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Industrial Biomaterial Visions

Spearhead Programme 2009–2013

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Abstract

VTT's Industrial Biomaterials Spearhead Programme 2009–2013 develops technologies and competencies utilising basic skills in chemistry, biotechnology, process technology, materials science, modelling and analytics. The technologies and competencies developed in the spearhead programme are directed to generate value chains that start from forest biomass and end up in selected high volume consumer products. In such a development the key is not to disturb the fragile value chains of the food sector.

The spearhead programme focuses on the development of materials and production technologies based on fibres and nanocellulose as well as biomass-based monomers and polymers. The aim is to integrate these new value chains into existing biorefineries (like pulp mills, biofuel production, brewing, and cereal sidestreams).

The results will be exploited by actors in the chemical, process technology and materials sectors, both domestic and global. Especially interesting target sectors are the plastics, process, forest and energy industries as well as packaging and building. The spearhead programme will cooperate closely with the Finnish strategic centres for science, technology and innovation, namely Forestcluster Ltd., Cleen Ltd. and Fimecc Ltd.

Preface

Cultivating biomass (grains, corn, cane/beet, trees, etc.) and sustainable refining of biomass into value-added consumer end-products and energy is nowadays a vital undertaking of any society. In Europe significant biomass resources are generated/grow in both field and forest. Whereas agricultural biomasses are predominantly used as animal feed or refined into human food, food ingredients and beverages, wood is mainly used as a source of energy and refined into paper, cardboard and sawmill products (tools, furniture, etc.). The distinctive feature of the greater part of these conventional biorefineries is that they are based on refining aimed at utilising only one main biomass component (e.g. starch, sucrose, vegetable oils or cellulose fibres).

In recent years, Europe has also seen specific new biorefinery concepts becoming reality. Most significant of these, apart from the many new bioenergy plants in operation, is the boom in production of first generation transport biofuels (i.e. bioethanol and biocomponents for diesel engines). Key feed stocks for the European biofuel industry include various grains (wheat, barley, etc.), sucrose from sugar beet, and vegetable oils, i.e. all so-called first generation raw materials. The emphasis of the biorefinery-related R&D in Europe is, on the other hand, strongly focused on the development of technologies needed to produce second generation biofuels. In this world cellulose-rich side-streams of both agriculture and forest-based industry, as well as so-called energy crops, play a central role (i.e. “lignocellulosics”).

Wood and agrobiomass are the most important raw materials for the European biorefining industries. The annual production of wood in Europe is about 450 million m^3 (about 265 Mt). The European kraft pulping industry is the main actor separating cellulosic paper-making fibres from wood chips, with its 23% share of the world production of kraft pulp[1]. Of the wood side-streams, representing over 50% (w/w) of initial wood biomass, only about 0.5 Mt/year are valorised to various by-products, while the rest, about 31.5 Mt/year kraft pulping sidestreams and 6–8 Mt/year of bark is mainly incinerated for steam and power generation or used for land construction.

About 260 Mt of cereal grains are produced annually in Europe, of which about 120 Mt is wheat. Currently only a part of the crop biomass is harvested for subsequent processing stages. Thus, significant amounts of the biomass remain on the fields (straw). Straw comprises a typical lignocellulosic matrix, of which the main components are cellulose (up to 50% of dry mass), hemicellulose (20–30%) and lignin (5–15%). Cereal processing by brewing or milling also generates significant amounts of non-food by-products such as brewer's spent grain (BSG) or oat hulls, which are currently used as feed or incinerated directly for energy.

In the Industrial Biomaterials Spearhead Programme technologies and competencies, which enable the creation of sustainable value chains, are being developed. The value chains begin from biomass and aim to end in selected high volume products/applications. The focus is on biomass raw materials, especially forest sector which do not weaken the possibilities of food value chains. The technologies and competencies identified as objectives of the programme are situated at different points on the value chains.

Biomass-based precursors

The availability and structure of polymeric and monomeric biomass-based precursors play an important role in development of performance polymers and materials. Therefore, efficient, structure-preserving physical, chemical and biotechnical matrix opening and fractionation methods will be optimally combined to liberate polymers or monomeric components from lignocellulosic raw materials. Novel biochemical tools and chemical synthetic routes will then be used for the conversion of precursors such as sugars and hydroxy acids into a form suitable for further synthesis of modified and specialty bio-based polymers. Advanced analytical methods will be used to characterize the wood-based polymeric and monomeric precursors.

Applied biopolymers

Here the modification of targeted biopolymers into novel latexes, adhesives and coating formulations using solvent-free technologies and high solid contents is the key. Modified cellulose and hemicellulose derived from forest industry value chains will be studied, and the materials produced will be evaluated, especially in paper and board as well as in composite applications. Side-stream lignin and proteins will be studied in selected EU level projects.

Natural composite fibre

Nano-fibres can be used to modify material properties and thus create products that better correspond to future market needs. Through its involvement in the Finnish Centre of Nano Cellulose Technologies, VTT studies new applications for cellulose as a raw material, substance and end product. The combination of wood and other natural fibres with selected polymers and plastics processing technologies offers exciting new opportunities for developing bio-composite and wood plastic composite products.

Converting technologies

New thermoplastic compounds and elastomers and processing methods will be developed in applications with other emerging technologies. In-situ converting, reactive compounding and short series conversion technologies will be developed. Advanced roll-to-roll and advanced printing technologies will be applied.

Materials in applications

The programme focuses on selected application areas such as packaging, building and vehicles/appliances. Renewable polymers will be developed, targeting for better product and environmental performance. Composites based on novel binders and fibre concepts targeting for passive building concepts will be developed. The main target is the creation of a healthy living environment with novel construction solutions.

Criteria for biomass based materials

The research approach of the spearhead programme is application-driven. Material applications include packages, building and consumer products. Several industries e.g. packaging, construction, vehicle, furniture, electronics, food product and the cosmetics industries can create added value for their products by using bio-based materials. Sustainability of the novel material solutions will be evaluated on product and social levels.

Summary

The industrial biomaterials programme aims to develop new sustainable materials from agricultural crops and wood. These materials will be used in the development of new high performance material solutions for selected application areas. The objective is to develop new value chains that either improve the profitability of present value chains or can be used to replace regressive value chains.

Ali Harlin
Programme Manager

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Executive summary

Growth of the world's population and economical growth in developing countries as well as the way in which the developed world uses the limited global resources leads to increasing competition for natural resources. The worst case estimates forecast that by the 2050s the consumption of several natural minerals and fossil fuels will overrun the reserves. Due to the growing concern on environmental impacts and the security of material supply, the target of resource saving has been integrated into European environmental legislation.

Increasing utilisation of bio-based materials and fuels as a substitute for non-renewables decelerates the depletion of some resources, such as oil and other fossil fuels. Cultivating biomass and refining biomass into value-added consumer end-products and energy is a vital undertaking of any society. In Europe, significant biomass resources are generated in both field and forest. The annual production of wood in Europe is about 450 million m^3 (about 265 Mt). 260 Mt of cereal grains are produced annually in Europe, whereof about 120 Mt is wheat.

The pulp and paper industry is one of the largest material industries in Europe. The forest industry widely exploits natural resources such as wood. Wood is used in producing different papers, boards, nonwoven products, sawn goods and panel boards. The total value of the forest industry production in Finland was in 2007 € 23.7 billion. The share of wood products including furniture was € 8.8 billion and that of pulp and paper € 15 billion.

Since the year 2000 the supply demand situation of the main products has changed radically. Major market growth is taking place in Asia while in Europe and USA the growth has been modest. The challenge for the forest industry is, on the one hand, to take care of the productivity of present operations and, on the hand, to indentify, develop and foster new business concepts alongside the present ones. New technologies, products and end-uses have to be addressed and integrated with present business in a way that increases the value.

Improved eco-efficiency is a boundary condition for the development. The main guidelines for assessing the carbon footprint are published by the British Standards Institute (2008, PAS 2050) and by the CEPI, the Confederation of European Paper Industries (2007). Conventional use of wood as a structural material appears to have, generally speaking, very clear climatic benefits, but it is difficult to project whether there may be some totally new wood-based products that might essentially increase the climatic benefits of using wood biomass. Several industries e.g. packaging, construction, vehicle, furniture, electronics, food product and the cosmetics industries, can create added value for their products using bio-based materials. What is called for is a focus on excellence in performance and properties such as mechanical and barrier properties, as well converting and end-use preferences.

The primary human activities influencing carbon dioxide emissions are food, habitation and personal transportation. Wood-based bioenergy has usually, but not always, a positive displacement factor. Refining wood-based biomass to liquid or gaseous transport biofuels (second generation biofuels) will have a lower displacement factor and lower conversion efficiency than in direct combustion, and the process requires substantial auxiliary energy inputs or alternatively higher biomass inputs. Ideas have increasingly been put forward for replacing petrochemicals with new bio-based platform chemicals, also enabling bio-based plastics.

Packaging – especially food and consumer goods packaging – will be a globally growing product area in the future. The packaging industry has seen a growing trend in recent years towards the use of plastics, and this has affected sales of metals, glass, and paper and board packaging. An understanding of the interaction of the environmental, social and economic factors will lead to practical solutions on sustainability. Sustainability, quality and functionality will influence consumer purchase decisions and tailored packaging concepts will set new demands for the packaging industry.

Plastic has an indirect effect especially on improving the food delivery chain. Biodegradable polymers, like polylactic acid, provide answers in waste problems related to the synthetic plastics. Synthetic plastic film packaging has been blamed for littering and severe environmental problems in the oceans. Still the biodegradable polymers lack of performance in the applications and in many case recycling. It seems evident, that the materials of today will remain because of performance, and the impact of fibre packaging may increase if the life cycle assessment can be influenced efficiently. In the sector efficient barrier solutions have marked potential in new product innovation.

In Europe the most of the naturally-reinforced plastic composite applications are related to the building and automotive sectors. Wood frame still dominates the small residential house building. However, the upcoming energy efficiency regulations can augment the role of other competing materials, such as concrete, light concrete blocks and bricks. The demand for better U-values clearly leads to using polyfoam insulators like polyurethane, which could even be partially or fully bio-based. This type of solution favours non-wood structures. If wood and wood-based composite materials are required to maintain their market share, totally new concepts need to be developed for tomorrow's market.

The automotive industry, as for vehicle producers in general, has typically three main technical concerns: production costs, safety and lately and increasingly, fuel economy. Among many other technologies, material science has a marked contribution to make to all three main issues. In composites for automotives and off-road heavy duty vehicles, the lightweight compared with the impact and torsion resistance, connectivity/joining and structural design together with fire resistance are the main issues. In transportable containers and tanks, the lightweight, high strength and properties like insulation or sensing functions are the main focus areas. Each application has its key properties, useful technologies and proof of principle products. To improve the properties of natural fibre-based composites, there are several modification possibilities within the capabilities. The principle routes are fibre modification or matrix modification combined with the addition of other ingredients such as nanoparticles or nanofibres.

Main technological assets are found in the combination of a broad spectrum of technologies. Emerging technologies on nanocellulose, thin films and nanoparticles are enabling new generations of lightweight and functional composite materials. Biomaterial chemistry provides options for bio-replacement through metabolic, entzymatic and catalytic conversions of platform chemicals form side-streams and leftovers. Development and implementation of proprietary materials takes place in vertically integrated collaborative projects, where universities still make a marked contribution. However, implementation requires close consultation with customers, and that is why the whole production chain is involved.

1. Introduction

Growth of the world's population and the economical growth in developing countries as well as the way in which the developed world uses the limited global resources leads to increasing competition for natural resources. The worst-case estimates forecast that, by the 2050s, consumption of several natural minerals and fossil fuels will overrun the reserves. These threatened resources include e.g. gold, silver, tin, copper and several rare earth metals, the consumption of which has grown significantly because of new applications in electronics. The demand for oil and other fossil fuels is also projected to grow by tens of percent in the next two decades. However, thus far the worst material depletion scenarios have not materialised due to the rising prices of reduced materials, the development of new technologies and exploitation of new stocks.

In principle, those natural resources which are not chemically transformed are non-depletable. From this point of view, oil and other fossil fuel reserves are in the greatest danger. In spite of this, the concern about energy and material security is justifiable. Due to incomplete material recovery during extraction and production processes as well as low recycling efficiencies, the reserves of non-renewable materials are only partly returned to the material cycle. The rest is diffused into the environment. The present development trends, such as the variety, growing complexity and miniaturisation of materials and products, create new challenges for the recycling business. For example, the amount of e-waste is increasing heavily and at the same time as the composition of the waste stream is rapidly changing.

Apart from resource depletion, the extraction and use of resources has significant environmental and social impacts. At the same time, the concern over the environment has increased due to the awareness of global warming, economic growth and environmental damage. It is predicted that in the future the environmental impacts will more and more limit and control the material supply. Sustainable use of water and the maintaining of water resources are already well-known challenges. Apart from a reduction of water consumption and a growing need for the introduction of alternative water sources (saline water, recycled waters, storm water), the shortage of water may influence the location of water-consuming activities such as water- intensive industries as well as the production of food and biomaterial stock. Water shortages may be the key factor limiting economic growth in many countries.

Due to the growing concern about environmental impacts and the security of material supply, the target of resource saving has been integrated into the European environmental legislation. The thematic strategy on the sustainable use of natural resources was published by the European Commission in 2005. The main aim is to facilitate and stimulate growth while at the same time ensuring that the state of the environment does not get worse. Inefficient use of resources and over-exploitation of renewable resources are seen as long term brakes on growth. The Finnish national strategy on sustainable resource use has also recently been published by Sitra.

The new way of thinking is presented in the revision of the EU waste management directive, which aims to reduce waste production by promoting a more efficient use of resources. The directive aims to further improve the requisites of waste recovery and recycling, e.g. by defining recovery targets for certain materials as well as the end-of waste procedure. European and international producer responsibility regulations (such as in the Waste electrical and electronic equipment-directive, end-of-life vehicles, batteries, C&D waste and packaging) enhance the recycling of relevant products and materials. Life cycle environmental, cost and social impact management will also be incorporated into waste management. The landfill directive aims at reduction of greenhouse gas emissions by reducing the amount of biodegradable waste dumped in landfills.

One of the challenges of sustainable resource use is that the actions to preserve the environment and restrict climate change may lead to new unforeseen environmental impacts. For example, miniaturisation of products and increased utilisation of composites and surface coatings as well as a growing use of ICT has complicated the recycling of materials. To ensure the environmental friendliness of the more efficient material use solutions, environmental aspects such as recyclability, energy and carbon impacts, water use etc. should be considered. In addition to the environmental dimension, sustainability includes social and economical aspects.

In many cases, substitution of rare resources with more freely available ones is a step towards sustainability. Increasing utilisation of biobased materials and fuels as a substitute for non-renewables slows the depletion of some resources, such as oil and other fossil fuels. In addition, the recovery of biobased materials may be easier than that of fossil materials and, for example, greenhouse gas emissions and the environmental impacts of material extraction may be reduced. The reduction of environmental impacts has, however, to be assessed case by case. It is not a self-evident benefit to use biomaterials.

The potential drawbacks of the introduction of renewable materials should be taken into consideration in the development stage and minimised by suitable measures. The growing use of biobased materials may result in shortage and increased competition for biobased resources. Soil erosion and degradation due to nutrient removal are also becoming more widespread problems. The availability of cultivated areas is decreased as urban area expands. The growing production of bio raw materials may further reduce the area available for food production, and may have a negative effect on biodiversity.

Closing of the material cycles and minimisation of the dispersal of the residuals into the environment generally reduces the environmental impacts of resource use. Life cycle assessment tools are needed in assuring positive environmental impacts in the total material handling chain. Even in the best cases, part of the material is lost in the recovery stage. Assessing the sustainability of the choices, such as material and energy recovery, may be a challenge due to the need for valuing and comparing different environmental impacts. In general, material recovery is prioritised in the hierarchy of waste legislation, but the priorities may be changed based on life cycle impact assessment.

To summarize, the sustainability of material use may be improved by paying attention to the following aspects (Sustainable Biomaterials Collaborative 2007):

1. use of common and/or renewable raw materials
2. balanced exploitation of the local resources
3. minimisation of the dispersal of residues into the environment. The fertility of soil and the supply of nutrients should, however, be maintained
4. assessment and reduction of environmental impacts throughout the production chain, including sustainable (and certified) production of biomaterials, primarily in areas which are suitable for production without irrigation
5. design and use of reusable and/or recyclable materials and products
6. reduction in the number of different materials (development of more generic materials)
7. reduction of the material use (the product specifications need to be fulfilled)
8. in addition to environmental aspects, health, safety and social aspects should be considered
9. avoidance of the use of harmful chemicals.

2. The efficient use of wood

2.1 Climatic viewpoint

From a climatic viewpoint, sustainably managed forests function as a store of biogenic carbon and a renewable source of biomass. In halting the rising CO_2 concentration in the atmosphere, forests can be utilised in alternative ways (Figure 1):

- Sequestration: accumulate more carbon (C) into forests materialized in net growth of their biomass stocks;
- Substitution: displace fossil CO_2 emissions using wood as an energy source instead of fossil fuels, thereby preventing emissions from permanent tectonic carbon stocks.

These mechanisms can be combined, and there are both trade-offs and synergy between them. Here we are assuming a baseline or reference (e.g. fossil fuel-based conventional energy system) with respect to which we are estimating cumulative carbon sequestration or a reduction in emissions. When considering substitution as a mitigation tool, we assume that biomass use is on a sustainable basis, i.e. harvested biomass is replaced by re-growth of new biomass, which can be rapid or could take over a century, which could be the case in managed boreal forests.

