THERMALLY MODIFIED TIMBER: RECENT DEVELOPMENTS IN EUROPE AND NORTH AMERICA

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Abstract. This state-of-the-art report presents the basic concepts in manufacture of thermally modified timber (TMT) to achieve increased dimensional stability and resistance to biological degradation. The reasons for the growing interest in thermo–hydro and thermo–hydro–mechanical techniques in Europe and the United States are discussed, and the physical and chemical changes that occur in wood during processing according to the latest research are also presented. Finally, the role of thermal wood processing in a sustainability of resource utilization context is discussed, along with future need in TMT research and development to contribute to the low-carbon economy. The results clearly show a knowledge gap in data supporting the environmental benefits of TMT compared with unmodified timber or other modification methods for timber.

Keywords: Environmental product declarations, low-carbon bioeconomy, product category rules, sustainability.

INTRODUCTION

Forest-based industries are continually developing advanced processes, materials, and wood-based solutions to meet evolving demands and increase competitiveness. One emerging treatment involves the combined use of temperature and moisture, in which force can be applied. This is referred to as the thermo–hydro (TH) and thermo–hydro–mechanical (THM) processes. Figure 1 shows a simplified synoptic diagram of the most common TH and THM processes based on what is achieved through the process. Thermal wood processing (thermal treatment) involves temperatures of 100-300°C and can have two distinctly different purposes: 1) softening the wood in steam or water to release internal stresses and make the wood easier to further process or 2) controlled degradation of the wood involving temperatures between 150°C and 260°C with the purpose of improving shape stability and decay resistance. Heat treatment of wood at greater than 300°C is of limited practical value because of the severe degradation of the wood material (Sandberg et al 2013). Wood aging is a further development of the classic thermal treatment processes currently used industrially. Wood aging operates in a temperature range between wood drying and thermal treatment (100-150°C), and the negative effects that a classic thermal treatment normally has on strength and brittleness of wood are therefore decreased. TH processing is also applied in many other processes that can be attributed to reconstituted wood products. A thermal treatment process can also be followed by compression in the axial or transverse direction of the wood. THM

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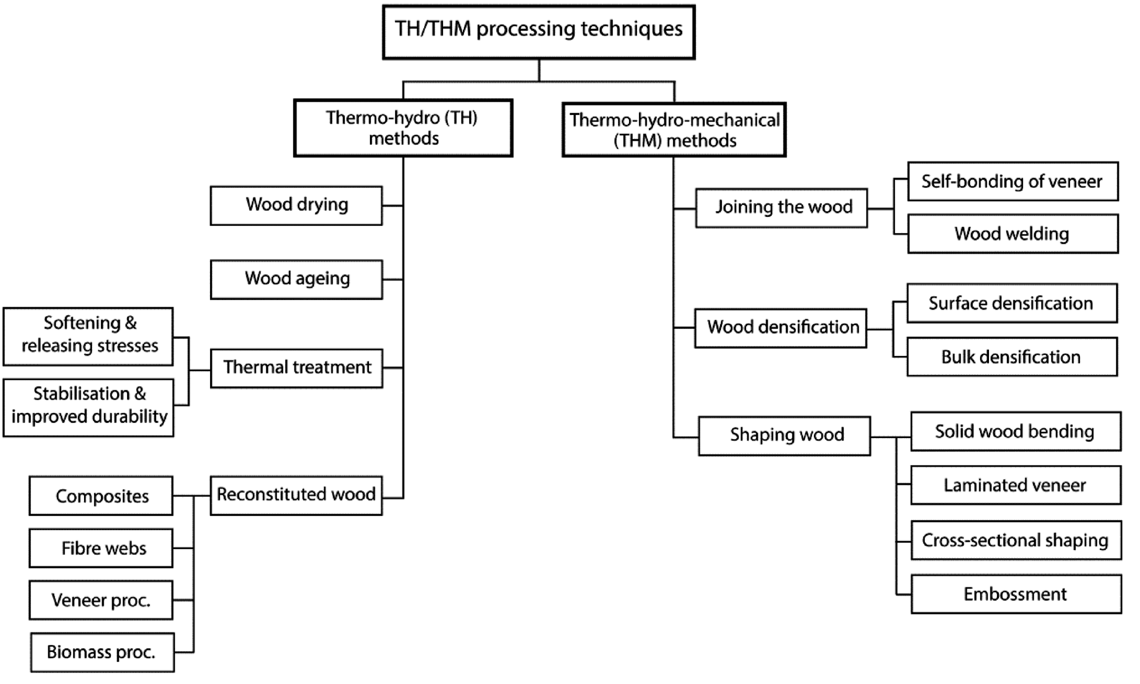

Figure 1. Classification of TH and THM processes (Navi and Sandberg 2012).

processes include three main areas of modification, namely joining, densification, and shaping of wood.

