, as shown below, the main source of forest biomass for energy, in both counties, consists of by-products from the industrial processing of sawlogs and pulpwood, an annual flow corresponding to 70–75 million m^3 biomass solid or 140–150 TWh (cf. Fig. 3).

The supply of primary forest biomass available for direct energy conversion is ultimately determined by the appraisal of the alternative uses. In Sweden, the supply of forest biomass available for energy purposes has been investigated many times, with different results (Björheden and Fick 2014). The reasons for the differences are not missing or incorrect data on standing inventory and forest growth but that the investigations have approached the question with different conditions and restrictions. In principle, all forest biomass can be used for energy production, but this is usually not seen as an economically viable alternative.

The average net export revenue for lumber or pulp is 3–4 times higher per volume unit of unbarked coniferous roundwood (Hakkila 2006) and up to 16 times higher if the product is paper (Björheden 2006) than if the wood is used for the production of energy to replace imported oil. As large a share of the annual felling as possible is consequently used as raw material for the forest industries. Less than 10 per cent of the annually harvested roundwood – normally of low quality or unwanted tree species – will be used directly as fuel, mainly in farms and rural private homes (Anon. 2013, Anon. 2014).

Thus, the forest industry actual need for wood is normally deducted from the tally of available quantities. The requirement of sustainable production is another common restriction. The latter requirement imposes the felling level to be lower than net forest growth, and that less fertile sites are partly exempt from the removal of forest biomass in addition to stemwood. Finally, technical and economic impediments are considered, i. e. forest areas that are too small or distant are excluded as are forest sites where harvesting conditions are too technically difficult to allow economic extraction of additional biomass.

In countries with developed and internationally competitive forest industries, like Sweden and Finland, this entails that the supply of forest biomass available for energy conversion will depend on and closely follow the felling levels induced by the demand for raw materials by the conventional forest industries. So far, thus, primary forest bioenergy has been retrieved only from harvestable fractions that are not demanded by the conventional forest industry. In principle, this is likely to prevail, unless energy prices rocket or, alternatively, forest biomass become very cheap.

In Sweden, the average net felling (excluding wood left in the forest) for the last five years amounts to 84 million m^3 stem volume ob. Annual felling results in approximately 125 million m^3 of solid biomass if also branches, foliage, tops, small trees and harvestable parts of the stump-root system are tallied. The felling level corresponds to 73 per cent of the annual growth, i.e. 27 per cent of the annual growth contributes to build-up of the standing inventory. The relative usage of forest biomass increment in Sweden is shown in Fig. 4.

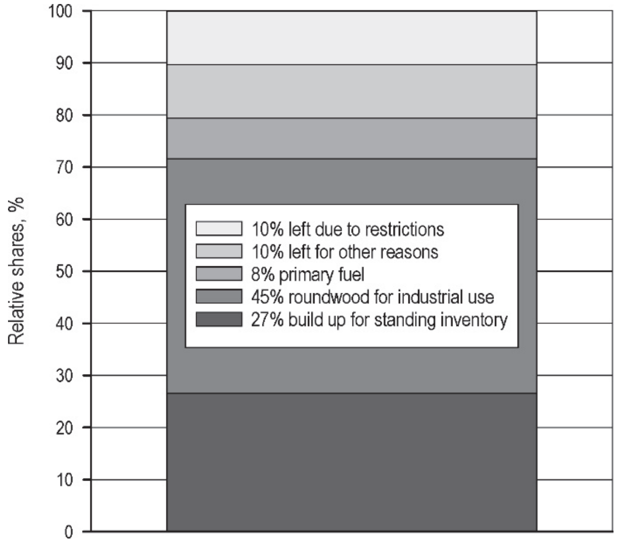

Fig. 4 Relative usage of forest biomass increment in Sweden (2009–2014). The procurement of primary forest biomass for energy conversion may be tripled without increasing the level of felling. The build-up of inventory corresponds to 27% of the annual increment. In principle, most of this volume could also be realized as feedstock