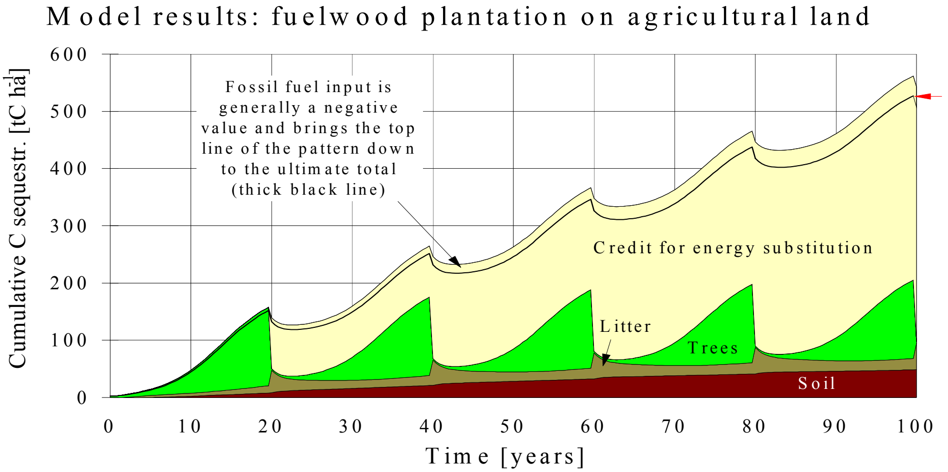

Figure 1. Schematic illustration of the carbon credits of sequestration and substitution (IEA Bioenergy Task 38 2009). The initial C stock is low (reforestation case) and regrowth of new biomass compensates the debits from harvesting quite quickly. There is a nearly cumulative C credit in time from energy substitution that displaces emissions from permanent fossil C sources, whereas C sequestration into biomass stocks is a saturating mechanism.

The sequestration mechanism is temporary and will saturate in the long run, due to natural limits to storing carbon in biomass or biomass-based products. The substitution credit, i.e. the displaced emissions from permanent tectonic carbon stocks, is cumulative; proportional to the amount of biomass used, and also operates when there is no net growth in biomass stocks. It provides long-term benefits in emission reduction, where part of the non-renewable and fossil-fuel based energy and material sources can be continuously replaced by sustainably produced biomass.

The substitution mechanism 2) may be even more effective if wood can be used as a material replacing energy-intensive or emission-intensive materials. This is because material substitution does not prevent energy substitution, as wood materials can usually be recycled for energy at the end of their lifecycle. The sequestration mechanism 1) applies to wood materials too, but it contributes to halting greenhouse gas concentrations only if there is *net* growth in the wood products and forest biomass stocks.

However, all wood use cannot be considered to contribute to the displacement of fossil emissions: For instance, there may be applications where wood does not compete with any other products. Furthermore, an increasing supply of wood energy or products could, instead of replacing fossil-based services, increase overall consumption and thereby emissions (leakage mechanism). As this kind of mechanism cannot realistically be described by the LCA-oriented approach used above, economic models could be helpful in analyzing the market mechanism involved in the use of wood and its impact on greenhouse gas emissions.

Although the substitution mechanism provides higher credits in the longer run, the situation might appear different when considering climate change mitigation in the short term. To limit global warming to the critical 2°C temperature threshold requires a 50%–85% reduction in greenhouse gas emissions by 2050. As a consequence, the timeframe for emission reductions obtained by the use of forest biomass becomes a factor to be considered. Figure 2 shows an alternative generic example of carbon credits and debits due to substitution. The payback time, i.e. the time taken to obtain any carbon credits from the use of forest biomass, can be quite long compared with the timeframe for emission reductions when: 1) the carbon stock of forest biomass is high in the initial state, 2) emissions that can be replaced by harvested biomass are relatively low (i.e. substitution is inefficient) and 3) re-growth of forest is slow after regeneration cutting of the stands. From a climate mitigation point-of-view, continuing C sequestration into high biomass stocks or just conservation of them could be defended in this particular case.

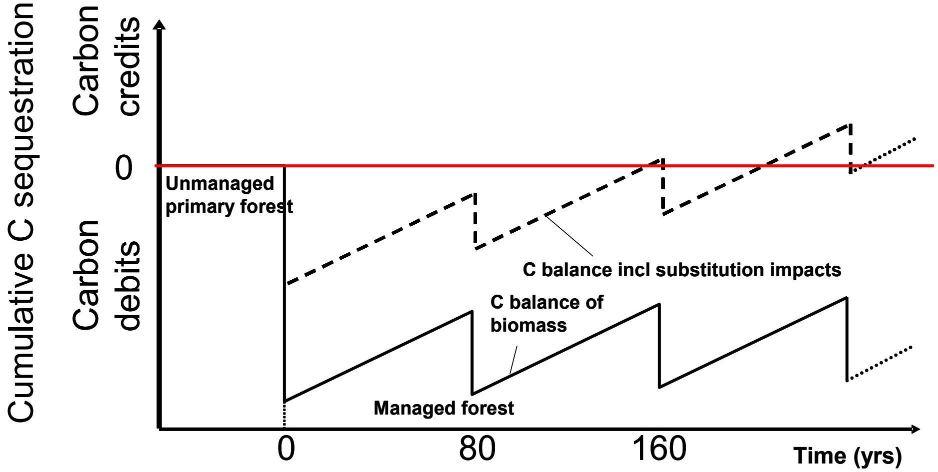

Figure 2. Schematic illustration of carbon debits and credits of utilisation of an old-grown forest, when the substitution benefit is low and re-growth of forest biomass slow.

Fossil C displacement factor DF is an efficiency indicator of substitution. It describes how much GHG emissions (e.g. tonnes of $C_{eq.}$) can be displaced by an increased use of biomass:

$$DF = (E_{ref} - E_{wood})/(BioC_{wood} - BioC_{ref}) \qquad (1)$$

where E_{ref} are the GHG emissions in tonnes of C_{eq} of the (fossil) reference product, E_{wood} are the GHG emissions from the wood product, $BioC_{wood}$ the of biogenic C in wood product in tonnes of C, and $BioC_{ref}$ the biogenic C in (fossil) reference product (usually = 0). (Thus $BioC_{wood}$ - $BioC_{ref}$ is the additional amount of biomass- based C used in the wood product compared to the reference product.) For instance, in Figures 1 and 2 the average displacement factor calculated for the whole wood biomass harvested defines is the size in the drop in cumulative C sequestration due to harvest and utilisation of biomass: the larger the factor, the smaller the drop and the shorter the carbon payback time. The total potential of forest biomass in long-term climate change mitigation is defined by the average substitution efficiency, the available forest area and the forest yield.

There appears to be no established practice for the definition of DF in the literature, and it may be calculated either for the end product (e.g. wood materials in a house) or for the round wood material chain (e.g. sawn logs). The factor could include the displacement of fossil C emissions of bioenergy from by-products or from wood material itself after demolition. The estimated DF values also vary depending on assumption of biomass portion that is utilised as bioenergy.

2.2 Findings on substitution by wood

Some general findings on substitution and displacement factors are as follows:

Wood-based bioenergy usually, but not always, has a positive displacement factor. In conventional use of wood and other biomasses, e.g. in cooking stoves and heating in developing countries, the conversion efficiency is often extremely low compared to their fossil-fuelled competitors. In addition, conventional bioenergy causes high emissions of black carbon and other climate forcers like methane, which might eliminate all its climate benefits, even if the biomass harvest were on sustainable basis. Besides, conventional bioenergy contributes to deforestation in tropical countries. Industrial use of wood-based bioenergy in modern combined heat and power plants appears to be the most efficient energy use of wood, where the conversion efficiency is high and the non-CO_2 greenhouse gas emissions are low. Refining wood-based biomass to liquid or gaseous transport biofuels (second generation biofuels) will have a lower displacement factor and lower conversion efficiency than in direct combustion, and the process requires substantial auxiliary energy inputs or alternatively higher biomass inputs. The emission displacement by liquid biofuel of replacing fossil diesel is thus lower per amount of consumed biomass than in direct combustion. However, the displacement factor for biofuel would be better in the case where fossil diesel is produced from coal some time in the future. Besides, there are other reasons for replacing fossil based transport fuels by biofuels, such as self-sufficiency objectives and energy security.

Quantitative estimates of displacement factors for *wood-based materials* in general involve many uncertainties due to difficulties in defining functional units and functionally equivalent non-wood reference materials. It is possible that some wood-based materials are worse from the climatic viewpoint than their non-wood competitors. For instance, use of some paper grades could be replaced by electronic media, having possibly positive impacts on climate change mitigation, but only preliminary analysis of this issue can be found in the literature (Moberg et al. 2009). Processing of pulp and paper is basically energy-intensive (calculated either per amount of raw material or per amount of end-product), though much bioenergy is used. Replacement of paper and reduction of its consumption would save biomass for other material and energy purposes with potentially higher displacement factors. However, some life-cycle studies indicate that from a climate perspective paper board as a packaging material surpasses its fossil-based competitors like plastic. Conventional use of wood as a structural material appears in general to have very clear climatic benefits as against its competitors discussed in the following. These benefits could, however, be jeopardized in case increased wood construction merely contributes to growing housing areas or to urban sprawl with increasing emissions from the transport sector. In addition, it is possible that some totally new wood-based materials will be developed that prove very favourable from the climatic perspective.

The main observation that is valid for all wood-based materials is that their substitution benefit – being proportional to the wood material flow and causing permanent emission reductions – is more important than the temporary sequestration impact – operating only when there is a *net* growth in wood product stocks. Substitution provides a tool applicable in the long-term climatic policy based on sustainable use of renewable material and energy sources.

2.3 Quantitative estimates of displacement factors

There are a great number of studies in the literature where wood is compared in climatic performance to other construction materials. The studies cover cases starting from single building parts (e.g. joists) to building elements (e.g. exterior walls) and whole buildings, ending the whole construction sector. To enable a comparison between materials, it is essential first to determine the equivalent units fulfilling the same function. For instance, in the previous study considering the whole new construction sector in Finland at the beginning of the 1990s, it could be roughly estimated that on average for 1 tonne of construction wood approximately 3.6 tonnes of stone-based materials could have been substituted (Pingoud and Perälä 2000).

Estimation of the true impacts on GHG emissions of wood materials and their competitors is not straightforward. One issue is, for example, the emissions from purchased energy, especially electricity, required in processing the building materials, which could be based on marginal or average energy profiles leading to very different specific emissions. Furthermore, in the GHG life-cycle analysis assumptions on future emission displacement are also made, for instance, what proportion of demolished wood is recycled to bioenergy, increasing the uncertainties. Very diverse assumptions can be defended, and this is reflected in the studies complicating their comparability and increasing uncertainties.

Sathre and O'Connor (2008) performed an ambitious review of 48 different studies on the greenhouse impacts of wood products and their competitors. Results of 20 studies enabled a meta-analysis in order to calculate the displacement factor for wood construction materials. In the meta-analysis, due to the diversity of the studies analyzed, a single displacement factor that incorporates all the GHG emission reductions reported in each study was calculated. The displacement factor was calculated for the *final product*, not for the amount of round wood used to produce the final wood product. Depending on the system boundaries of the study, these included fossil fuel emissions from material production and transport, process emissions such as cement reactions, fossil emissions avoided due to using biomass by-products and post-use wood products as biofuel, carbon stock dynamics in forests and wood products, and carbon sequestration and methane emissions of landfilled wood materials, which makes the quantitative estimates partly incomparable. For instance, in eq. (1) of this chapter the carbon stock dynamics of forests and wood products is excluded from DF and is assumed to be described separately.

A displacement factor is valid only for wood used in place of other, more carbon-intensive materials. The displacement factors calculated should not be misinterpreted to suggest that a GHG emission reduction will result from each and every piece of wood used, regardless of how it is used. The use of wood in applications for which wood is typically used will not result in a GHG emission reduction, except to the extent that emissions would have been greater if non-wood materials were used instead. Thus, depending on the context, a displacement factor can be a measure of *either* the GHG that is avoided because something is made of wood when it could have otherwise been made of non-wood materials, *or* of the potential reduction in GHG emission if something made of non-wood materials were instead made of wood (Sathre and O'Connor 2008).

Quantification of the effects of the displacement factor is further complicated in economies where energy and/or material consumption is supply-limited. In this case, an additional unit of biomass fuel or material may not displace the use of fossil fuel or non-wood material, but instead be used in addition to it. This "leakage" results in the actual climate benefit of using wood products being somewhat lower than the potential benefits. In general, the studies reviewed in the meta-analysis by Sathre and O'Connor (2008) do not address this issue, mostly being case studies of wood substitution in place of specific non-wood materials. Several of the studies considered do model wood substitution on a national or global level, but their results are defined in terms of the (assumed) actual displacement of non-wood materials by wood materials that occurs at those levels.

This heterogeneity of study methodologies and assumptions brings advantages and disadvantages to the meta-analysis. While making inter-study comparisons more difficult, it adds to the robustness of the overall results by showing displacement factors for a range of different product substitutions and analytical methodologies. Some variability is inherent in the determination of displacement factors. Each study reviewed showed a unique result, which varied with physical ("real") factors like the type of forestry and wood product, the type of non-wood material it is compared against, and the post-use fate of the wood. It also varied with the analytical methodology and assumptions used in the analysis, which adds additional uncertainty. In the meta-analysis, the data available in some studies allowed the calculation of a single displacement factor, with no indication of the range of variability. Other studies reported data on several scenarios or assumptions, which allowed the calculation of high and low estimates of the displacement factors. The calculated displacement factors are listed in Table 1. The calculated displacement factors averaged 2.0, and range from a low of -2.3

to a high of 15.0. The wide range of calculated displacement factors was due to the inclusion of "extreme" scenarios in some of the studies, and differences in system boundaries between studies. The few cases of negative displacement factors, in which the GHG emissions of wood products were greater than those of alternatives, were the result of worst-case wood disposal options that are unrealistic in current practice, according to Sathre and O'Connor (2008). The middle estimates of the displacement factors ranged from 0.2 to 6.0, with most lying in the range of 1.0 to 3.0. The average of the low estimates was 0.7, and the average of the high estimates was 4.4. The average middle estimate, with a value of 2.0, could be viewed as a reasonable estimate of the GHG mitigation efficiency of wood product use, over a range of product substitutions and analytical methodologies.

In a Finnish study (Pingoud et al. 2009) the displacement factors were calculated for *raw material harvested*, energy wood and sawlogs (Table 2). The sawlogs were assumed to be used in construction of multi-storey houses in wood. The calculation of the displacement factors was based on the data collected in the Finnish-Swedish case study (Gustavsson et al. 2006) on GHG impacts of building two wooden houses in Viikki, Finland, and Växjö, Sweden, compared with their functionally equivalent concrete reference houses.

Table 1. Low, middle, and high estimates of displacement factors of wood product substitution (tC emission reduction per tC of additional wood products used) based on data from various studies (Sathre and O'Connor 2008).

Reference	**Application**	**Estimates**		
		Low	**Middle**	**High**
Börjesson and Gustavsson, 2000	Apartment building	–2.33	4.21	7.48
Buchanan and Levine, 1999	Hostel building		1.05	
	Office building	1.13	1.17	1.20
	Industrial building		1.60	
	House	–0.55	3.57	15.0
Eriksson, 2003	European construction sector	1.36	1.66	1.95
Eriksson et al., 2007	Construction materials	4.43	5.97	7.50
Gustavsson et al., 2006	Apartment building 1	1.94	3.76	5.58
	Apartment building 2	0.37	1.82	3.27

Gustavsson and Sathre, 2006	Apartment building	–0.10	2.30	7.33
Jönsson et al., 1995	Solid wood flooring	0.01	0.21	0.32
Koch, 1992	Mixture of wood products		2.20	
Künninger and Richter, 1995	Utility pole (treated roundwood)	0.58	2.47	4.36
	Utility pole (glulam)	0.14	1.98	3.82
	400V transmission line	1.53	2.73	3.92
	20 kV transmission line	1.03	3.39	5.75
Lippke et al., 2004	House	0.92	1.57	2.21
Petersen and Solberg, 2002	Roof beams	–0.76	0.40	1.27
Petersen and Solberg, 2003	Wood flooring	–0.76	0.36	1.15
Petersen and Solberg, 2004	Wood flooring	0.08	1.72	12.9
Petersen and Solberg, 2005	Review of Scandinavian studies	–0.88	0.66	3.02
Pingoud and Perälä, 2002	Finnish construction sector	0.45	1.09	4.05
Scharai–Red and Welling, 2002	House 1	0.32	0.64	0.96
	House 2	2.25	2.76	3.27
	3-storey building	1.46	2.26	3.06
	Warehouse	0.66	1.21	1.77
	Window frame	2.74	4.15	5.56
Sedjo, 2002	Utility poles		1.59	
Upton et al., 2006	House 1	–0.008	0.40	2.16
	House 2	2.75	2.85	6.63
Valsta, 2007	Literature survey	1.00	2.00	3.00
Wemer at al., 2005	Swiss construction sector		1.60	
Averages		0.7	2.0	4.4

From the results in Table 2 it can be seen that the variations in the estimated displacemant factors for the two house cases is large, and the impact of the assumed marginal fuel is significant. It should also be noted that the displacement factors for the wooden houses is marginal, i.e. calculated for the *additional* wood use in wooden houses ($BioC_{ref}$ is not equal to 0 in eq. 1), as also in the concrete reference house some wood material is used. (This means that the displaced emissions due to the wooden house cannot be calculated just by multiplying DF by the *total* amount of wood based C used to build the wooden house, but multiplying DF by the *additional* amount in the wooden house with respect to the concrete house.)

Table 2. Displacement factors estimated by Pingoud et al. (2009).

	Displacement factor
Saw logs used for the Swedish wood-frame building***	**1.5**- 2.1*…**
Saw logs used for the Finnish wood-frame building*** (with timber facing)	**0.9**- 1.3***
Energy wood for CHP	**0.5 - 0.9**
*Marginal fuel = Coal, **Marginal fuel = Natural gas ***The displacement factors describe the GHG emission reductions with respect to a functionally equivalent concrete building	

According to the study of Soimakallio et al.(2009) the quantitative estimation of the displacement factor for Fischer-Tropsch (FT) diesel fuel produced from logging residues compared with fossil diesel is very uncertain, especially if the electricity purchased in the processing is maximized. This is due to the high uncertainties of the emissions from electricity production. In case the use of biomass is maximized and purchased electricity minimized in the FT process, the displacement factor is most likely less than 0.4 for the FT biofuel plant integrated to a modern pulp and paper mill and of the order 0.3 for a stand alone plant.