Thermally modified timber (TMT) is, according to CEN (2007), wood at which the composition of the cell wall material and its physical properties are modified by exposure to temperature greater than 160°C and conditions of decreased oxygen availability. The wood is altered in such a way that at least some of the wood properties are permanently affected through the cross section of the timber. This product is related to heat-treated wood, but to distinguish it from heat sterilization at lower temperature (≈55°C) with the purpose of killing pests in solid wood materials and preventing their transfer between continents and regions, we use the terms thermal treatment/processing and TMT.

In recent decades, developments in the area of thermal treatment have accelerated considerably. During the 1980s, French and Japanese industries began to modify wood with the help of heat to increase resistance to microbial attack. Since then, interest in thermal treatment has increased and several thermal treatment processes for treatment of sawn timber were developed in Europe.

Thermal treatment is wood modification in a strict sense because the material undergoes chemical changes. The process essentially involves a controlled degradation of the wood primarily resulting in the destruction of hemicelluloses. The thermal treatment process is in most cases performed in a vacuum, in air, or with an inert gas such as nitrogen. Preheated oil can also be used; in which case, the oil acts as a heat transfer medium and also excludes oxygen from the wood. The underlying reason for applying thermal treatment is the increasing demand for environmentally friendly high-durability wood, ie to increase the service life of wood materials without the use of toxic chemicals.

Kutnar et al (2015) gave an overview of recent developments of THM-treated wood ranging from surface densification, compressed wood, and shaped wood. In this study, the purpose was to present the role of thermal wood processing in a sustainability of resource utilization context and to document what thermal wood processing should achieve to contribute to a low-carbon economy and beyond.

BIOECONOMY

For many years to come, the world's political and economic decisions will be determined by resource and energy scarcity and by climate change as a topic related to consumption of fossil energy. In these circumstances, a balance has to be achieved between economics, ecology, and social welfare that can be summed up as sustainability, which was put forward at the end of the 20th century and has been inseparably linked to forestry ever since.

The forest sector and wood-based industries are challenged by this change and tend to participate in the sustainability debate. This is for obvious reasons, because the concept of sustainability that is now related to the global economy first came from these industries. Indeed, nobody questions the value of the forest for mankind and the environment, and nobody questions the value of the multitude of products made of wood. Wood, especially sawn timber, has during the last 50 yr to a large extent, disappeared from technological applications (Radkau 2007). Therefore, its contribution to sustainability fails to appear in the one area in which it would be most significant—as a substitute for energy-intensive materials. New modification methods for wood, such as thermal modification, are attempts to reintroduce wood to technological applications without changing the eco-friendly characteristics of the material.

Wood is in volume the most important renewable material resource (Rowell 2002). In all aspects of human existence, wood use appears to be the most effective way to optimize resources and to decrease the environmental impact associated with mankind's activities. However, because timber possesses good but not outstanding properties, this is not an easy thing to achieve, and in view of the new materials emerging, it becomes noticeably more difficult. The only properties wood has that reign supreme are ecological fitness and, possibly, low cost.

In the European Union (EU), measures are being discussed in economics and science that seek to improve the sustainability of resource utilization. European policy is affecting and, indeed, directing current research, development, and marketing in the EU. This has been especially true for the introduction of industrial processes for manufacture of TMT. The main policies having a direct impact on the forest-based sector are the EU Sustainable Development Strategy (European Commission 2009), which was published in 2006, and revised in 2009, the EU Roadmap 2050 (European Commission 2011), and the recycling society directive, Directive 2008/98/EC (European Parliament Council 2008). The forest-based sector can considerably contribute to the European Commission's ambitious CO_2 emissions reduction goal of 80% by 2050, ie Roadmap 2050, with innovative production technologies, decreased energy consumption, increased wood products recycling, and the reuse and refining of side-streams.

The need to decrease the whole-life energy consumption of buildings has highlighted the role that wood can play in construction. When buildings have net-zero energy consumption, a major part of their overall environmental burden consists of their embodied energy and the associated greenhouse gas emissions. Compared with other construction materials, the energy needed to convert a tree into the final product is significantly lower, resulting in wood products having a low embodied energy.