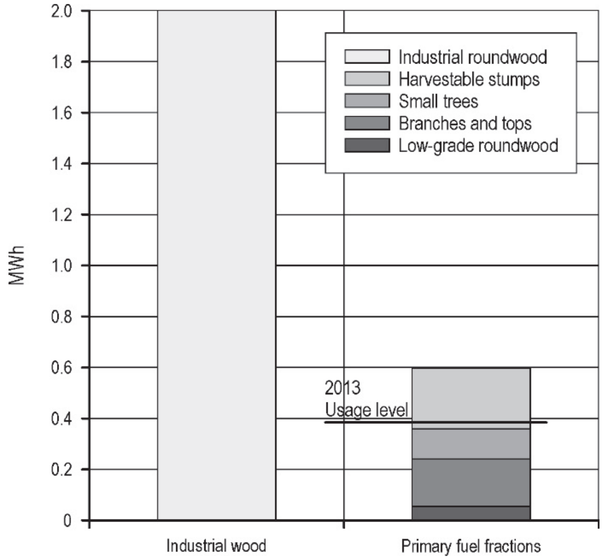

Fig. 5 After deducting volumes for ecological and techno-economic restrictions, each m^3 of harvested roundwood releases a potential primary fuel feedstock with an energy content of at least 0.6 MWh. The figure shows the Swedish usage level 2013 of these fuel fractions. The harvest of primary fuel may be tripled

2.6 The role of conventional forest industries in the forest-energy value chain

The logging operations carried out to supply the conventional forest industry with roundwood of different qualities also mobilizes forest biomass suitable for bioenergy. As shown in Fig. 5, each harvested m^3 of industrial roundwood yields another 0.3 m^3 (=0.6 MWh) of biomass in the form of fuel fractions such as low grade roundwood, small trees, slash and stumps. In Sweden, the large-scale procurement of wood for the conventional industry will thus contribute effectively to making wood fuel resources available at low costs. This fuel feedstock is a consequence product only to be burdened with their induced incremental costs.

The forest industry's most important contribution to the value chain of energy is, however, not that it makes available biomass that is poorly suited to the current industrial production. The main contribution is, instead, that by-products from industrial processing will become available in large volumes. Bark, sawdust, breakage and black liquor is used almost entirely for energy production, turning a potential waste into a valuable resource. In fact, forest industries are forerunners in substitution of fossil fuels – the Swedish forest industry uses some 50 TWh of forest bioenergy/year, corresponding to 25 million m^3 of solid biomass. As shown in Fig. 6, between 45 and 50 per cent of the biomass in industrial wood becomes available for energy conversion. In comparison to this, the Swedish extraction of primary fuels is modest (Nilsson 2006, Thorsén and Björheden 2010).

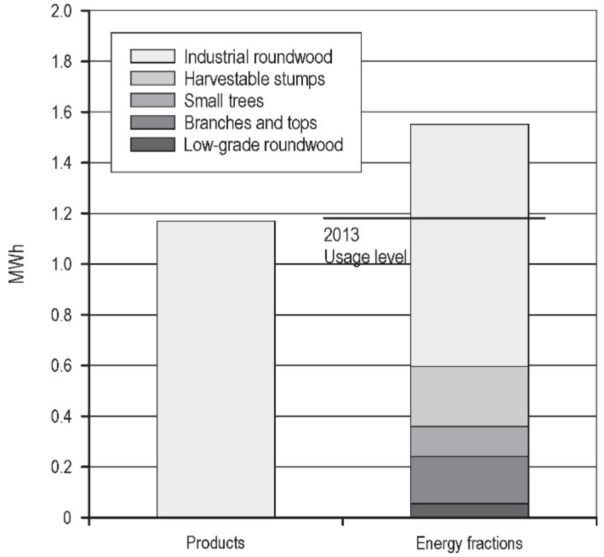

Fig. 6 In Sweden, after industrial processing, 45 per cent of the biomass of a m^3 sob of roundwood is turned into fuel feedstock by-products, representing 0.9 MWh. These by-products are practically completely used. Thus, in 2013, more than five times more energy was gained from by-products of industrial wood, than from the harvest of primary forest bioenergy fractions

Today, fuel with a forest origin is the single most important energy source in the Swedish energy balance. This large-scale use of forest biomass for energy purposes was initially developed to reduce dependence on oil. With time, however, climate issues have become increasingly important.

From a climate perspective, durable products are preferable. And all products made from biomass can be converted into energy when their useful life is over. The old debate question »pulp, saw or burn?« should be replaced by the exclamation »pulp, saw and burn!«. Reuse of biomass-based products, with energy conversion as the final step, is a way to maximize the benefits and value of the Swedish forest from a combined climate-and-economic perspective (Joelsson and Gustavsson 2012).