2.4 Estimates on GHG impacts of sequestration and substitution on national level

According to the Finnish national GHG emission inventories (Statistics Finland 2009) carbon sequestration into forest biomass was 32.81 Mt of CO_2 in 2007, varying between 25.71 and 40.69 Mt of CO_2 in the 2000s. Sequestration into wood products was, according to the inventories 1.22 Mt of CO_2 in 2007 varying between 0.31 and 1.27 Mt of CO_2 in the 2000s.

The figures above can be compared with the roughly estimated substitution credits of wood use in Finland. According to Finnish Forest Research Institute (2008) the primary energy in waste liquors and other by-products, waste products from the forest industries, and use of solid wood fuels in heating and power plants and small-sized dwellings was totally 295 PJ in 2007. Energy use is nearly a half of all wood use in Finland. In terms of biomass, it was approximately 17 Mt of dry matter content and 8.5 Mt of biogenic C. If, instead of wood energy, fossil fuels were used, the fossil C emissions would have been approximately 15–30 Mt of CO_2 higher (assuming about the same conversion efficiency, in reality somewhat lower) depending on the replaced fossil fuel (natural gas, oil, coal, peat). Replacement of *all* wood-based bioenergy in Finland by fossil fuels would not be possible in practice, but even the above estimate of the rough magnitude of displaced fossil fuel emissions is illustrative.

Domestic consumption of sawn wood was in 2006 about 5.2 Mm^3 and consumption of wood-based panels 1.1 Mm^3. Converting these two to carbon flows is roughly 1.5 Mt C. If no wood products were used, the emissions would have been 4 Mt of CO_2 higher when applying the low estimate displacement factor (0.7), 11 Mt of CO_2 higher when applying the middle DF (2.0) and 24 Mt of CO_2 higher when applying the high DF (4.4). This calculation is, of course, unrealistic, but it illustrates the order of magnitude of the impact of material substitution.

An increased use of wood as a source of energy and material would create additional savings in fossil C emissions, but on the other hand the C sequestration into forests would decrease too. From the above calculations we can conclude that carbon sequestration into wood products is quite small compared with the climatic benefits of energy and material substitution. To these substitution benefits must be added the impact of the potentially displaced emissions in the export markets of Finnish wood products, not estimated here.

To summarise, the climatic benefit due to substitution is a product of the wood product flow and displacement factor. To have significance for national emission reductions, the mass flow of biomass used for displacement must be sufficiently large, but simultaneously the efficiency of the wood use should be high, preferably maximizing the displacement per consumed biomass. It is difficult to project, whether there might be some totally new wood-based products that could essentially increase the climatic benefits of using wood biomass. The re-growth of forest biomass is slow in Finland compared with most forested regions in the world, leading to longer C payback times for biomass use. The payback time is, however, the shorter the higher the displacement factor (assuming no change in growth rate). Currently most of the residues are left in the forest after final felling. When not utilised for bioenergy they decay quite rapidly without any benefits in the displacement of fossil fuels. This potential could be used to increase the average displacement factor of harvested wood. From the climatic viewpoint, it is justifiable to develop uses of forest biomass providing maximal emission displacement per harvested biomass, but simultaneously considering the constraints due to biodiversity and other non-GHG issues.

3. The forest industry

3.1 The industrial use of wood

The forest industry widely exploits natural resources such as wood. Wood is used in producing different papers, boards, nonwoven products, sawn goods and panel boards. The production volume of the main product groups are shown in Figure 3.

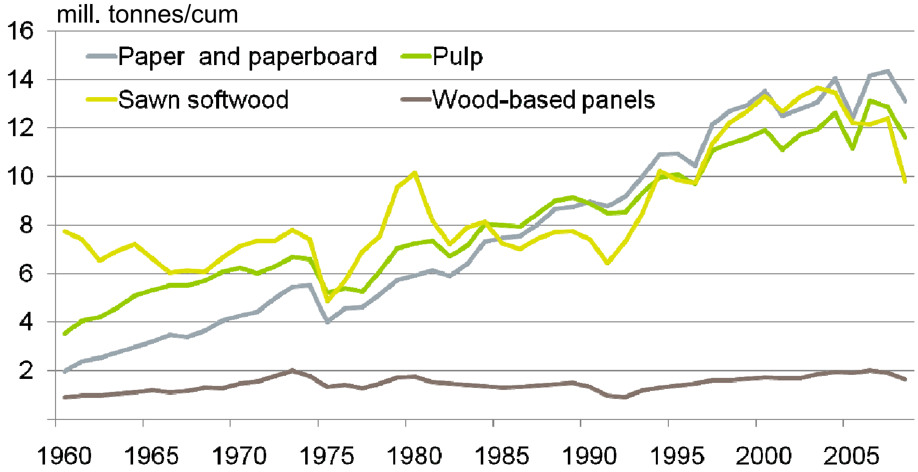

Figure 3. Production volume of the main forest products (Finnish Forest Industries Federation).

Papers are used in various printing processes in the production of books, catalogues, magazines and newspapers. A substantial amount of paper is consumed as office paper. Finally, at the end of their life cycle, most of the paper products (approximately 60% in Europe) are recycled, and the recovered fibre is reused as raw material in production of paper and board products. Laminating, baking and adhesive papers as well as label papers, tissues and diapers are examples of much specialised end-uses.

Packaging is an area where fibres and boards have an important role. Corrugated boxes, folding boxboard, liquid packaging boards, bags, sacks, packing papers, cups and plates are examples on the very versatile uses of wood fibre.

Panel boards such as particle and fibre boards and veneer are used in the production of furniture and parquet. Wood is also widely used as a construction material, and it is a very important raw material in the production of furniture. Prefabricated houses, log houses, saunas, doors and windows represent products with high value added.

The total value of the forest industry production in Finland was in 2007 € 23.7 billion. The share of wood products including furniture was € 8.8 billion, and that of pulp and paper € 15 billion. The share of different products is shown in Figure 4.

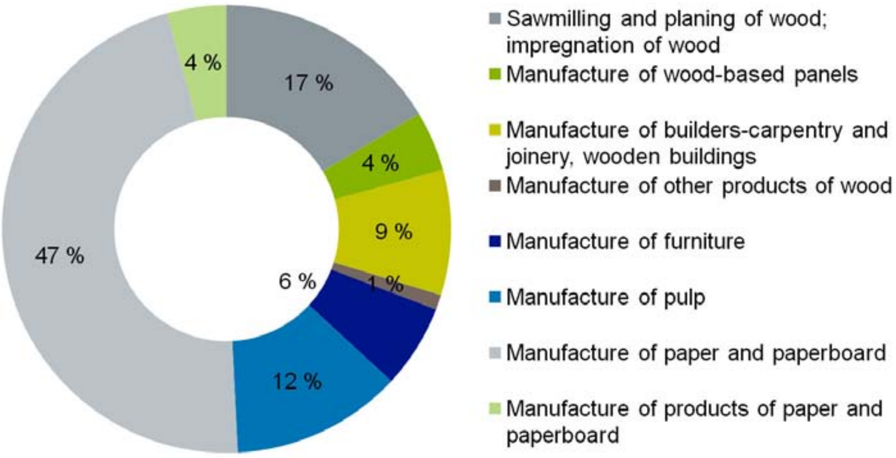

Figure 4. The value distribution of the forest industry production (Finnish Forest Industries Federation, Member Companies' annual and interim reports).

Chemical products are also co-produced with pulp and paper. Tall oil, xylitol, β-sitosterol are produced on industrial scale. Lately the separation of lignan from wood knots has been studied to extract hydoxy-matai-recinol for use as an antioxidant.

A substantial part of the raw material, that is bark and black liquor and bio sludge from effluent treatment, is used in energy production to provide steam and electricity to the production processes. About 75% (262000 TJ) of mill fuels are derived from wood and about 46% (13 TWh) of the electricity is produced by forest industry itself.

3.2 Profitability

Since the year 2000, the supply and demand situation of the main products has changed radically. Major market growth is taking place in Asia, while in Europe and USA the growth has been modest. Only a few of the largest companies have been able to make profit any more (see Figure 5). The monotonic decline of profits of the largest companies is alarming.

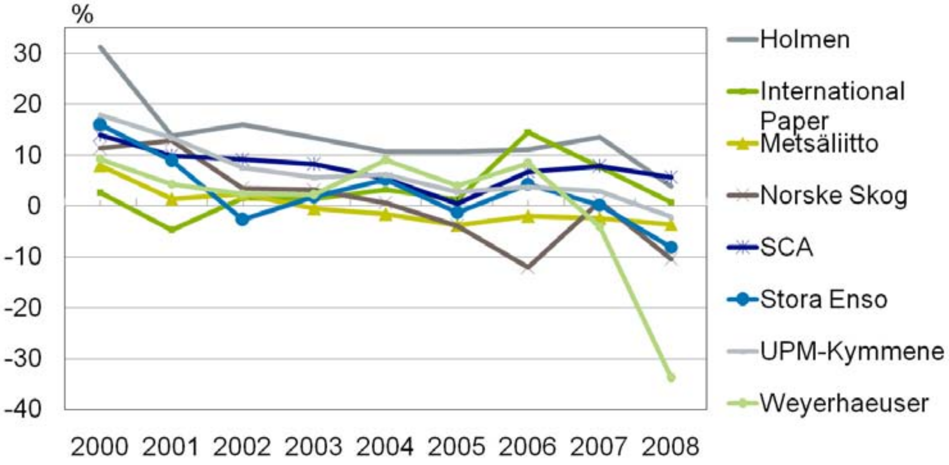

Figure 5. Profits before taxes in selected forest industry companies relative to turnover (Finnish Forest Industries Federation, Statistics Finland).

Overcapacity of production is one reason for the poor economic performance. Companies have not been fully able to transfer the increases in wood raw material, energy, chemicals and labour costs into the selling prices of the products. Earlier it was possible to compensate the higher costs by investing in high-speed and highly automated machines and by cutting logistic costs.

Now the best profitability is achieved through utilisation of cultivated eucalyptus forests. Uniform raw material quality, low harvesting and transportation costs with the best available Kraft technology are factors for overwhelming competitiveness.

High market growth in Asia and high profitability of eucalyptus pulps in South-America are attractive investment objectives. Finnish forest industry has lately invested overseas roughly as much as in Finland. New capacity has been constructed abroad, whereas the focus in Finland has been in rebuilds. Few of the older mills have been demolished as unprofitable and companies have started to reduce personnel costs. The position of paper is also threatened by the very fast development in information technologies. There are already clear signs in the reduced consumption of newsprint paper. The newspaper business is very dependent on advertising.

3.3 Challenges

The pulp and paper industry is one of the largest material industries in Europe. The European forest-based sector is very important with its pulp, paper, sawn good and wood-based panel products. It delivers 8% of EU manufacturing's added value. It provides income to about 16 million forest owners and 3–4 million jobs working in industry including machinery, equipment, instrumentation, IT-systems, chemical and energy providers. The forest-based sector is even more important to Finland than to any other country, while the export share of forest industry is about 20%.

It is also important to secure the operational preconditions of the forest-based sector in the future. Industry has recognised the needs for change. A common vision for the forest-based sector extending to 2030 has been established by the major stakeholders and a strategic research agenda of the Forest Technology Platform has been defined (Table 3). The objectives are to increase competitiveness and to ensure economic growth while protecting the environment. Innovative products and new markets together with smart applications derived from societal needs are the cornertones for value creation.

Improved eco-efficiency is a boundary condition for the development. Clearly there is a need for new products and technologies that consume less energy, wood and water with a lower environmental footprint, and that increase the value of the product portfolio. There is a need to transform the forest-based sector from a resource in a knowledge-intensive direction. New business concepts also need to be developed.

The challenge to the forest industry is, on the other hand, to ensure the productivity of present operations and, on the other hand, to indentify, develop and foster new business concepts along the lines of the present ones. New technologies, products and end-uses (also new markets) have to be addressed and integrated with present business in a way that increases the value.

Table 3. Strategic objectives of forest-based value chains (The Forest-Based Sector Technology Platform, www.forestplatform.org).

	Forest-Based Value Chains				
Strategic objectives	**Forestry**	**Wood products**	**Pulp & Paper products**	**Bio-energy**	**Specialities**
1. Development of innovative products for changing markets and customer needs	1-6: Commercialising soft forest values	1-1: A new generation of functional packaging 1-4: Living with wood 1-5: Building with wood 1-10: New generation for composites	1-1: A new generation of functional packaging 1-2: Paper as a partner in communication, education and learning 1-3: Advanced hygiene and health care 1-8: Pulp, energy and chemicals from wood bio-refinery 1-10: New generation of composites	1-7: Moving Europe with help of bio-fuels 1-8: Pulp, energy and chemicals from wood bio-refinery	1-8: Pulp, energy and chemicals from wood bio-refinery 1-9: Green specialty chemicals 1-10: New generation of composites
2. Development of intelligent and efficient manufacturing processes, including reduced energy consumption		2-4: Advanced technologies for primary wood processing 2-5: New manufacturing technologies for wood products	2-1: Reengineering the fibre-based value chain 2-2: More performance from less inputs in paper products 2-3: Reducing energy consumption in pulp and paper mills	2-3: Reducing energy consumption in pulp and paper mills 2-6: Technologies to boost heat and power output	
3. Enhancing availability and use of forest biomass for products and energy	3-1: Trees for the future 3-2: Tailor-made wood supply	3-2: Tailor-made wood supply 3-4: Recycling wood products - a new material resource	3-2: Tailor-made wood supply 3-3: Streamlined paper recycling	3-2: Tailor-made wood supply	3-2: Tailor-made wood supply
4. Meeting the multifunctional demands on forest resources and their sustainable management	4-1: Forests for multiple needs 4-2: Advancing knowledge of forest ecosystems 4-3: Adapting forestry to climate change				
5. The sector in societal perspective	5-1: Assessing the overall performance of the sector 5-2: Instruments for good forest sector governance 5-3: Citizens´perceptions				

In tandem with the European Technology Platform, a National Research Strategy has also been formulated for Finland, aimed at creating sufficient competence for the renewal of the Finnish Forest Cluster. The first projects launched under the research strategy are Intelligent and Resource Efficient-Production Technologies, and Biorefinery that Utilises Wood Diversely. Other projects to be implemented in the coming years cover areas such as Smart Wood and Fibre Products, New Products Made from Wood-Based Materials, Customer Solutions of the Future, Sustainable Forest Management, and Increased Value for Wood Biomass.

3.4 Availability of wood raw material

In terms of raw material availability, the Finnish forest industry has the potential to increase its wood raw material consumption, since industrial wood consumption is lower than the annual growth increment of Finland's forest resource (Figure 6).

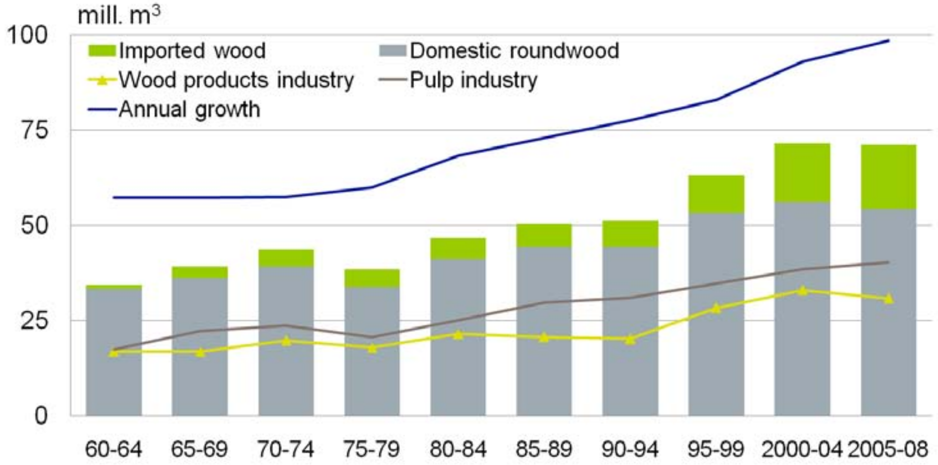

Figure 6. Industrial wood consumption and annual growth (Finnish Forest Industries Federation, Metla).

As a result of the EU's climate control policy, the demand for wood for energy production is increasing. According to its national target, Finland must increase its share of renewable energy sources (RES) from 29% to 38% by 2020. As this increased demand for RES cannot be met by wind energy alone, the forest industry will face increasing competition for wood raw material. Direct use of roundwood for energy production should be avoided. Subsidised tariffs for bioenergy would have a major detrimental impact on the forest industry. The forest industry is currently vulnerable to high raw material costs. Value chain optimisation and added value products, together with a 'more from less' approach are needed.

Increased demand for bioenergy does, however, also provide new business opportunities. Finland's forest industry, with its efficient, extensive, wood procurement infra-structure, covering harvesting, transportation, wood handling facilities and energy systems, could rise to the challenge. Its modern Kraft mills could be converted into biorefineries, where forest biomass including forest residues, urban waste and agricultural crops are fractionated and processed into fibres, energy, fuels and chemicals. This calls for extensive research and development throughout the value chain, from forest to end-use.

3.5 Focus areas for RTD

The goal of transforming the Finnish forest sector from a resource-based industry to an increasingly knowledge-based industry cannot be realised in the short term. The overall efficiency and profitability of existing production processes must first be improved in order to enable the development of new products and processes. Increased process energy and raw material efficiency is the main focus. Efficiency improvement in mechanical pulping and in the use of thermal energy is essential. Air and water recycling must also be increased.

In terms of efficiency improvement, several key focus areas for research and technology development must be pursued, starting with the forest. The diversity of our forest resources must be respected, and we must use our forests in ways that are sustainable. The relationship between wood growth conditions and wood quality is well known, but we lack the means of controlling wood quality, in terms of maximising added value, in subsequent production process.