It is vital that wood can be used effectively through the whole value chain, from forest management and multiple uses of forest resources through new wood and fiber-based materials and processing technologies to new end-use concepts. Fossil fuel consumption, potential contributions to the greenhouse effect, and quantities of solid waste tend to be minor for wood products compared with competing products (Werner and Richter 2007). Preservative-impregnated wood products tend to be more critical than comparative products with respect to toxicological effects and/or photo-generated smog, depending on the type of preservative. Unfortunately, the number of life cycle assessment (LCA) studies of wood-based composites and modified wood is relatively limited, are geographically specific, and use of a variety of databases and impact assessment protocols. The aim of the "carbon economy" is to mitigate climate change and promote sustainable development by decreasing energy consumption, pollution, and emissions while increasing performance.

As a consequence of increased competition from traditional and new industries based on renewable resources, forest resources must be considered limited. There are forecasts showing that, already in 2020; European consumption of wood might be as large as the total European combined forest growth increment (Jonsson et al 2011). According to the Communication "Innovating for Sustainable Growth: A Bio-economy for Europe," Europe needs to radically change its production, consumption, processing, storage, recycling, and disposal of resources (European Commission 2012). Thus, bioeconomy is considered one of the key elements for smart and green growth in Europe. The "Strategic Research and Innovation Agenda for 2020 of the Forest-based Sector and the Horizons-Vision 2030" view forest-based sector as a key actor and enabler of the bio-based society.

THERMAL PROCESSING OF WOOD

Thermal treatments of sawn timber have been investigated for many years and are now commercialized. In the beginning of the 20th century, the use of heat and moisture in wood processing came into focus, and it was observed that wood dried at a high temperature changed color and had greater dimensional stability and lower hygroscopicity than untreated wood (Tiemann 1915; Koehler and Pillow 1925). After World War I, comprehensive studies were made of the effect of kiln-drying temperature on the strength of wood for the aviation industry in the United States (Wilson 1920). Systematic research on how to improve wood properties by thermal treatment was made by the US-based group led by Alfred Stamm in the 1940s (Stamm 1964) and in Germany by Burmester (1973). Burmester studied the effects of temperature, pressure, and moisture on wood properties in a closed system, and the process was named Feuchte-Wärme-Druck (FWD).

The exact method of treatment can have a significant effect on the properties of the modified wood, and the most important process variables are the treatment atmosphere, the choice of closed or open system, the choice of wet or dry systems, the use of a catalyst, the wood species, the time and temperature of treatment, and the dimensions of the processed material.

One of the first commercial thermal treatment units in Europe was based on Burmester's work and was started in Germany about 1980 but was never industrialized on a great scale (Giebeler 1983). During the two decades preceding the turn of the century, the development of TMT in Europe was intensive and four new methods entered the market. The Plato process (Proving Lasting Advanced Timber Option) was developed in the 1980s by Royal Dutch Shell in The Netherlands and is now used by the Plato Company in the Netherlands. In France, the first studies related to thermal treatment were related to renewable energy from biomass in middle 1970s by Ecoles des Mines de Paris and Saint Etienne (Candelier 2013). In the late 1980s, torrefied wood was developed and advantageous properties of the thermal-treated wood such as increased dimensional stability and durability from fungal attacks were highlighted. The retification process for thermal treatment was developed from that research. It was not until 1993, when VTT Technical Research Center of Finland together with industry developed the ThermoWood process that got established as an industrial process for improving wood properties. This process is licensed to members of the International ThermoWood Association (founded in 2000), and the ThermoWood process is dominating the market for manufacture of thermal-treated wood in Europe. Because the boiling points of many natural oils and resins are greater than the temperature required for the thermal treatment of wood, the thermal treatment in a hot oil bath is a feasible option. The oil heat treatment (OHT) process was developed in Germany, and the process is performed in a closed process vessel. Table 1 shows the processing conditions for the previously mentioned thermal processes.

On the basis of the development of these processes, new thermal treatment processes have also been emerging in other countries, mainly in Europe. Several wood species are used, with different process conditions depending on species and the final use of the product. Common for the different processes is the use of sawn timber and treatment temperatures in the range of 160-260°C, but differences exist in terms of process conditions such as the use of media for the process (steam, nitrogen, or different vegetable oils).

Finland (ThermoWood) is the largest producer of TMT in the world and by far the biggest of all the commercial wood modification businesses. The production volume has been progressively increasing since 2001, and in 2014, the production of ThermoWood was 150,000 m^3. Production is mainly from scots pine and norway spruce, and 80% of the production is sold within Europe. Today, the total annual production of TMT in Europe is about 300,000 m^3.