2.7 Technological development for improved procurement of forest biomass for energy

The development of technologies and methods to enable and streamline the harvest of additional biomass for energy became necessary. Apart from such roundwood that is not demanded by industry because of decay or other defects, the primary fuel fractions (logging residues, small sized trees and harvestable stumps) are bulky, difficult to handle, heterogeneous, wet and often contaminated and represent a low value. The development of technologies and methods to enable harvest of primary fuel feedstock reflect these problems but also include attempts to reduce the amount of mineral nutrients removed from the forest – especially in the branches and tops.

As mentioned, the first Swedish development efforts were made as an appendix to the research programme »Whole Tree Utilization«, (Anon. 1977). It has been followed by several more dedicated programs, in Sweden normally funded by the Energy Authority (Nilsson and Lönner 1999). Richardson et al. (2001, 2003) provide a brief review of the early technical development. Later, programmes funded jointly by the government and forestry made significant contributions to development and systems evaluations. Hakkila (2004), Thorsén and Björheden (2010) and Iwarsson Wide and Björheden (2016) offer broad reviews of this recent development, which are summarized in the following section.

With a few exceptions, the technology proven in Finland and Sweden, builds on the idea of piggy-backing on conventional forestry, using almost the same machines as in conventional harvest, with minor modifications to address the difficulties of the primary assortments. Examples of modifications are residue grapples simplifying loading of residues and decreasing the risk of contamination, detachable extra wide loading racks on the forwarder to allow full loads of the bulky fuel fractions and accumulating felling and harvesting heads for small sized trees, addressing the problem of very small piece sizes, an invention that has become standard also for harvesting of small sized pulpwood.

The most important specialised equipment for additional forest biomass harvest is tractor or truck mounted technology for comminution – chippers for clean fuels and crushers for contaminated fuels such as stump-wood. The main reasons that decentralised comminution has become a viable solution are that, in addition to producing a ready fuel, it will significantly reduce the bulk density of the material, decreasing transport costs, simplify the subsequent handling. Several bundling, baling and compaction devices that have been developed have offered the same level of compaction and simplified handling but have not been able to provide economic feasibility to any large extent. Also, designated stump harvesters have been developed. They have become rather common in Finland but are presently used only for experimental purposes in Sweden.

2.8 Conditions for value creation in the forest-energy value chain

One of the causes for the modest introduction of highly specialized equipment for harvest of residual forest biomass is the delimited scope for value creation in the forest-energy value chain, illustrated by Fig. 7. There are several reasons for this. Forest products have mainly been used to generate heat, which is the simplest form of energy, with the lowest value. Another reason is that fuel feedstock, which mainly consists of by-products from logging and industrial processes, is very heterogeneous, difficult to handle and bulky. A troublesome seasonality of demand makes it necessary to store the biomass over longer periods. This adds significant costs to production. However, the main reason for the difficulties to increase the profitability of forest-based energy is the very low overall energy price established in the post-war period.

This fact forms an impediment for refinement of forest biomass into more attractive forms of biofuels as syn-gas based FT diesel, DME, methanol, hydrogen, etc. (Bengtsson 2012). There are well known and researched technologies for such refinement, but the processes are costly and need to be run in large scale to be viable. This, on the other hand, induces diseconomies of scale as the supply area and the following transport costs increase. The economic incentives for forest owners or the traditional industry to venture into large scale facilities for solid-to-gas or solid-to-