This calls for both macroscopic and microscopic characterisation methods and detailed application studies with different wood qualities. Ideally, these characterisation methods should be applicable in forest stand conditions, so that logs can be directed to their optimal uses in connection with harvesting. We are not only interested in physical parameters, but also in the chemical composition of wood raw material. Physical parameters are important for mechanical wood processing, whereas knowledge of wood chemical composition is important when extracting chemicals from wood. At the microscopic level, fibre wall thickness and fibre length are key parameters for fibre-based products. For certain new fibre applications, however, we must go even deeper and be able to characterise wood material at its fibrillar- or nano-scale.

Monitoring of wood/fibre quality throughout the value chain may serve as a cornerstone for the development of new eco-efficient and added-value products. In addition, methods and machinery need to be developed that are sustainable, viable and cost-effective for the production, harvesting and transportation of forest biomass, including forest residues.

Fibre or surface properties may be diversified through chemical or biochemical modification to change their chemical behaviour or to improve their compatibility with different coatings or printing inks or polymers, or just to change the charge density or water sorption capacity of the product and develop new applications for paper-like substrates.

Wood fibres are incredibly strong and durable construction units. Finding ways to mimic the natural characteristics of wood fibre could lead to the creation of ultra-strong composite structures for constructive purposes in the form of panels and foams. The use of oil-based polymers in composites can be replaced with biopolymers derived from wood, resulting in composites made from totally renewable materials.

Reinforcing of composites with wood fibres requires, among other things, competence in separating and aligning the fibres in a polymer matrix and in bonding the fibres with the polymer phase. The resulting flow behaviour of the fibre polymer mixture, and the rigidity and porosity of the composite structure, as well as resistance against temperature and moisture changes and moulds, are important process and product properties to control. In this respect, specific customer and consumer needs should serve as the guidelines in for finding the right pieces to each puzzle.

Depending on what kind of product is to be produced, new products may be produced either along a production line by utilising the material flow of a side stream, or by being an essential part of the main stream. Utilisation of bark and black liquor, activated sludge and flue ashes are examples of the former. Extraction of hemicelluloses, resin acids and lipophilic extractives are examples of the latter. From the new product point view, new process integration with existing processes reduces investment and operation costs, but it also increases the complexity of the process. The feasibility and attractiveness of new mill concepts should therefore be analysed using modern modelling and simulation tools. What the plant of the future will look like is a frequently asked question.

New products can also be produced by refining existing products. For example, chemical derivatives can be produced from cellulose. New ideas are, however, needed in this area. Cellulose fibre can also be fractionated into micro fibrils or nanocellulose. Sulphur-free lignin separation using an organosolv type cooking method is one promising area, especially when the fibre properties of the cellulose are not the main objective. Cellulose can also be depolymerised into glucose, which can then be used as a platform for the production of fuels, chemicals and materials.

4. Sustainability in the forest industry

4.1 Life-cycle thinking in the forest industry

Sustainability and life-cycle thinking are essential elements both in environmental management and in European environmental policy. It is one of the key factors in all industrial competitiveness, and increasingly affects business-to-business relationships and consumers' attitudes. Environmental legislation is tightening and setting constraints on all industrial activities.

There are various sustainability tools that are based on life-cycle thinking, such as environmentally oriented product design, life cycle assessment (LCA) and carbon footprint. The question of climate change has dominated the discussion on sustainable development and brought out needs to reduce greenhouse gas emissions by reducing energy use, finding new and renewable energy sources and increasing material efficiency.

As concerns the forest industry, sustainability should be considered more as a possibility than a threat. The industry uses renewable resources and produces recyclable products and bio-energy. Research into the Finnish forest industries has proactively worked with life-cycle assessment right from the 1990s by developing LCA tools and methodology. In recent years the work has been focused on carbon footprint methodology. The main research topics have been benchmarking environmentally friendly technology, raw materials and transport solutions.

4.2 Tools to life-cycle thinking

There are several tools for defining and communicating about sustainable products. Tools that are based on life-cycle thinking give a holistic view of environmental, economic and social issues throughout the product's value chain. Life-cycle assessment and carbon footprint in the context of fibre products will be shortly introduced in the following chapters. Fibre-based packaging and locally applied material/energy solutions are discussed as an example of fibre product and business concepts.

4.2.1 Life-cycle assessment (LCA)

Life-cycle assessment is widely used to evaluate the environmental impacts of products during their life-cycle. LCA has become an important tool for environmental management, and the methodology has gained a strong foothold in European environmental policy. In the forest industry, LCA has been utilised to provide information for strategic decision-making and in benchmarking of products and processes. It is also used to provide information for eco-labelling and product specific eco-profiles.

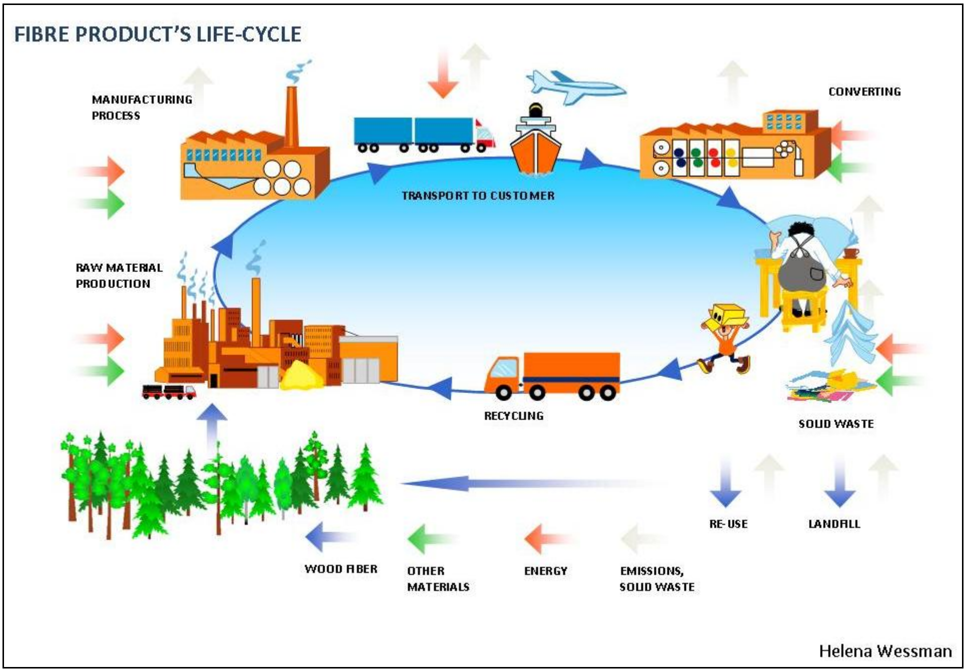

Figure 7. Fibre product's value chain.

LCA is a standardized method (ISO 14040, 14044). The framework for LCA calculation can be defined as cradle to gate, cradle to customer or cradle to grave. Figure 7 above illustrates a cradle to grave assessment for fibre-based product. The value chain begins from forestry (forest growth and harvesting) where wood will be transported to the pulp and/or paper mill. This is followed by the printing and/or converting and finally by the end-use phase including recycling, disposal and landfill. The respective energy production, material and chemical consumption and transport will be connected to the calculation.

Inputs and outputs of the value chain are dependent on the product and the production process. If we are thinking about greenhouse gas emissions, the most significant source of fossil carbon dioxide (CO_2) is external energy production. Depending on the chosen framework, over 75% of the total fossil CO_2 emissions can originate from energy production. Approximately 10–15% of fossil CO_2 comes from transport, and less than 5% from forest management. These figures are highly product, process and country-dependent. Other greenhouse gases like methane (CH_4) and nitrous oxide N_2O originate mainly from landfill, where the total amount might be minor, but their effect on climate change is higher than with CO_2.

NOx and particles belong to air emissions from the energy and process phases especially NOx emissions from the pulping process have been increasing slightly. Sulphur emissions from the pulping process have dramatically decreased over time, but due to the long shipping transports from South America and Asia the share of sulphur emissions has increased. Nutrients, like phosphorous and nitrogen, cause eutrophication and they are discharged from the pulp mill process together with chemical oxygen demand (COD).

4.2.2 Carbon footprint

The carbon footprint is based on a life-cycle approach and value chain thinking. It is a tool that has been widely taken into use in environmental communication, especially in the packaging industry and among retailers. The carbon footprint can be calculated for products, processes, services, companies – in the near future for individual persons as well.

The main guidelines in assessing the carbon footprint are published by the British Standards Institute (PAS 2050) and by the CEPI, the Confederation of the European Paper Industries. The carbon footprint methodology development work in ISO standardization started in early 2009 and is expected to be finished within two years.

In a carbon footprint, both the greenhouse gas emissions from fossil sources and bio-carbon bound in the product are included. The carbon footprint sums up the amount of carbon dioxide (CO_2) and other greenhouse gas emissions (e.g.

methane CH_4 and nitrous oxide N_2O) produced throughout a product's lifecycle. The carbon footprint is usually expressed as carbon dioxide equivalents that have been assessed for different greenhouse gases according to the International Panel of Climate Change (IPCC). For the time being, the carbon sequestration (or change in biogenic carbon balance) is not taken into account, because no justified calculation method is available, and it will require further research to develop one. However, carbon stored in the product is purely based on mass balance and will be calculated for cradle-to-gate calculations to provide additional information.

The questions of carbon balance and the use of renewable energy are strongly linked together. Carbon footprint is a proper tool to specify potential bio-energy sources in the product's value chain, and, it has pointed out, the environmental importance of product's end-use options.

Forest and long-term fibre products are known as a carbon sink. It is most likely that in future, when calculation methodology has developed further, the products will be 'carbon ranked' based on their ability to bind CO_2 over time.

4.3 Sustainable fibre packaging

Packaging – especially food and consumer goods packaging - will be a globally growing product area in the future. Sustainability, quality and functionality will influence consumer purchase decisions, and tailored packaging concepts will make new demands on the packaging industry. Willingness to reduce material consumption together with a changing business environment is changing the role of secondary packaging, which is expected to grow in the future. Material efficiency, energy efficiency, new materials and flexible production lines are, and will be, the key challenges for the industry.

Fibre-based packaging materials have a good opportunity to replace glass and metal in some context. Fibre-based packaging is lighter to transport and can be reused as an energy source in the end-use phase. Combining fibre with other materials will produce new packaging applications and reuse possibilities.

As an example of a packaging industry, Tetra Pak has successfully used EcoDesign and carbon footprint in its environmental communication and highlighted the new packaging solutions. The company's climate programme focuses on three parts:

1. Increase the share of renewable materials and energy
2. Increase the recycling and recovery of packages
3. Increase the efficiency of production and transportation

According to the company's policy, consumers have to be informed of the product carbon footprint in a scientifically sound and comprehensible manner. This will lead to reliable communication at company and product level to foster climate-conscious purchase decisions and use patterns.

4.4 MiniMill – a future business concept?

Big is not necessary beautiful anymore in the European forest industry, nor are wide and fast paper machines – the production concepts have been forced to be re-analyzed in order to find energy savings over the whole value chain.

The so called MiniMill-concept gives a good start to further thinking on sustainable, site-specific production plant in the future. The process, which is claimed to use 50% less energy than in a traditional pulp mill, was tested at a pilot scale in 2007 by Ahlstrom in UK. The actual concept still has problems with the chemical recovery stage, but the principle of this local application gives a fascinating concept for urban areas. A closed-loop concept cuts carbon emissions by benefiting from local raw materials and reduces waste and transporting.

According to the concept, carbon emissions will be reduced by using the local fibre and waste and producing biobased energy as a side-stream to the local grid. Raw material can be waste paper, wood or waste pellets. The general idea of the original MiniMill is not far away from the integrated pulp mill, it is the scale that is different.

4.5 Summary

Environmental discussion is at the moment focussing on material and energy efficiency. The claim is that there should be no waste coming out of the system, only inputs to another system. As concerns the use of forest fibre flow, the trend is to increase the use of wood fibre in bio-energy production. However, bioenergy can be produced in several stages in the fibre product's value chain. In order to clarify the carbon footprint of the whole fibre chain in Finland, there should be a study of the impact of the alternative uses of fibre and production of different fibre-based products.

The future drivers for product sustainability research can be summarized as follows:

- Use of renewable raw materials and bio-energy
- Recyclability and material reuse
- More from less thinking in energy, resources and costs
- Global social acceptance and the need to show product's 'bio-status'.

Benefits of the sustainable processes, products and business concepts for the industry, for society and finally for the consumer, can be described as in Figure 8.

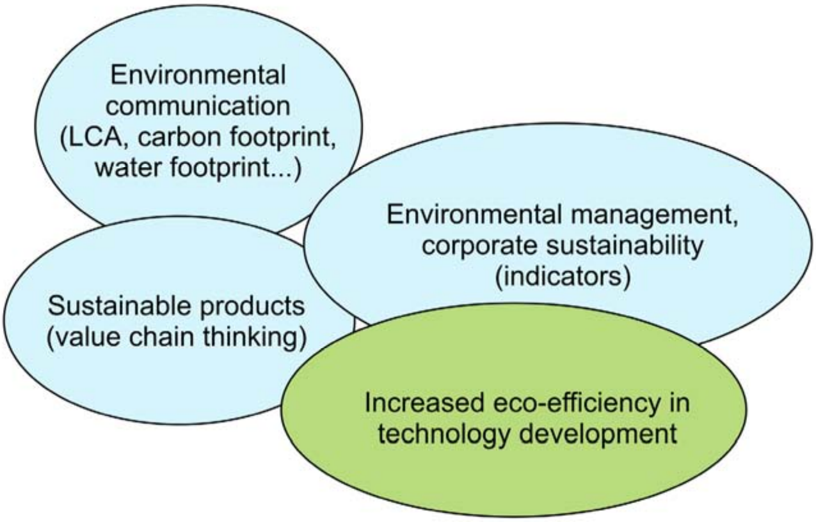

Figure 8. Basic elements for sustainable products, processes and business concepts.

5. Emerging biomaterials

Synthetic polymers are essential in modern world for packaging and appliances. The oil-based materials are debated and several more sustainable solutions are proposed due to concerns on waste management and sustainability. Typical for material science, there are multiple choices for certain application. Biobased polymers are not exception, and there are several different technologies of bio-based polymer. Each of these provides answers for different requirement on product performance and sustainability, e.g. waste managements versus recycling.

Natural fibres and polymers benefit biological processes efficiently and are fully compatible with the ecological system of nature even if their production is consuming natural resources. However, the properties of the materials, like paper, are limited, for example, in wet strength and barrier properties. Modified natural polymers have improved properties, but their production is also more resource-demanding, where industrial bio-chemistry has recently improved.

Biodegradable polymers, like poly lactic acid, provide answers to waste problems compared with synthetic plastics. Synthetic plastic film packaging has been claimed to produce littering and cause severe environmental problem in the oceans. Also polymer composite and thermo-set materials are collecting critics due to a lack of options of recycling.

Bioreplaced biopolymers, materials like green polyethylene, polyamide, polyester and polyurethane, are the same or very similar to their respective synthetic plastics, but produced fully or partially from renewable raw materials. The materials can be re-circulated or reused just like synthetic polymers, but provide biomass energy if combusted or carbon sequestration if dumped in landfill.

5.1 Polymer consumption

World consumption of polymers exceeds 300 million tonnes (year 2006 250 M tonnes) and when including polymers like paint, glues, latexes and synthetic fibre the figures are close to half a billion tonnes per annum. CO_2 emission of polymers is about 3% of global CO_2 emissions (27 Gt/a).

Biodegradables are produced less than 1 million tonnes (Fig. 9), which is mainly modified starch. When comparing that with the annual production of synthetic polymers, it is less than 1 per cent of the whole. By comparison, the annual production of paper is totally 328.1 million tonnes[1].

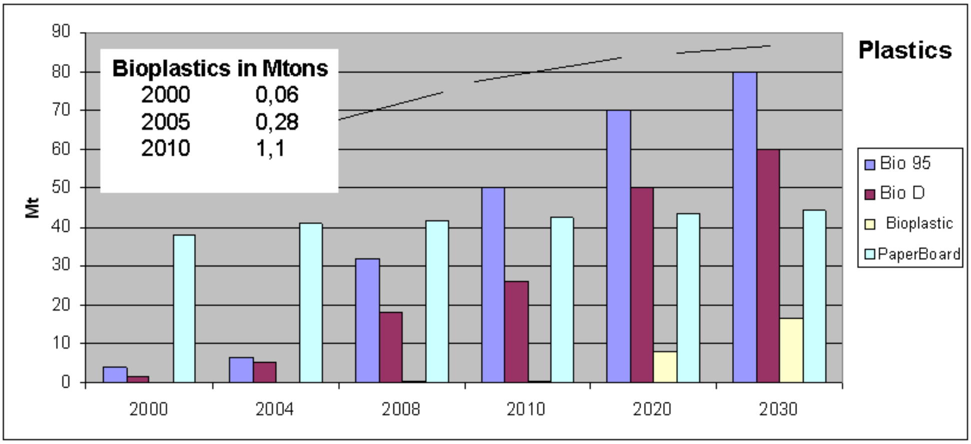

Figure 9. Worldwide manufacturing capacity of bioplastics.

The major biodegradable polymer produced from renewable materials is polylactic acid. Depending on the source, the net effect of carbon foot print reduction is typically less than 20% lower than that of synthetic plastic. Thermoplastic starch (TPS) blends have a substantially reduced carbon footprint compared to plastics such as polyethylene, polypropylene, biodegradable polyester or polylactic acid (PLA) (British Plastics & Rubber, 2008). Criticism has in particular been directed at perto-chemically produced biodegradable polymers.

The conclusion should be that biomass-based plastics do not provide a marked reduction in greenhouse gases as such, but sustainability has to be involved in the usage of the plastics in its applications.

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[1] AFOCEL LEC Contact: P.A. Lacour (paul-antoine.lacour@afocel.fr), UNECE/FAO 16 Sept. 2005.

5.2 Indirect influences of plastics

The main human activities that influence the carbon dioxide emissions are food, habitation and personal transportation (Nissinen and Seppälä, 2008). Plastic has an indirect effect, especially on improving the food delivery chain. Some effect is possible also in the field of light vehicles and energy-efficient houses. Below are the expressed values for the individual’s carbon dioxide emissions in Finland.

Tremendous quantities of food are wasted after production – discarded in processing, transport, supermarkets and kitchens. It is claimed that up to half of food is wasted. In the United States, for instance, as much as 30 percent of food is thrown away. The policy brief, “Saving Water: From Field to Fork – Curbing Losses and Wastage in the Food Chain,” calls on governments to reduce by half, by 2025, the amount of food that is wasted after it is grown, and outlines attainable steps for this to be achieved (Environment News Service, 2009).

If we assume that food wastage could be reduced by a moderate 15%, the net effect would be in the magnitude of utilization of all the polymers and plastics in the world. When we also assume a 5% saving in transportation and housing, the net effect is nearly double. In conclusion, the performance of the polymers and plastics is very important compared to their net carbon foot print.

5.3 Business interest

Wal-Mart is a very controversial player in the world of sustainable packaging. Since the initial announcement of their decision to focus on sustainability and use the Packaging Scorecard to evaluate the environmental footprint of their suppliers, there have been many debates as to what this means for the industry and whether it is helping or hurting the green movement. The major brands say that, while Wal-Mart has a long way to go towards achieving certain environmental standards, they are good at accepting criticism and making changes.

- Arm & Hammer announced the release of new environmentally-friendly cleaning products that are designed to reduce packaging waste
- Coca Cola is aiming to reduce carbon dioxide emissions by reducing the weight of their aluminium cans
- Sainsbury’s, the European retailer, has recently launched compostable packaging for wet products
- Aveda launches the first ever Cap Recycling Programme.

If nothing else, Wal-Mart has triggered many companies to revisit their sustainability goals and make changes now (Intertech Pira 2009).

5.4 Peak oil influence

Peak oil means the season, when the oil production has reached its maximum, but the consumption has not yet been adopted. It has a marked influence on the oil price and its stability. High and especially unstable raw-material prices have a negative impact on the plastics industry.

The oil-based polymers have a marked influence on all oil-based products, including synthetic plastics. Rapid modifications to the business models are difficult, while the production including the petrochemical industry and plastic converting factories is typically very efficiently integrated and capital-intensive. The oil price influence is less pronounced in high quality printing papers than converted papers e.g. laminated boards, where the price levels are declining.

5.5 Biomass in petrochemicals

Increasingly in the first decade of the millennium ideas have been put forward to replace petrochemical platform chemicals with new bio-based chemicals. The cornerstone for the discussion is the DoE report on the 20 top bio-based platform chemicals. The ideas were readily accepted in the research community. However, it has quickly been shown, that the platforms are more difficult to achieve than expected.

Biofuels and components have opened up new way of thinking. Recently there has been a development in routes for biomass to be utilized in the synthetic polymer processes for ethylene[2], propylene and partially bio-based polyethyleneterefta-late[3]. The result is in the performance of comparable products with the existing ones and carbon footprints, which in the best case are markedly favourable.

5.6 Raw-material base

Raw-material base has a marked influence on the bio-based polymers' sustainability. Agricultural products are at a disadvantage because of nitrogen compounds

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[2] Brazchem and Dow projects on green PE based on sugar cane ethanol.

[3] duPond Sorona and Coca-Cola PlantBottle.

from fertilizers. Apart from that, the new fields from the rain forest will lead to extensive methane emissions. Finally, the water foot print for planted areas is marked. Traditional examples of such products are cotton, sugar and corn.

Forest biomass from audited forestry does not have that complication, and the biomass can be considered really carbon sequestering systems for carbon dioxide. Still it is vitally important to evaluate that case by case, while even the forestry may become net greenhouse gas source.

Simplest route to sustainable carbon is bio-refine sidestreams and especially biomass waste. Examples of that are agricultural production residuals such as straws and husk. Another possibility is backing and brewing residuals. Actual food, like starch, benefiting in biomaterial production has increasing ethical issues. The residuals of forest industry, such as saw dust, lignin and recycled or rejected pulp are also under discussion a great deal.

5.7 New era of bioreplacement

All the sidestreams and waste fractions are under intensive research for biofuel components. The sidestreams and residuals of the bio-fuel production are increasing. Just as oil refining has resulted in the petro-chemical industry, the emerging biofuel industry will analogically lead to the creation of bio-based chemical industries.

New development is leading towards synthetic polymers produced increasingly from bio-based raw materials. The bioreplaced polymers have a high performance, which is combined with renewable raw materials. In well optimized conditions it is possible to produce plastic products with an excellent life cycle analysis.

5.8 Example

In the blown moulded products in May 2009 the Coca-Cola Company unveiled a new plastic bottle made partially from plants. The “PlantBottle™” is fully recyclable, has a lower reliance on a non-renewable resource, and reduces carbon emissions compared with petroleum-based PET plastic bottles. Traditional PET bottles are made from petroleum, a non-renewable resource. The new bottle is made from a blend of petroleum-based materials and up to 30 percent plant-based materials. The aim is eventually to introduce bottles made with materials that are 100 percent recyclable and renewable.

6. Sustainable packaging

The packaging industry has seen a growing trend in recent years towards the use of plastics, and this has affected sales of metals, glass, paper and board packaging. More recently, the growing concern for the environment has presented opportunities and challenges to all parts of the industry. Paper and board packaging is well positioned to withstand these pressures, and indeed benefit from them. At the same time, changes in any part of the economy, from the price of oil to the opening up of the Chinese market, affects the opportunities available.

6.1 Trends in packaging

Packaging is closely linked to consumer preferences. Evaluation of various trends and transforming them into functional applications helps to sell products. However, package design is also where the adoption of a trend can get complicated. Timing is essential; too early and the target consumer is missed and too late the novelty is lost. Visual trends are pronounced because of the product's brand and its promise, but also beyond that.

In packaging, trends tend to develop slowly, because there are longer lead times in product development cycles, and emerging trends are difficult to select, because there are many in the different stages of a trend's life cycle. Early adopters and influencers come from small start-up brands that have less at risk, while big brands adopt them carefully. When we see large brands begin to use specific trends, we know it is a trend that is toward the top of the bell curve.

Consumers are at different stages of acceptance, which makes it essential to learn the buying habits of specific target audiences. Package designers need to know how far the brand can be stretched without breaking the comfort zones but still motivating a purchase.

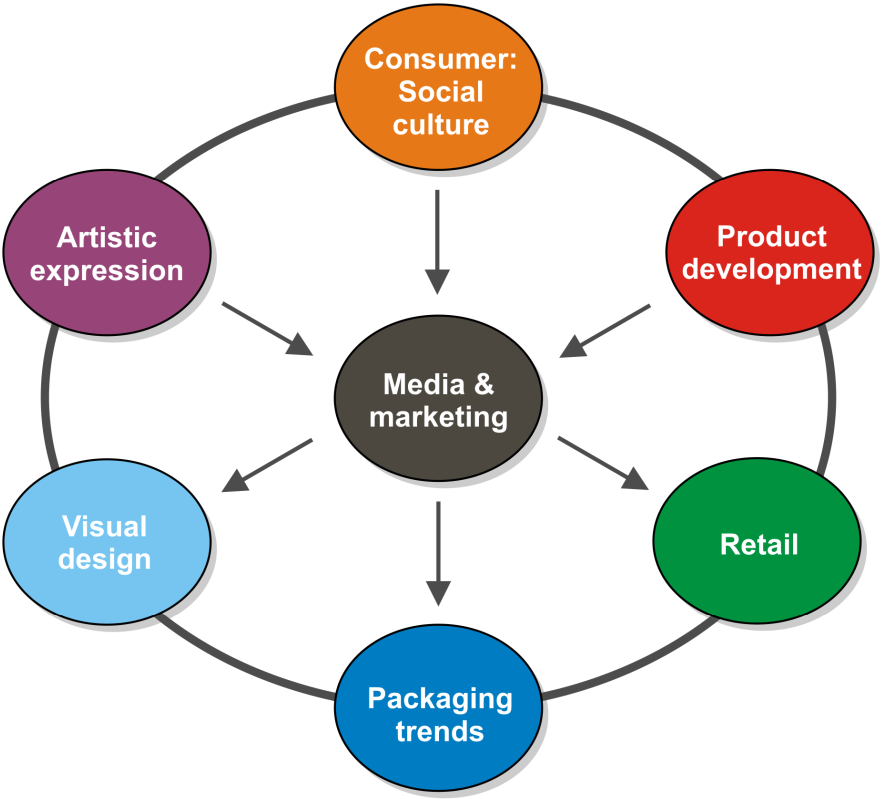

Figure 10. Trend development in packaging (Dupuis, 2007).

There are some 10 trends influencing a larger set of strategic issues that grow out of a variety of consumer, artistic, business and media trends, and thus shape packaging on a global scale (Figure 10). According to Amcor there are three global consumer megatrends that impact the food and beverage industry today: convenience, health and indulgence.

Convenience: Over the past two decades we have seen the global emergence of a convenience-oriented society. Changes in family structure, a greater number of women in the workforce, longer working hours and an increase in commuting time drive this. A greater proportion of adult consumers are now living on their own, sharing with friends, or living with a partner and without children. Also the ageing global population, the proportion of people aged 60 years and over, is growing faster than any other age group and is expected to increase by 694 million or 223%.

Health and Nutrition: The consumer focus on health and nutrition is driving changes in packaging that provide more detailed product information, hygiene standards, tamper-proof seals, a longer life for fresh produce, smaller-sized portions, and the use of colours and materials that emphasise ‘natural and healthy’.

Indulgence: The consumer focus on health and nutrition has not reduced the demand for indulgent and premium products, as well as ethnic and exotic meals. Indulgence remains a key role for food and drink, whether for relaxation and reward, or as part of a celebration.

6.2 Sustainability in packaging

Environmental concerns have given life to the sustainability and green movements, which hopefully represent more than simple trends and will mean real behavioural changes affecting all aspects of packaging. Consumers are more aware of materials and the waste that packaging creates. Wal-Mart has gotten into the game, establishing a scorecard rating system that assigns each product a number evaluating its effect on the environment. More people understand the idea of a carbon footprint and are questioning how many resources it takes to bring something to market.

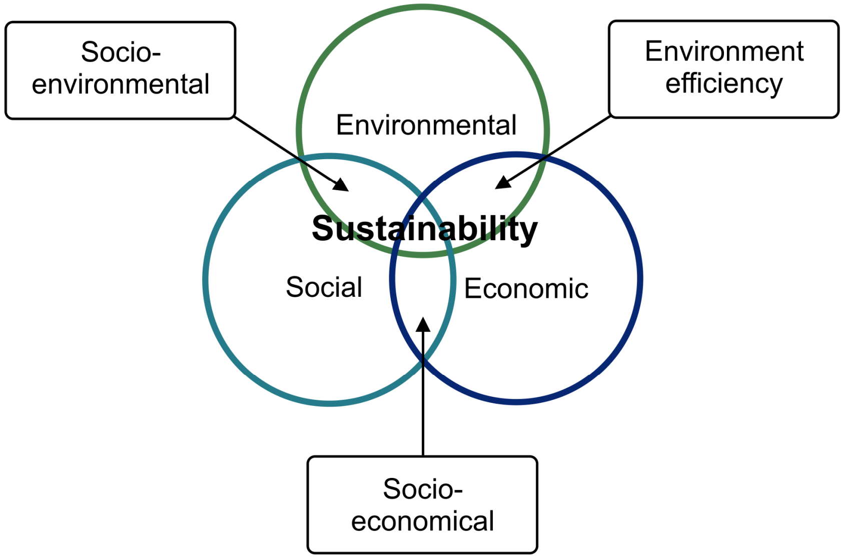

Figure 11. Three spheres of sustainability (figure modified from Rodriguez et al., 2002).

Understanding of the interaction of the environmental, social and economic factors will lead to practical solutions on sustainability (Figure 11). Solution is not solely in the applying bio-based raw materials to produce biodegradable polymers. It is essential to consider especially in the packaging applications the net value and environmental impact of the context when considering the packaging material and application. Especially vital is the issue of biodegradability, while the primer target for the packaging materials is recycling.

It seems evident, that materials of today will remain because of performance, and the impact of fibre packaging may increase if the life cycle assessment can be influenced efficiently. As well it seems possible, that bioreplaced polymers may become increasingly combined with of the demands on packaging performance. That is partially because of the instability in oil prices but also demands for biobased materials.

6.3 Barrier materials

With almost 90% of these products consumed by packaging, most of which is for food, the market for functional and barrier coatings is linked not just with the overall packaging market, but with the global economy as a whole.

The global market for functional and barrier coatings for paper and board was valued at $3,778 million in 2007, growing at 3.1% per year. Growth is expected to have fallen in all world regions in late 2008. Growth will be negative in many parts of the developed world in 2009 and into 2010, returning to positive growth towards the end of that year. In the emerging economies of central and Eastern Europe and Asia, recent exceptional growth rates will fall in 2009 and 2010, but growth will climb again in late 2010 to 2014. This growth will not reach the same level that has been seen in recent years. Growth in these emerging economies will lift the global market for functional and barrier coatings, to permit a modest compound annual growth rate (CAGR) of 2.7% to 2014, when the market will be worth of $4,552 million.

The main products used as functional or barrier coatings on paper and board are extrusion polymers, which account for 46% of the market; aluminium foil makes up a further 18% of the market. The main market for these materials is liquid packaging board (LPB), which is used for fresh and long-life liquid products such as dairy, fruit and vegetable juices, soups, etc. Fresh products do not need the same degree of barrier protection as long-life products. This means that the many grades of LPB used for this application comprise about 75–80% paperboard and 20–25% polyethylene (PE), coated on both sides of the board.

6.4 Disposable Serviceware and Packaging

In Europe most of the naturally reinforced plastic composite applications are related to the building and automotive sectors. Packaging is not mentioned in the market overview – it is not an important sector for naturally-reinforced plastic composites at the moment.

The market volume of foodservice disposable packaging was $ 30 billion worldwide (2006). Foodservice disposables are expected to have a growth rate of about 24% CAGR. The potential for WPCs is 75% of disposable packaging. If we assume that 30% of that material could be replaced by WPCs, then in 2014 the potential for WPCs is $ 40 billion in worldwide.

6.5 Technical targets

For achieving the requirements of the market place there are several technologies and solutions. VTT has turned the megatrends into technical topics:

- **Interactivity** increases information available in packages for marketing purposes and logistics efficiency
- **Safety** reduces risks assessment of piracy, terrorism and pandemics
- **Sustainability** is enabled with materials with fewer natural resources consumed, a reduction in oil dependency, and fewer losses in the food chain.

In the interactivity VTT has developed printable electronics. Bioactive paper is one asset in the field of the safety. Sustainability combines several technologies and materials. Especially two entities seem to be marked in achieving the targets with non-food biomass, namely:

- **Low resourced production**, which targets reduced energy and raw-water consumption especially in fibre material production. However, that is not sufficient, and marked improvements in the material properties, such as barrier and strength are requested.

- **Biomass-based raw materials** are both an issue of availability of convenient biomass fractions. As important is the conversion efficiency through understanding the biomass.

7. Energy efficient building

Upcoming regulations:

- 2010: energy consumption of residence buildings is 30–40% lower than that of today (national level)
- The EU's goal by 2015: energy consumption of newly built residential houses only 25% from the existing level. This means that the need for heating energy is -70% compared to regulations in 2008.

The passive energy house is a building where the inside temperature is on a comfortable level throughout the year without any heating or cooling system connected. In the following table (Table 4) there are some numerical data for different geographical locations in Europe.

Table 4. Characteristics of outside wall.

City	**According to the building regulations**		**Passive house**	
	U-value W/m^{2}K	Insulation mm 1)	U-value W/m^{2}K	Insulation mm 1)
Rovaniemi	0.25	165	0.06 2)	600
Helsinki	0.25	165	0.09 3)	400
Berlin	0.30	125	0.15 2)	250
Madrid	0.66	55	0.34 2)	110

1) Heat conductivity 0.035 W/mK; 2) Passivhaus Institut, Darmstadt: Heating demand 15 kWh/m^2 ;
3) VTT: Heating demand 20 kWh/m^2.

The heating energy demand for passive houses is 30 kWh/m in Northern Finland, 25 kWh/m in Central Finland and 20 kWh/m in Southern costal area. Compared with Finnish figures, the corresponding energy demand values for passive house concept in other part of Europe are lower. For heating energy the figures are about 15 kWh/m^2 for Eastern and Southern Europe.

To meet the insulation requirements for energy-efficient house building requirements in Finland the following thickness of different insulation materials are required for outside walls:

- 200 mm polyurethane
- 250 mm polystyrene
- 300 mm rock/ glass wool
- 600 mm saw dust/ plane shavings
- 800 mm light concrete
- 900 mm solid wood.

For passive houses the insulation thicknesses are even greater. Figure 12 gives an example of an energy-efficient residential house in Pietarsaari. Also some figures on insulation and energy consumption are given in the Tables 5 and 6.

Figure 12. Outside overview picture of the finished house.

Table 5. U-values of the example house in comparison with a standard house in 2008.

	Pietarsaari 1993	**Standard house in 2008**
Component	**U-value [W / m^{2}K]**	
Exterior wall	0.12	0.24
Roof	0.09	0.15
Floor	0.1	0.19
Exterior door	0.4	1.4
Window	0.7	1.4

Table 6. Breakdown of energy consumption.

Category	**Energy demand (kWh/m^2)**	**Energy bought (kWh/m^2)**
Heating	31	13
Hot water	34	13
Household machinery	16	11
Household electricity	17	11
Total	98	48

When all building types are concerned, about 40% of the exterior walls are made of concrete, 40% are made of wood and 15% of steel. In non-residential house building, concrete had a 45% share, wood about 30% and 25%.

Wood dominates in the small residential house building sector. About 85% of all the frames are made of wood, 10 % from concrete and the rest are made of brick.