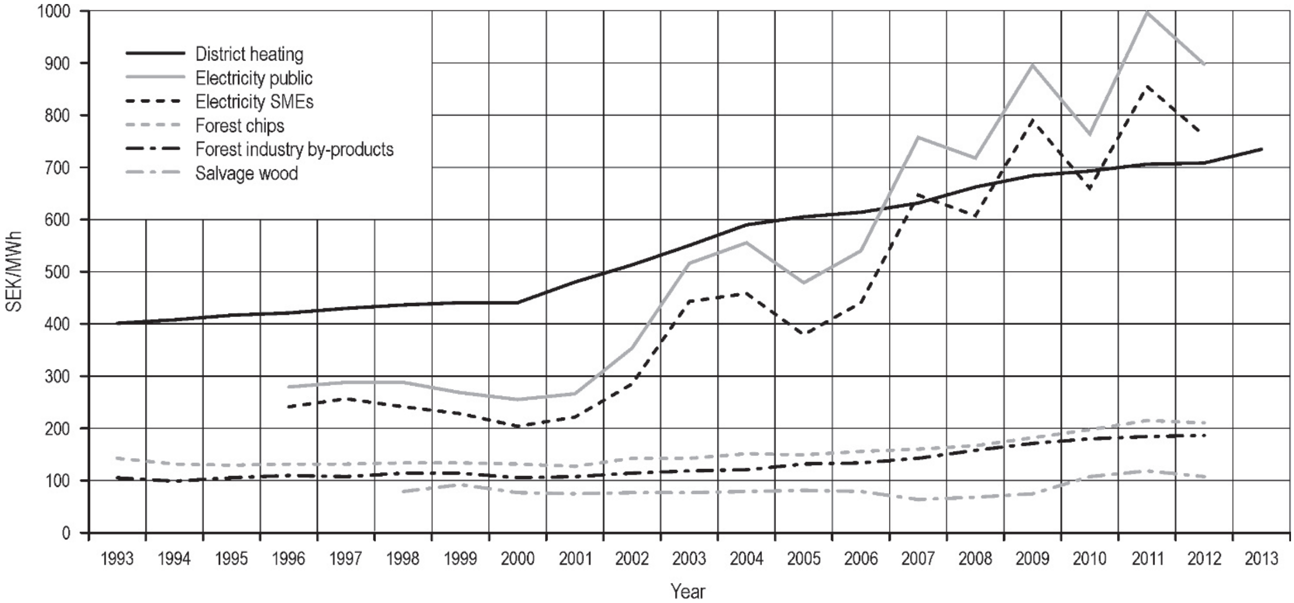

Fig. 7 Solid wood fuels (by-products, primary chips and recycled wood) have a low real-price development compared to more qualified energy carriers as electricity or fossil liquid fuel. Current prices in SEK per MWh

liquid refineries for the primary fuel fractions will thus be limited.

In spite of the difficulties mentioned in the previous sections, the achievements of forest based bioenergy are impressive in both Sweden and Finland. According to the Renewable Energy Directive (2009/28/EC), 49% of the consumed energy in Sweden should be based on renewable sources by 2020. This target was reached already in 2012 and has since been surpassed (Kühmaier et al. 2017). Also Finland is overshooting its trajectory, and renewable energy in Finland grew to 38.7% of t energy consumption in 2014, achieving a second place (joint with Latvia) in terms of renewable share of energy consumption, behind Sweden in first position with a 52.6% share (Eurostat 2016)

The Swedish climate policy targets are, however, even more ambitious, aiming at net zero GHG emissions by 2050 and »fossil free« road transports by 2030 as pointed out by Cintas et al. (2017), who even mention a possibility of reaching »negative emissions« to increase the allowable GHG emissions for the rest of the world. It seems unlikely that these goals will be fulfilled without powerful and sustained control or incentive systems.

3. Conclusions

Most governments are working hard to maintain and develop welfare. Abundant availability of energy is the basis for achieving this objective. The already existing combined heat and power production, as a simple and straightforward addition to heat production, will continue to thrive (and the need for process heat opens this possibility also for countries in temperate zones). However, it is not likely that any major investments will be seen in high end biofuels from additional forest biomass, until game changing events occur, such as e. g. much higher fossil energy prices, highly efficient enzymatic cellulose technologies or strong international subsidies/fees favouring biofuel.

The EU member states show varying success in fulfilling the RED goals for renewable energy, seemingly coupled to the national incentive systems. On the EU level, the general incentives are weaker. The Union does not have a common carbon taxation system and the ETS returns very low prices on carbon dioxide emissions. Also, globally, the agreements on climate gases have been relative failures (Cooke 2012), including fairly straightforward initiatives such as the international CO^2-emmission rights trade (Zacher 2015). Together, such failures and weaknesses mean that the incentive to invest is very limited. The ILUC directive (EU) 2015/1513 (Indirect Land Use Change) introduced in 2015 will, if anything, slow down the development of renewable fuels for the transport sector.

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