Wood frame still dominates the small residential house building. However, the upcoming energy efficiency regulations can augment the role of other competing materials, such as concrete, light concrete blocks and bricks. The demand for better U-values clearly leads to more airtight and thicker wall structures, especially when ordinary glass/rock wool insulation materials are used. These demands can be better fulfilled by using polyfoam insulators like polyurethane, which could be even partially or fully biobased. This type of solution favours non-wood structures. If wood and wood-based composite materials are required to maintain their market share, totally new concepts need to be developed for tomorrow's market.

8. Biocomposites

Biocomposites are composite materials comprising one or more phase(s) derived from a biological origin. In terms of reinforcement, this could include plant fibres such as cotton, flax, hemp and the like, or fibres from recycled wood or waste paper, or even by-products from food crops. Regenerated cellulose fibres (viscose/rayon) are also included in this definition, since ultimately they too come from a renewable resource, as are natural 'nanofibrils' of cellulose and chitin (Fowler et al. 2006). Matrices may be polymers, ideally derived from renewable resources such as different polysaccharides (e.g. starch, cellulose), made by bacterial growth (polyhydroxyalkaonates), polymerised from vegetable oils, tall oils or monomers such as lactic acid (PLA). Matrices can be also biodegradable polymers from synthetic, fossil-derived monomers (polycaprolactone, polyvinylalcohol). In some cases the definition of biocomposite may also contain either 'virgin' or recycled thermoplastics, such as polyethylene, polypropylene, polystyrene and polyvinyl chloride, or virgin thermosets, such as unsaturated polyesters, phenol formaldehyde, isocyanates and epoxies which are more often called as WPCs (wood plastic composites). Here this terminology for biocomposites contains only biopolymers and fibres from renewable origin.

Biocomposites offer a significant non-food market for crop-derived and lignocellulosic fibres and resins. The main markets for biocomposites are in the construction (Riedel and Nickel, 1999) and automotive sectors, whilst furniture (Hautala et al. 2004), packaging and consumer product sectors also offer good product possibilities, but the real applications have still been limited. New environmental regulations such as End of Life Vehicle (ELV) and the Waste Electrical and Electronic Equipment Directive (WEEE) and societal concerns have triggered the search for new materials, products and processes that are compatible with the environment. The main motivation for developing biocomposites is to create a new generation of fibre-reinforced plastics competitive with glass-fibre reinforced composites, but which are environmentally compatible in terms of production, use and removal. The replacement for glass-fibre becomes more acute when product reuse or recycling at the end of life becomes more the norm through environmental legislation. Natural fibres are biodegradable, and renewable resource-based bioplastics can be designed to be either biodegradable or not, according to the specific demands of a given application (Mohanty et al. 2005).

The new biocomposite applications will be assessed through life cycle assessment (LCA) compared to existing material. Natural fibres are usually 'greener' and the greatest impact on environment comes from the polymer matrix, which is proved to be more environmentally safe (Garrain et al., 2007).

The techniques used to manufacture biocomposites are based largely on existing techniques for processing plastics or composite materials, which makes biocomposites quite easily applicable to the real products. These techniques include press moulding, hand lay-up, filament winding, pultrusion, extrusion, injection moulding, compression moulding, resin transfer moulding and sheet moulding compounding. The majority of current biocomposite materials are based on thermoplastic polymers, mainly due to high curing temperatures and the still limited number of thermosetting biopolymers. Even though the normal thermoplastic processing methods are applicable to biopolymers, the use of fibrous, quite thermally sensitive polysaccharide containing reinforcements, is causing some restrictions to the processing, and some modifications to the normal processes may be needed e.g. in minimising the effect of shear forces and temperature decrease.

New opportunities and applications for biocomposites will be likely to arise e.g. in the building sector which is responsible for producing huge volumes of waste, which could be utilized. There is significant potential in the replacement of preservative-treated wood and new, 'environmentally friendly' materials are needed for off-site construction. Fibre from products such as MDF (medium density fibreboard), chipboard or other waste streams from the pulp and paper industry is used to manufacture a range of cost-effective and environmentally effective materials and products (Fowler et al. 2006).

There is an immerse opportunity in developing new biobased products, but the real challenge is to design sustainable biobased products through innovative ideas. Green materials are the way to the future. Two different approaches for biocomposites and bioplastics are presented here. One is for biocomposites for automotives and the other is thin walled injection-moulded products of bioplastics or biocomposites. Those are different approaches, but reveal some of the problems linked to biocomposites.

8.1 Biocomposites in automobiles

The automotive industry, as for vehicle producers in general, typically has three main technical concerns: production costs, safety and lately increasingly fuel economy. Among many other technologies, material science has a marked contribution in all the three main issues.

8.1.1 Business

The automotive industry is managing the erratic fluctuations of price of fossil fuel and raw materials. This leads certain manufactures and their subcontractors to select key renewable and abundant resources considering also regional issues.

The use of biobased polymers (lignin, polyols, furans) and natural fibre composites is increasing. For example, Toyota Motor Corporation announced (Bio-Japan 2008 conference) that it plans to replace 20% (in mass) of plastics with bioplastics used for its automobiles by 2015. With a company-wide goal to reduce CO_2 emissions, the world's leading company aims to gradually replace materials including polyvinyl chloride (PVC), polyurethane (PU) and acrylonitrile butadiene styrene (ABS) with polypropylene (PP) made from renewable sources in its interior parts. Ford say in their press release that they are moving towards more eco-friendly products utilising more biobased and recycled materials in their cars (http://media.ford.com/article_display.cfm?article_id=30398). Mazda claims the development of bioplastics from cellulose will be employed in their cars in 2013 and they are already using PLA-based textiles in car interiors. The joint research of Mitsubishi Motors Corp. with Aichi Industrial Technology Institute has developed a biocomposites of polybutylene succinate (PBS) and bamboo fibre for car interiors. Fiat is also strongly committed – as stated in their sustainability report – to reduce the environmental impact of transportation by reducing vehicle weight and CO_2 emissions (Biopolymer car hand-out data from CRF (Centro Ricerce Fiat).

Development and implementation of proprietary materials takes place in vertically integrated collaborative projects, where universities still have a marked contribution. However, implementation requires close communication with customers, and that is why the whole production chain is involved.

8.1.2 Composite technology

In composites for cars and off-road heavy duty vehicles the light weight compared with the impact and torsion resistance, connectivity/joining and structural design together with fire resistance are the main issues. In transportable containers and tanks the light weight, high strength and properties like insulation or sensing functions are the main focus areas. Each application has its key properties, useful technologies and proof of principle products.

Automotive industry is one of the most important industry areas for natural fibre and biocomposite utilisation. A new passenger car can contain up to 50 different parts made from these materials. Typical parts are e.g. in-door inserts, roof covers, headliners, trunkliners, spare wheel covers, arm rests, seat back covers or in console and there are more to come with the increased material properties and availability of materials. The main techniques to process these are press moulding and injection moulding.

The new technologies are required to produce light high-performance and sustainable composite materials with high added value properties for the automotive and off road heavy-duty vehicle sectors aim of reducing fuel consumption and CO_2 emissions. A weight saving of only 1 kg/a car equals about 1 Mton CO_2 saved, considering that annually over 60 million cars are sold globally (http://ec.europa.eu/environment/etap/index_en.html).

Composite modelling, property simulation and structure design, including woven fibres and foamed inner parts in composites, are essential when obtaining the lightest possible structures with high performance. Matrix selection will include environmentally efficient biobased matrices, like furan, lignin and vegetable oil-derived thermosetting resins and thermoplastic biopolymers. Also more conventional matrices (epoxy, polyolefins, which may in future be bioreplaced,) with high mechanical and physical properties, especially crash absorption and wear resistance, will be used as a reference with new hybrid fibre combinations.

Advanced natural fibre modifications and treatments, the use of nano-scale additives and fibres and polymer matrix modification including the use of biobased binders, together with structure design and tailored processing technology, make it possible to develop light high-performance, ecoefficient composites. Natural fibres from renewable resources are largely CO_2-neutral and offer a sustainable approach. Their production requires limited energy and due to their even lower weight than e.g. glass fibres, very energy-efficient materials can be constructed.

To improve the properties of natural fibre-based composites, there are several modification possibilities within the capabilities. The principle routes are fibre modification or matrix modification combined with the addition of other ingredients such as nanoparticles or nanofibres. The novel approach in this project is to create hybrid composites of nanoparticles/nanofibres, recycled carbon fibres and natural fibres (like flax and hemp or wood). For this, a range of partners are gathered together from the natural fibre community and composite manufacturers already utilising nanoparticles.

New hybrid composite materials may also offer other benefits. It is expected that, by adding long natural fibres and recycled carbon fibres to nanomaterials, the creep and impact resistance of the composites can be improved substantially. By selecting functional nanoparticles, some additional functionalities can be added to the composites (e.g. fire resistance, electrical properties, resistance against biological attack or UVradiation) besides fibre-matrix coupling.

8.1.3 Processing

One of the most important stages during processing is likely to be compounding of the fibres, nanomaterials and matrix polymer together. The main problems to overcome are in feeding and dosing of fibrous materials and nanosized material. Innovative pre-blending technologies are needed in order to overcome feeding and dosing problems as well as reducing health and safety issues. Furthermore, the dispersion, wetting and coupling of modified fibre surfaces with different matrix systems with nanoscale materials is recognized as a critical factor. Regardless of the manufacturing method, this factor is one of the most crucial in the development of the composite’s strength and toughness. To achieve these goals for nanoscale materials requires highly skilled expertise in selecting and using the process equipment for a given manufacturing technique.

Through process and polymer development we expect to reduce the emissions during compounding by 80%. Short and long fibres are typically processed by extrusion or injection moulding. Continuous fibre composites are processed by such processes as Resin Transfer Moulding (RTM) and pultrusion, which will require the nanoparticles to be dispersed into the fibre or polymer beforehand. The processing techniques traditionally used traditionally with glass fibres reinforcements are going to be used for natural fibres. Consequently, a lack of knowledge, e.g. referring to the selection of process variables, still exists. To utilize the mechanical capabilities of natural reinforced composites in a more optimized way, a well-adapted process technology is required. Particularly with respect to homogeneity and thermal stability, the properties of glass fibres and natural fibres differ significantly. Parameters for a new production process require consideration of both ensuring general processability and avoiding thermal damage to the fibre component.

The selection of the resin matrix is limited to polymers with low melt-points. This is due to the fact that thermal degradation of natural fibres begins as low as 160°C, resulting in a decomposition of waxes. When temperatures are above 230°C, cellulose decomposes quickly. This obviously leads to a reduction in fibre strength, inevitably affecting the mechanical properties of the later composite. However, to ensure sufficient flow capabilities of the binder component throughout the moulding process, temperatures of at least the stated magnitude are required. Keys to minimizing this degradation include lower process temperatures and low residence times.

8.1.4 Local requirements in Scandinavia

In Scandinavia there are fewer cars produced and more other vehicles. This leads to two main visions in local development. First, it is essential to develop value added sourcing of biomaterials for biopolymers. Research require marked international co-operation. Based on the research, it is possible to develop manufacturing methods, which are suitable for short series manufacturing typical for other than automotive composites.

9. Thin walled injection-moulded bioplastics

In all injection moulding products the overall trend is towards thinner wall structures without losing properties like strength. Thinner wall structures are bringing weight savings, smaller size, gains in material costs and process time with faster processing cycles. New product segments areas are adapting this manufacture method, which is energy saving and helps to replace products prepared previously from wood or metals. Thin wall injection moulding products are e.g. in following product segments:

- laboratory and medical devices (pipettes and their tips, syringes, storage boxes, parts in medical electronic devices etc.)
- portable electronics (casings and inner parts etc.)
- computers
- caps and closures
- disposable foodware and houseware
- toys and games
- car parts (holdings, panels, casings, switches, buttons etc.)
- personal care (tooth brushe, razors, lipstick covers, powder cases etc.).

The biggest market increase is predicted for caps and closures as well as personal care products.

9.1 Thin walled injection moulding processing

The processing of thin wall injection moulding products is much more challenging than traditional injection moulding, due to the higher pressures, stricter process control, new gas ventilation and mould design, higher dimensional accuracy demands and better self-cleaning properties needed for material flow. Thin wall products typically have wall thickness below 2 mm and below 1.2 mm in more demanding applications from a processing point of view (Weiss, 2009). Those demanding process conditions set special requirements for polymer viscosity, thermal behaviour and crystallization properties. Thin wall structures and high process pressures limit the use of highly filled and especially fibre-filled materials. Reinforcing/filler particles have to follow the material flow of quite low viscosity polymers. In that case nanoparticles could be the only potential fillers/fibres for these applications.

Polymers currently used in thin wall applications are liquid crystal polymers, polyamides and thermoplastic polyesters. Polymers used in injection moulding generally are PP, ABS, Nylon, HDPE, PC, Acetal, PS, LDPE, thermoplastic polyester, PVC and high temperature thermoplastic polymers. If we think of which biobased polymers currently on the market could replace those very good, but oil-based polymers, we have to think first of the drivers, those direct research and in some time-scale also industry to use materials based on renewable resources. The main drivers are:

- More polymers from renewable resources (increased production capacity), more competition between producers, **lower price**
- **Increasing consumer interest**
- **Advertising and environment friendliness** (good image) increase interest and demand
- New environmental **laws and regulations**
- **New polymer grades** with tailored and enhanced properties
- In some aspects **biodegradability** is a property in demand (disposable tableware, pipette tips…)
- Also **non-biodegradable** products from renewable raw-materials
- **Closed CO_2-cycle**
- Increased industrial help and interest: e.g. The New Bioplastics Recycling Consortium is established in the USA to develop economical and efficient recycling systems for biopolymers and markets for recycled biopolymers in addition to make them into economical and sustainable development packaging materials. (http://imm.plasticstoday.com/imm/articles/consortium-formed-expand-recycling-options-bioplastics; Press release from Primowater corp, August 2008)

- Depending on the amount of oil-based additives, the energy saving of e.g. starch-based plastics is 12–40 GJ/t plastics and saving in emissions are 0.8-3.2 tonnes CO_2 compared to PE. (Patel 2002).

The main restriction in using materials based on renewable resources is currently their low production capacity and polymer availability. New polymers are being developed, some are in the pilot-phase and only a few are available on an industrial scale (PCL, CA, CAB, PVAL, PLA, cellulose regenerates).

Biopolymers suitable for injection moulding and possibly some grades also for thin wall injection moulding are:

Polylactide
Producers : NatureWorks (USA), (Tate&Lyle pilot, England))

Polyhydroxybutyrate PHB and other like PHBV
Producers: P&G (Nodax, USA), Telles (Mirel, USA), Biomer (P226 etc., Germany), Tianan (Enmat, Germany)

Polybutadiene succinates, -adiapates and terephtalates PBAT, PBS (Biodegradable partly oil-based)
Producers: BASF (Ecoflex and Ecovio, Germany), Mitsubishi (Japan)

Polycaprolactone PCL
Producers: Perstorp (CAPA), Union Carbide (TONE)

Polyamide PA (castor oil-based)
Producers: Arkema (PA11, France)

Above-mentioned polymers as base raw material is used in following blend products:

- Mater-bi and Origo-bi produced by Novamont (Italy)
- Bioplast 2189 produced by Stanelco (Germany)
- Bio-Flex produced by FKur (Germany)
- Sorona polymer (PPT)-based on bio-PDO-technology produced by DuPont (USA).

9.2 Market potential

The market potential for thin wall biobased injection moulding materials could not be found as such in any database, so an estimate has had to be made based on biopolymer information, plastic use injection moulding and the aforementioned replaceability estimates of engineering plastics. The world consumption of plastics is estimated to be 255 billion kg in 2010. Thermoplastic consumer products represent about 2.04 billion kg at the same time.

Plastics consumption in injection moulding products is 7.23 billion kg and in consumers products will be 2.07 billion kg in 2010 (Maniscalco, 2007). Zhao (2009) has estimated a yearly increase of 2.8% in 2009 and a market value of 14.7 billion dollars. It is still unclear how big an amount is in thin wall products, but their proportion is increasing faster than other plastics.

The biggest markets for biodegradable and natural polymers are in films, bottles and food packaging, where the main processing methods are extrusion or blow moulding. The consumption of biodegradable plastics in the USA is about 0.1% of total world plastic use and the USA uses about 40% of all the plastics in the world. So bioplastics currently represent about 0.2% of the world plastics consumption. However, it is estimated that in 2010 the bioplastics market share will be 1.5–4.8%, with a production capacity of 140,000 tonnes and a 20% yearly increase, which further favours increased production capacity and the demand for bioplastics and products based on those. By 2013 the market share is estimated to be € 700 million (Michael, 2009; Press release, 2008). If we estimate **the market share for thin wall biobased polymers applications at 2013, it is probably about € 100-300 million**.

Companies processing with injection moulding in Finland are somewhere between 50 and 100. According to AMI Plastics (Applied Information Ltd.) there are about 13,000 injection moulding companies. All of those are mainly SME companies making tailored production series for different customers.

9.3 Conclusions

Products that can be produced by injection moulding are huge and widely diverse. Injection moulding processing companies are mainly small SME companies with flexible production lines. They are able to change easily from one product to another. Also their raw material selection can easily be changed so that they can adapt biopolymers quite easily to their portfolio without huge product development efforts, if the polymer properties are suitable. Transfer towards thinner walls, lower weight and smaller (compare electronics, phones) and less raw material consuming products is requiring new process/innovations to equipment, moulds and polymer grades. Products/applications currently made from wood or metals can be replaced by using better (bio)polymer grades, due to lower processing costs and fewer unit operations. There is no clear picture how big a share materials from renewable resources can have in thin wall injection moulding applications. The present estimate is about € 100–300 million in 2013 in Europe, which can still be too low an estimate. Markets can be bigger than estimated due to biopolymer image increases, availability and better polymer grades.

The use of biomass-based fillers and fibre reinforcement in thin wall injection moulding products is limited mainly to nanosized fibres and particles and their property-enhancing characteristics. The biggest problem in filler use comes mainly from very demanding processing conditions.

Research needs related to thin wall injection-moulding products and biomaterials are in the following areas:

- **Biopolymer development for highly demanding process conditions**
- **Nanosized fibres and fillers effect in biopolymers** (including nanosized cellulose)
- Coupling agents for nanoparticles, UV-additives, hydrophobisation and functionalities
- Increase of heat resistance and impact strength in biopolymers
- Suitability of biopolymers to different applications
- **Application related biodegradability and fungal growth research**
- **Process development**

10. Sidestreams available

Biorefinery concepts improve chemical pulping through sidestream converting. High-energy impact fractions are thus in demand in the bio-fuel business. However, components with higher oxygen may be more useful in chemical and polymer applications.

For example, STFI in Sweden has developed a Lignoboost technology that improves chemical pulping efficiency through fractionation of sulphonate lignin, a process that promises wide application. While Wagenigen University in the Netherlands, is researching lignin for phenol resin, Borregaard in Norway already has several lignin chemicals on the market. VTT is researching lignin cracking, enzymatic oxidation, pyrolyse and gasification. Still, the quality of industrially available lignin is poor for use in polymer materials, and cracking produces a wide variety of products, both of which tend to lead dominantly to energy use of the lignin.

The forestry industry also recovers several minor biocomponents, such as terpentines and methanol. Tall oil has traditionally been used in several products e.g. in the paint, ink, and techno-chemical industries. Development is ongoing, as a tall oil binder developed by VTT demonstrates. Meanwhile tall oil producers are involved with projects such as SunPine's (Sweden) work with tall oil diesel. Bark-based suberin is also available and is being studied by e.g. Minho University in Portugal, though still with limited applications.

Hemicellulose is not industrially available, apart from what is extracted in viscose production and used as a protective chemical in chemical pulping. When hemicellulose is decomposed, hydroxyl acids are formed, a process now being studied by Forestcluster Ltd in Finland. Both monomers, such as glycolic acid, lactic acid and 2-hydroxybutanoic acid, and bioactive components such as glycoisosaccharinic acid and 2,5-dihydroxy-pentanoic acid are arousing interest and offer new opportunities.

11. Emerging technologies

11.1 Chemical engineering

Chemical engineering is the branch of engineering that deals with the application of physical science (e.g. chemistry and physics), and life sciences (e.g. biology, microbiology and biochemistry) with mathematics, to the process of converting raw materials or chemicals into more useful or valuable forms. In addition to producing useful materials, modern chemical engineering is also concerned with pioneering valuable new materials and techniques.

The modern discipline of chemical engineering encompasses much more than just process engineering. Chemical engineers are now engaged in the development and production of a diverse range of products, as well as in commodity and specialty chemicals. These products include high performance materials needed for aerospace, automotive, biomedical, electronic, environmental, space and military applications.

11.1.1 Fractionation

Utilizing forest and agrobased lignocellulose as a raw material in novel lignin and hemicellulose-based biorefineries requires research in several areas: i) improved harvesting and stabilization methods for biomass (esp. straw), ii) tailored fractionation/pre-treatment methods that render the biomass components available for enzymatic, microbial, thermal and/or chemical up-grading, iii) efficient ways to use the five-carbon sugars in agrobiomass or hardwoods, iv) finding added value applications for lignin and hemicellulose-based polymers (as well as proteins and the natural polyesters), v) efficient exploitation of cellulosic fraction as carbon source for bioethanol or other sugar platform products, vi) improved gasification with less char and a higher energy content, and vii) possibility to integrate low-value sidestreams into gas, power and heat networks.

The bulk of the lignin available industrially today originates from kraft pulping. Kraft lignin is, however, highly modified, and thus less suitable as feedstock for production of high-value products. Wood residues and agrobiomass contain sulphur-free lignin. Efficient enrichment/separation technologies are needed to exploit these lignins efficiently. Cereal lignins are less understood with respect to their structure. Separation and fractionation of biomasses is developing, such as novel fractionation methods like hot water extraction.

Hemicelluloses, i.e. xylan and glucomannan, have various potential applications. Åbo Akademi in Finland has studied membrane technologies to separate galactoglucomannan (GGM) for a mechanical pulping sidestream, while METLA, the Finnish Forest Research Institute, has proposed dynamic hot water extraction for the same. VTT and Central Laboratorium Oy have studied *in-situ* methods for hemicellulose modification to high quality dispersion with very low glass transition temperatures and film formation of the polymers.

Synthetic polymers and modified starch can be replaced with the *in-situ* modified hemicellulose in coatings and adhesives. Earlier Xylophan, Sweden, has demonstrated xylan films useful in packaging materials. Hemicellulose expands less, is sufficiently moisture resistant, and its oxygen and oil barrier is markedly good. Now further modification of the hemicellulose polymer can be done already during fractionation.

The difference between agro and forest xylan is also important. Hence, agroxylan contains highly reactive pherulic acid groups, which expands the application potential of the polymers significantly. Besides the polymeric structures released, oligomers and monomers will also be available as a result of fractionation.

As an example of the new wood refining paradigm, VTT has developed a new biomass pre-treatment method, which is more susceptible to enzymatic hydrolysis than current methods. In this new method pulp was processed in an alkaline water solution in an oxygen atmosphere and in the presence of a copper-phenanthroline complex as the catalyst. The pre-treated materials obtained were further converted into an ethanol solution utilising hydrolytic enzymes and yeast cells.

Catalytic oxidation also provides a new type of oxidised lignin. The whole logic of production changes when no fibre is recovered but is eventually converted to e.g. succinic acid, which is useful in several chemicals and polymers. Hydrolytically-produced white lignin has been introduced in thermoplastics at the University of Mie in Japan, and development of plastics is ongoing at TUT in Finland.

Wood-based sugars also enable chemical manufacturing furans and polymers, where the process is glucose hydrothermolysed to 5-hydroxyfuran; Fraunhofer ICT, Germany, has developed polyester technology based on 2.5-furandicarboxylic acid. In addition, Transfurans in the Netherlands and Tecnaro in Germany have introduced promising bio-composite products in related processes.

11.1.2 New pulping methods

The availability and prices of raw materials have changed rapidly. Even annual plants have been found interesting as a source for fibre, which has led to the development of novel pulping methods. The technology as a whole, however, needs to be developed.

Sulphur-free pulping, as developed by Chempolis in Finland, is a good example. Taking advantage of formic acid in digestion offers new possibilities in raw-material handling, in product offerings and in the utilisation of sidestreams.

VTT has further developed a phosphorous acid-based organosolv process, which enables higher fibre yield and recovery of high quality precursors: for example the lignin available in nano-particles which are reactive and sulphur free. In its other form, as developed by Biotech in Germany, all the cellulose is available as sugar components.

Furthermore ethanol sulphur dioxide digestion is being researched at the University of Maine in the USA. The process enables more efficient recovery of fractions for bio-refineries. Such a development promotes the idea of processes where the importance of the cellulose fibre is less pronounced and simultaneously the chemicals for pulping are more bio-based.

11.1.3 Catalysis

Catalysis is essential for the biorefinery and gerren chemistry. Some of the largest-scale chemicals are produced via catalytic oxidation, often using oxygen. Examples include nitric acid (from ammonia), sulphuric acid (from sulphur dioxide to sulphur trioxide by the chamber process), terephthalic acid from p-xylene, and acrylonitrile from propane and ammonia. Many other chemical products are generated by large-scale reduction, often via hydrogenation.

Many fine chemicals are prepared via catalysis; methods include those of heavy industry as well as more specialized processes that would be prohibitively expensive on a large scale. Examples include olefin metathesis using Grubbs' catalyst, the Heck reaction, and Friedel-Crafts reactions.

11.1.4 Green chemistry

Green chemistry, also called sustainable chemistry, is a chemical philosophy encouraging the design of products and processes that reduce or eliminate the use and generation of hazardous substances. As a chemical philosophy, green chemistry applies to organic chemistry, inorganic chemistry, biochemistry, analytical chemistry, and even physical chemistry. While green chemistry seems to focus on industrial applications, it does apply to any chemistry choice. Click chemistry is often cited as a style of chemical synthesis that is consistent with the goals of green chemistry. The focus is on minimizing the hazard and maximizing the efficiency of any chemical choice. It is distinct from environmental chemistry which focuses on chemical phenomena in the environment.

11.1.5 Metabolic engineering

The Cell Factory focuses on a fundamental understanding of the molecular biology and physiology of industrially important organisms. We develop improved strains and biotechnical processes for the production of bulk chemicals, such as polymer precursors and biofuels, and fine chemicals such as pharmaceuticals. Furthermore, we generate strains for brewing, and for efficient production of enzymes and other proteins.

VTT's key expertise includes metabolic pathway engineering and protein production technologies. We have a significant understanding of the physiology of eukaryotic microbial production hosts, brewing and plant biotechnology.

In the development of cell factory genomics and systems biology techniques are applied, complemented with high-throughput screening strategies, to analyse, develop and further improve production hosts. Transcriptomics, proteomics, metabolomics and fluxomics are applied in the analysis of cells, in both research and production conditions. The data guides us in tailoring efficient production organisms and in building cell-level models. Comparative genomics is efficiently used to exploit biodiversity, while comparative genome hybridization is used to understand the genomic traits of production organisms. Advanced online technologies and process modelling are being applied and developed for the monitoring and optimization of bioprocesses.

11.1.6 Top value chemicals

The report of top value biochemicals identifies twelve building block chemicals that can be produced from sugars via biological or chemical conversions. The twelve building blocks can be subsequently converted to a number of high-value bio-based chemicals or materials. Building block chemicals, as considered for this analysis, are molecules with multiple functional groups that possess the potential to be transformed into new families of useful molecules. The twelve sugar-based building blocks are 1,4-diacids (succinic, fumaric and malic), 2,5-furan dicarboxylic acid, 3-hydroxy propionic acid, aspartic acid, glucaric acid, glutamic acid, itaconic acid, levulinic acid, 3-hydroxybutyrolactone, glycerol, sorbitol, and xylitol/arabinitol.

11.1.7 Polymer synthesis

The study of polymer science begins with an understanding of the methods in which these materials are synthesized. Polymer synthesis is a complex procedure and can take place in a variety of ways.

Polymer synthesis is essential for the novel material developed of the novel monomers. Especially important are ring opening and polycondensation polymerizations. A wide variety of novel polymers have recently been developed worldwide. Several new polymers are under development or piloted, but only a few materials are commercially available. Beyond this are the possible novel glues, adhesives and latices.

11.1.8 Enzymology

One approach is chemo-enzymatic fibre modification, which is applicable for lignin containing fibre materials. Two different enzymatic methods can be used for wood or fibre activation:

1. Removal of pectins from green flax or
2. Functionalisation of cellulose-based material

via lignin residues present (Mohanty et al. 2005). Furthermore some screening tests have already been carried out on enzymatic modification of the lignocellulosic reinforcement. Chemo-enzymatic modification of the chemical and molecular properties of the polymer can be used to enhance the possibilities of stabilizing the polymer matrix as well as the gas-polymer matrix interphase in a foamy structure (Grönqvist et al. 2006; Buchert et al.2000). Additionally the compatibility within a composite can be improved by tailoring the polymer and/or the matrix properties. Among properties which can be introduced by chemo-enzymatic functionalisation are, for example, charge, hydrophobicity and conductivity of the material.

11.2 Nanotechnology

One of the main routes to be explored to realise enhanced lightweight fibre composite materials is the addition of nanoparticles and nanofibres. Nanomaterials combined in different matrices are known to have new or enhanced properties compared to the same materials of bigger particle size due to their high aspect ratio and surface area. Nanomaterial additives can provide improvements in several properties of composite materials such as (Muasher and Sain 2006; Matuana 2007; Hay and Shaw 2000):

- Mechanical properties (e.g. Strength, modulus and dimensional stability)
- Fibre matrix adhesion in composites
- Decreased permeability to gases, water and hydrocarbons
- Decrease of water uptake with high fibre ratio in composites
- Thermal stability and higher heat distortion temperature
- Fire resistance and reduced smoke emissions
- Chemical and weather resistance, e.g. UV-resistance
- Surface appearance, optical clarity
- Electrical conductivity.

Typical nanomaterials currently under investigation include nanoparticles, nanotubes, nanofibres, fullerenes and nanowires. In general, these materials are broadly classified by their geometries (Schmidt et al. 2002) in three classes: particle, layered, and fibrous materials (Thostenson et al. 2005). In fibrous or particle-reinforced polymer nanocomposites, dispersion of the nanoparticles and adhesion at the particle-matrix interface play crucial roles in determining the mechanical properties of the nanocomposites. Without proper dispersion, the nanomaterial will not offer improved mechanical properties over that of conventional composites. In fact, a poorly dispersed nanomaterial may degrade the mechanical properties (Gorga and Cohen 2004).

11.2.1 Silicates

Silicate clay minerals and graphite have been used in various polymer systems including epoxy, polyurethanes, vinyl ester, etc. (Chandradass et al. 2008; Haque et al.2003; Hamidi et al.2008). Koo and Pilato (2005) investigated polymer nanocomposites for high-temperature applications using cyanate ester, epoxy, phenolic, nylon 11, etc. They demonstrated that nanoclays play a key role in reducing the flammability on coating systems, which are key properties in the automotive sector.

Polyhedral Oligomeric Silsesquioxanes® (POSS) are nanoparticle size molecules those can be thought of as the smallest particles of silica possible. However, unlike silica or modified clays, each POSS molecule contains covalently bonded reactive functionalities suitable for polymerization or grafting POSS monomers to polymer chains. Each POSS molecule contains nonreactive organic functionalities for solubility and compatibility of the POSS segments with the various polymer systems. Those can be introduced in polymers in liquid or solid form and depending on chemical functionality they can be added to many different polymer systems.

11.2.2 Carbon nanotubes

The majority of the research in carbon nanotube/polymer composites has utilized thermoplastic matrices, like PP (Ansari et al. 2009) or polymethyl methacrylate (PMMA) (Zeng et al. 2004) due to their easy processability. However, research has also been conducted with thermo-setting materials, epoxies being the most commonly used (Sulong et al. 2006; Rana et al. 2009). Another kind of nanocomposite materials using inorganic particles like ZnO, SiO_2, SiC, etc. have also been studied (Zheng et al. 2003).

11.2.3 Nanocellulose

Nanocellulose is a natural nanomaterial that provides a large range of possibilities to obtain superior material properties for different end products (e.g. composites). Application areas for nanocellulose can be found in mouldable lightweight, high strength materials and composites for construction, vehicles, customer products and furniture. VTT is active in finding new production methods for and applications for nanocellulose as a member of Finnish Nanocellulose Center (founded in 2008) (Handout 2008).

Nagakaito has produced biocomposites using microfibrillated cellulose (MFC) derived from kraft pulp with phenolic resin as a binder. Because of the unique structure of nano-order-scale interconnected fibrils and microfibrils greatly expanded in the surface area that characterizes MFC, it was possible to produce composites that exploit the extremely high strength of microfibrils. The Young's modulus and bending strength achieved values up to 19 GPa and 370 MPa, respectively, with a density of 1.45 g/cm2, exhibiting outstanding mechanical properties for a plant fibre-based composite (Naka-Gaito and Yano 2005).

11.3 Converting

11.3.1 Thin films

There is demand for new renewable materials and in general lightweight materials due to brand owners, retailers and eventually consumers favouring more sustainable packaging solutions. Many of the existing packaging materials utilize a combination of different polymers and aluminium foil, which makes both material recycling and energy recovery challenging.

New innovations are thus needed in order to develop new fibre-based packaging solutions and to enhance the functional properties of these materials. These innovations include novel multilayer structures that may possibly be made with different vapour deposition and coating technologies, including silica and carbon thin layer technologies.

11.3.2 Plasma

Air pressure plasma has been developed considerably over recent years, including the plasma aided polymer deposition. Plasma is advantageous compared materials produced by conventional polymerization means. Plasma deposited films are pinhole free, chemically inert, insoluble, mechanically tough, thermally stable and highly coherent and adherent to variety of substrates.

Paper and cellulosic materials hold a good promise of being candidates for flexible packaging materials, provided that suitable barrier properties such as water repellence and grease resistance are imparted to them. One of the methods to achieve these objectives is to surface modify paper/cellulose by applying thin polymer coatings on the surface. As one alternative, fluorocarbon thin films produced by plasma enhanced chemical vapour deposition (PECVD) offer several advantages over the films. VTT has tested replacement of fluorocarbon POSS silica.

11.3.3 Foam technology

Foam coating is generally used in the textile industry. Both hard and flexible foam is made for various products, like low-density flexible foam used in upholstery and bedding. Polyurethanes are widely used in high resiliency flexible foam seating, rigid foam insulation panels, microcellular foam seals and gaskets, though combining biopolymers and foam seem promising.

Tecnaro's resins' newest innovations, which will be developed more in this project, include foamable resins using traditional extrusion processes or new innovative foaming methods e.g. microwave foaming (Tecnaro, 2009).

11.4 Materials

11.4.1 Bioreplaced thermoplastics

Furfural, the raw material for furfuryl alcohol, is produced from the hemicellulosic part of agricultural wastes, making it a renewable and CO_2-neutral chemical. Transfurans Chemicals (TFC) has developed a new range of furanic resins. The novel resin systems, BioRezTM and FuroliteTM are suitable in a wide range of formulations as the matrix for binding glass, rockwool and carbon fibre, as well as natural fibres or as an impregnating agent for porous substrates. BioRezTM resins are available as moulding resins or as water soluble impregnation resin, and are generally curable at elevated temperatures.

Lignin is a renewable raw material base for Tecnaro's resins. Their products ARBOFORM®, ARBOBLEND® and ARBOFILL®can be processed by injection moulding, extrusion, calendering, blow moulding, thermoforming or pressing into moulded parts, half-finished product, sheets, films or profiles.

Polylactide acid (PLA) is thermoplastic, biodegradable aliphatic polyester from renewable raw materials (corn starch or sugarcane). It can be made into sheets, fibres/non-wovens, injection moulded or extruded objects, filled with fibres/fillers or even foamed. It has some restrictions due to biodegradability and low temperature resistance (T_g about 60°C), which can be tailored upwards by suitable nucleating agents. The main producers of PLA are NatureWorks (USA), Toyota and PURAC Biomaterials (Netherlands). Galactic and Total Petrochemicals operate a joint venture, Futerro, that is are developing a second generation of polylactic acid product with their own enhanced technology from GMO free raw materials (Futerro, 2009; Wikipedia, 2009).

11.4.2 Bio thermosets

Polyols are developed based on natural oils, like soya. Dow's work on natural oil-based polyols, which began in the early 1990s, culminates with this next-generation technology, producing bio-based polyols that are virtually odour-free and can be customized to deliver enhanced performance benefits in a broad array of applications. Polyols made with RENUVA™ technology will help manufacturers of commercial and consumer products in the furniture and bedding, automotive, carpet and CASE (coatings, adhesives, sealants and elastomers) markets to more effectively differentiate themselves and meet their customers' growing demand for finished products that are both high quality and environmentally sound.

For flexible polyurethane, different monomers from modified soybean oil were used for this purpose: soybean oil monoglyceride, hydroxylated soybean oil prepared from two different routes and soybean oil methanol polyol. They were mixed in different proportions with an industrial polyol (1:0 to 1:3), a diisocyanate and with two catalysts: N,N-dimethylbenzylamine and *tert*-butylperoxy-2-ethylhexanoate. All the PU produced using N,N-dimethylbenzylamine formed foams within 7 to 9 minutes. If an industrial polyol was added, the foam cured at room temperature after a few minutes. Stress-strain curves and density of the PU foams were measured and compared with the same parameters of an industrial PU. The best PU based on soybean oil that could be used in the sports shoes industry was obtained from soybean oil monoglyceride; its foam presents small, uniform closed-cells and its apparent density closely resembled that of industrial PU. The other soybean oil polyols produced open-cell foams that can be used in various applications, such as automotive interiors and office furniture. The new PU foams are compared with our previous biocompatible foams made with 100% soyoil and a CO_2 blowing agent (Bonnaillie et al. 2009).

FuroliteTM resins are formulated for applications where stability under heat, fire or corrosive environment is needed without the use of flame retardant additives (TransFurans Chemicals, 2009).

The earliest commercial synthetic resin was based on a phenol formaldehyde resin (PF) with the commercial name Bakelite, and was formed from an elimination reaction of phenol with formaldehyde. In homes, the most significant sources of formaldehyde are likely to be pressed wood products made using adhesives that contain urea-formaldehyde (UF) resins. Pressed wood products made for indoor use include: particleboard (used as sub-flooring and shelving and in cabinetry and furniture); hardwood plywood panelling (used for decorative wall covering and used in cabinets and furniture); and medium density fibreboard (used for drawer fronts, cabinets, and furniture tops). Medium density fibreboard contains a higher resin-to-wood ratio than any other UF pressed wood product and is generally recognized as being the highest formaldehyde-emitting pressed wood product.

KARATEX-glue and the LIGNOBOND-method based on high molecular weight sulphate lignin were developed for production. KARATEX-glue was used for wet bonding veneer and particle board with a benefit on very low formalin emission. Rights were sold to Metsäliiton Teollisuus Oy in 1980 who started production based on ultra filtration in an Äänekoski sulphate pulping unit, but not any more. The PF market today is 1M tonnes pa. Alternatively, new products could be considered, such as phenol formaldehyde foam, which is primarily used for thermal insulation, exhibiting low density and high oxygen index compared with other phenolics. It has very low density, linear expansion and high oxygen index compared with other phenolics, but low tensile strength.

11.4.3 Bio-based latexes

There is only very limited selection of bio-based latexes on the market. However, products are clearly missing. The escalating price of oil-based raw materials has forced users to consider alternatives to SB and SA latexes, although the recent dip in oil prices has brought some confusion.

The high oil prices have opened up opportunities for bio-polymers – my own experience has been in products based on starch, soya protein and chitosan. The options in paper coating seem to be:

- substitute some of the latex with bio-polymers
- substitute all of the latex with bio-polymers (a cost performance issue)
- develop a formulation which meets the green issues required (sustainability, recyclability etc), so higher cost but lower environmental impact.

There are a number of products which can be used to reduce or eliminate the use of oil-based latexes. The biopolymer consumes only 1% of the fossil fuel, whereas synthetic polymer consumes 99% of the fossil fuel for its production. New biopolymer can be obtained as slurry with 40% solids and matches many of the requirements of latex. At this point I would describe it as highly modified tapioca-based starch which could be used from 50–100% replacement for latex. However, it should likely have some of the disadvantages of natural binders as regards process performance. For further improvements starch is needed as the core and the insolubilizer as a shell which works as coating binder or other natural biopolymer base.

12. Spearhead programme summary

In the majority of the existing lignocellulose-based biorefineries (e.g. pulp mills), lignin and hemicellulose have been given minimal attention, although it is evident that in future biorefineries these components may be converted into products of value. Both lignin and hemicellulose could be converted into chemically attractive precursors or platform chemicals, which could replace oil as the raw material in the production of chemicals and further in the production of performance polymers and biomass-based plastics. The value of these components can be exploited through two different approaches:

1) the biomass can be broken down into its monomeric building blocks and convert them through biochemical or chemical routes into biofuels or platform chemicals and then further into polymers, or
2) targeted mechanical, enzymatic and/or chemical methods can be used as partial breakdown methods of the biomass, enabling recovery of the polymeric structures for their further functionalisation into polymers.

In most cases the most feasible overall concept will be obtained by combining both of these approaches.

There is an emerging technology in the field. The main focus areas for the VTT industrial biomaterials spearhead programme is to find value added applications for the biomass. The arenas are selected carefully to fulfil the requirement of industrial potential and national benefit:

- Packaging materials is a field, where all the former knowhow and emerging technologies can be combined to benefit reorienting the pulp and paper industry
- Low-energy wood-houses (especially insulation materials) will support the local construction material and building industry to achieve marked GHG emission reductions

- Biomass-based plastic products (especially thin walled consumer products) enable totally new business opportunities in global markets with improved sustainability and economy.

To reach the targets several technologies are required and need to be combined to achieve sustainable results. However, the focus areas are:

- Fractionation and in situ modification
- Metabolic engineering, enzymology and biopolymer catalysis
- Nanotechnology, especially nanocellulose and thin films
- Composites, including fibre and foam composites
- Phenomenology and business modelling.

Dedicated research is needed in developing new types of biorefineries that deliver new material solutions to global markets. This will be achieved through an innovative combination of the multidisciplinary strengths within VTT, our partner and customer organizations. It is essential to develop and find ways to best commercialize high-volume value added products for sustainable biomaterial everywhere. Finally a goal is achieved by improving and expanding the performance of biomass-based materials on profitable and sustainable development.

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References

Ansari, M. N.M., Hanafi, I. & Zein, S. H. S. 2009. Effect of multi-walled carbon nanotubes on mechanical properties of feldspar filled polypropylene composites. J. Reinforced Plastics and Composites, 28 (20), 2473–2485.

Bonnaillie L. M. Campanella A. Wool R.P. Jayaraman R. 2009 http://acs.confex.com/acs/green06/techprogram/P27274.HTM.

British Plastics & Rubber Article date: April 1, 2008.

British Standards Institute 2008. PAS 2050 – Assessing the life cycle greenhouse gas emissions of goods and services.

Buchert, J., Pere, J., Miettinen-Oinonen, A., Puolakka, A. & Johansson, L.-S. 2000. Surface modification of cotton and flax fibres and fabrics, Symp. Biotechnol. Textiles Ind.Povoa de Varzim, PT, 3–7 May 2000.

Chandradass, J., Ramesh Kumar, M. & Velmurugan, R. 2008. Effect of clay dispersion on mechanical, thermal and vibration properties of glass fiber-reinforced vinyl ester composites. J. Reinforced Plastics and Composites, 27, 1585–1601.

Confederation of European Paper Industries (CEPI) 2007. Framework for the development of carbon footprints for paper and board products.

Dupuis, S. 2007. Ten directions – Packaging: Trends to watch in 2008. Step Online Nov/Dec 2007. http://stepinsidedesign.com/STEPMagazine/Article/28812/index.html.

Environment News Service 2009. http://www.ens-newswire.com/ens/aug2008/2008-08-22-01.asp.

Finnish Forest Research Institute 2008. The Statistical Yearbook of Forestry 2008. 9 Energy. http://www.metla.fi/metinfo/tilasto/julkaisut/vsk/2008/vsk08_09.pdf

Fowler, P A, Hughes, J M & Elias R M 2006. Review: Biocomposites: Technology environmental credentials and market forces, J Sci Food Agric 86:1781–1789.

Futerro, 2009. Info from Futerro.

Garrain, D., Vidal R., Martínez P., Franco V., Cebrián-Tarrasón D. 2007. LCA of biodegradable multilayer film from biopolymers, 3rd international conference of life cycle management, Zurich, August 27–29.

Gorga, R.E. & Cohen, R.E. 2004. Toughness enhancements in poly (methyl methacrylate) by addition of oriented multiwall carbon nanotube, J. Polym. Sci., Part B: Polym. Phys., 42(14) 2690–2702.

Grönqvist, S., Rantanen, K.; Alen, R., Mattinen, M.-L., Buchert, J. & Viikari, L. 2006. Laccase-catalysed functionalisation of TMP with tyramine. Holzforschung 60(5), 503–508.

Gustavsson, L., Pingoud, K. & Sathre, R. 2006. Carbon dioxide balance of wood substitution: comparing concrete- and wood-framed buildings. 21 p. Mitigation and Adaptation Strategies for Global Change, 11(3), pp. 667–691.

Hamidi, K.Y., Aktas, L. & Altan, M.C. 2008. Effect of nanoclay content on void morphology in resin transfer molded composites. Journal of Thermoplastic Composite Materials, 21, 141–163.

Handout 2008. Nanocellulose center, Application possibilities for nanocellulose.

Haque, A., Hussain, F., Derrick, D. & Shamsuzzoha. S. 2003. Glass/epoxy polymer nanocomposites: manufacturing, structures, thermal and mechanical properties. Journal of Composites Materials, 37(20), 1821–1837.

Hautala M. Pasila A. & Pirila J. 2004. Use of hemp and flax in composite manufacture: a search for new production methods. Compos Part A: Appl. Sci. 35: 11–16.

Hay, J. N. & Shaw, S. J. 2000. A Review of Nanocomposites.

IEA Bioenergy Task 38. 2009. Greenhouse Gas Balances of Biomass and Bioenergy Systems. Task 38 Folder. Joanneum Research, 2002. http://www.ieabioenergy-task38.org/description/task38folder.pdf.

Intertech Pira 2009. http://www.intertechpira.com/blog.asp?step=1&mode=viewsingle&blogCategoryID=19.

Koo, J. & Pilato, L. 2005. Polymer nanostructured materials for high temperature applications, Sample J., 41, 2.

Maniscalco, M. 2007. Market Snapshot, Consumer Products; Injection Moulding Magazine, Sept. 2007.

Matuana, L. 2007. Artificial wood-based wood flour and nanoclay reinforced rigid PVC matrix, 3rd Wood Fibre Polymer Composites International Symposium, CTBA, France.

Michael, D. 2009. Biopolymers from crops, Their potential to improve enviroment. http://www.wondu.com/.

Moberg, Å., Johansson, M., Finnveden, G. & Jonsson, A. 2009. Screening environmental life cycle assessment of printed, web-based and tablet e-paper newspaper, Second edition. Reports from the KTH Centre for Sustainable Communications. ISSN:1654-479X. TRITA-SUS Report 2007:1.

Mohanty, A. K., Misra M. & Drzal L. T. 2005. Natural Fibres, Biopolymers, and Biocomposites, CRC Press 2005, 23–30.

Muasher, M. & Sain, M. 2006. The efficacy of photostabilizers on the color change of wood filled plastic composites. Polymer Degradation ans Stability, 91(5) 1156–1165.

Naka-Gaito, A.N. & Yano, H. 2005. Novel high-strength biocomposites based on microfibrillated cellulose having nanoorder-unit web-like network surface, Appl. Phys. A 80, 155–159.

Nissinen, A. & Seppälä, J. 2008. Tuotteiden ilmastovaikutuksista kertovat merkit. Selvitys Vanhasen II hallituksen tulevaisuusselontekoa varten. Valtioneuvoston kanslian julkaisusaraja 11/2008, Yliopistopaino, Helsinki. 50 p.

Patel, M. 2002. Review of life cycle assessments for bioplastics, Paper presented to the Congress on The Industrial Applications of BioPlastics 2002, Central Science Laboratory, York UK .

Pingoud, K. & Perälä, A.-L. 2000. Arvioita puurakentamisen kasvihuonevaikutuksesta. 1. Skenaariotarkastelu potentiaalisesta puunkäytöstä ja sen kasvihuonevaikutuksesta vuosien 1990 ja 1994 uudisrakentamisessa. 2. Rakennuskannan puutuotteiden hiilivaranto Suomessa: inventaariot vuosilta 1980, 1990 ja 1995 [Studies on greenhouse impacts of wood construction. 1. Scenario analysis of potential wood utilisation in Finnish new construction in 1990 and 1994. 2. Inventory of carbon stock of wood products in the Finnish building stock in 1980, 1990 and 1995.] Espoo 2000, Technical Research Centre of Finland, VTT Julkaisuja –

Publikationer No. 840. 58 p. + app. 14 p. http://www.vtt.fi/inf/pdf/julkaisut/2000/J840.pdf.

Pingoud, K., Pohjola, J. & Valsta, L. 2009. How to assess the forest sector for favourable climatic impacts: Forestry and wood products integrated. Manuscript submitted for publication. 47 p.

Press release from Primowater corp.August 2008. http://imm.plasticstoday.com/imm/articles/consortium-formed-expand-recycling-options-bioplastics.

Rana, S., Alagirusamy, R. & Joshi, M. 2009. A Review on carbon epoxy nanocomposites. J. Reinforced Plastics and Composites, 28, 461–487.

Riedel U. & Nickel J. (1999) Natural fibre-reinforced biopolymers as construction materials: new discoveries. Angew Makromol Chem 272: 34–40

Rodriguez, S.I., Roman, M.S., Sturhahn, S.C. & Terry, E.H. 2002. Sustainability Assessment and Reporting for the University of Michigan´s Ann Arbor Campus. Report No. CSS02-04.

Sathre, R. & O'Connor, J. 2008. A Synthesis of Research on Wood Products & Greenhouse Gas Impacts. Vancouver, B.C. FPInnovations – Forintek Division. 74 p. (Technical report TR-19). http://www.forintek.ca/public/pdf/Public_Information/technical_rpt/TR19%20Complete%20Pub-web.pdf.

Seppälä, J., Mäenpää, I., Koskela, S., Mattila, T., Nissinen, A., Katajajuuri, J.-M., Härmä, T., Korhonen, M.-R., Saarinen, M. & Virtanen, Y. Suomen kansantalouden materiaalivirtojen ympäristövaikutusten arviointi ENVIMAT-mallilla, Suomen ympäristö 20, p. 119.

Schmidt, D., Shah, D. & Giannelis, E.P. 2002. New Advances in Polymer/Layered Silicate Nanocomposites, Current Opinion in Solid State and Materials Science, 6(3) 205–212.

Soimakallio, S., Mäkinen, T., Ekholm, T., Pahkala, K. Mikkola, H. & Paappanen, T. 2009. Greenhouse gas balances of transportation biofuels, electricity and heat generation in Finland – Dealing with the uncertainties, Energy Policy 37, pp. 80–90.

Statistics Finland 2009. Vuoden 2007 viralliset päästöluvut Ilmastosopimukselle ja Kioton pöytäkirjalle. 14 June 2009. http://www.tilastokeskus.fi/til/khki/2007/khki_2007_2009-04-24_tie_001_fi.html.

Sulong, A. B., Park, J., Lee, N. & Goak, J. 2006. Wear behavior of functionalized multi-walled carbon nanotube reinforced epoxy matrix composites. J. Composite Materials, 40, 1947–1960.

Sustainable Biomaterials Collaborative 2007. Sustainable Bioplastics Guidelines. Version 7–6/25/2007. http://www.sustainablebiomaterials.org.

Tecnaro, 2009. http://www.tecnaro.de.

Thostenson, E., Li, C.,Chou, T. 2005. Rev. nanocomposites in context, J. Composites Sci. Technol. 65, 491–516.

TransFurans Chemicals 2009. http://www.transfurans.be.

Weiss, K. Troubleshooter 2009. Secrets of Successful Thin-Wall Molding. http://www.ptonline.com/articles/200202ts1.html.

Zheng, Y.P., Zheng, Y. & Ning, R.C. 2003. Effects of nanoparticles SIO_2 on the performance of nanocomposites, Materials Letter, 57(19), 2940–2944.

Zeng, J., Saltysiak B. JohnsonW. S. Schiraldi D. A. & Kumar, S. 2004. Processing and properties of poly (methyl methacrylate)/carbon nano fiber composites, Composites Part B-Engineering, 35(2), 173–178.

Zhao, S.; Analysis US Injection moulded plastic industry; January 2009; http://www.articlesbase.com/business-articles/analysis-us-injection-molded-plastic-industry-714683.html.

Wikipedia, 2009. www.wikipedia.org.

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Industrial Biomaterial Visions

Spearhead Programme 2009–2013

Abstract

VTT's Industrial Biomaterials Spearhead Programme 2009–2013 develops technologies and competencies utilising basic skills in chemistry, biotechnology, process technology, materials science, modelling and analytics. The technologies and competencies developed in the spearhead programme are directed to generate value chains that start from forest biomass and end up in selected high volume consumer products. In such a development the key is not to disturb the fragile value chains of the food sector.

The spearhead programme focuses on the development of materials and production technologies based on fibres and nanocellulose as well as biomass-based monomers and polymers. The aim is to integrate these new value chains into existing biorefineries (like pulp mills, biofuel production, brewing, and cereal sidestreams).

The results will be exploited by actors in the chemical, process technology and materials sectors, both domestic and global. Especially interesting target sectors are the plastics, process, forest and energy industries as well as packaging and building. The spearhead programme will cooperate closely with the Finnish strategic centres for science, technology and innovation, namely Forestcluster Ltd., Cleen Ltd. and Fimecc Ltd.

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