Outside Europe, research has not been as focused on development of industrial processes for thermal treatment for improved wood properties. North America has recently showed a growing interest in both the product and the process. In 2004, the United States restricted the use of chromated copper arsenate–treated softwood timber for children's playgrounds, finishing materials for waterfront homes, and in pallets used to transport food. Similar restriction has been in action in the EU and Canada since 2004 and 2015, respectively. This opens opportunities for the increased use of wood not treated with toxins. In North America, annual production of softwood timber is roughly 90 million m^3, of which ≈20 million m^3 are treated for

Table 1. Examples of thermal treatment processes and their processing conditions.

Process	Approximate year	Trademarks	Initial MC (%)	Temperature[a] (°C)	Process duration (h)	Pressure (MPa)	Atmosphere/heat transportation media	Comments
FWD	1970		10-30	120-180	≈15	0.5-0.6	Steam	Closed system
Plato	1980	PlatoWood	14-18	150-180/170-190	4-5/70-120 up to 2 wk	Super atmospheric pressure (partly)	Saturated steam/ heated air	A four-stage process
ThermoWood	1990	ThermoWood	10 to green	130/185-215/80-90	30-70	Atmospheric	Steam	Continuous steam flow through the wood under processing that removes volatile degradation products
Le Bois Perdure	1990	Perdure	green	200-230	12-36	Atmospheric	Steam	The process involves drying and heating the wood in steam.
Retification	1997	Retiwood, Bois Rétifié, Réti, Retibois, Retitech, Retifier	≈12	160-240	8-24		Nitrogen or other gas	The nitrogen atmosphere guarantee a maximum oxygen content of 2%
OHT	2000	OHT (Company name + OHT, eg Menz OHT)	10 to green	180-220	24-36		Vegetable oils	Closed system

[a] Treatment temperature for different stages of the process is separated by /.

outdoor decks, sill plates, interior framing in termite-prone locations, and other uses. Treating softwood lumber with preservatives can make the difference between complete disintegration within months in the worst conditions and the same wood lasting decades.

Production units and research were established in Canada slightly after the breakthrough of TMT in Europe. The Perdure process (Le Bois Perdure) is a French thermal treatment process that was the first process established in Canada (by PCI Industries in 2003). Today, there are several industrial plants in the Québec region (Esteves and Pereira 2009). In addition to the Perdure process, the ThermoWood process as well as "own built" thermal treatment units are in production in Canada. In 2012, there were 7 manufacturers of TMT in Canada and 10 in the United States. In 2004, Westwood Corp. was the first company in the United States exhibiting thermal-treated wood at the International Woodworking Fair in Atlanta, and two years later at the same fair, the Finish companies Jartek Inc. and Stellac Inc. were also exhibitors. The Westwood process is a further-developed ThermoWood process specially adapted for hardwood species. The company markets both TMT and their patented process. The companies Jartek and Stellac were licensees of the ThermoWood process.

In 2008, Jartek installed their first equipment in a plant located in Minnesota, and Stellac started their plant in Indiana for manufacturing thermal-treated decks made of softwood under the brand name PureWood. The market for thermal-treated softwood in the United States is different from that in the EU. Softwoods in the United States are typically used for construction purposes, which demand completely different moisture standards than those of Europe. In the United States, the MC for building materials is 20-25%, compared with the European standards of 8-14%. In 2008, the Perdure process was also introduced in the US market with a production plant located in New Hampshire. Mostly softwood is processed, and the products can be found in the United States under the brand name Cambia. Inspired by the activities in Europe, the Natural Resources Research Institute at the University of Minnesota, Duluth, took the initiative to develop an American Section of the International Association for Testing and Materials standard similar to the European Technical Specification for TMT (CEN 2007), but still there is no such standard.

Although thermal-treated wood can now be used in many common applications, the market is still limited. Heat-treated wood is suitable for various uses, mainly in which it is exposed to weather and humidity variations above ground eg for outside use as cladding, terraces, garden furniture, saunas, and windows but also for interior use such as kitchen furniture, flooring, decorative panels, and stairs. However, its properties and low physical strength do not allow it to be used in wooden structures. TMT was first developed to improve the performance and durability of softwoods, but it has more recently been extended to boost the performance of hardwoods, allowing certain low-durability hardwoods to be used outdoors with no additional protection. Examples of thermally modified hardwood species are birch, aspen, ash, soft maple, tulipwood, and red oak (with the best results from quartersawn timber).

PHYSICAL CHANGES IN WOOD DUE TO THERMAL PROCESSING

Thermal treatment significantly influences the properties of wood, eg hygroscopicity and dimensional stability, resistance against fungi and insects, mechanical properties, and also properties such as color, odor, gluability, and coating performance (Table 2). Loss of mass of the timber during thermal treatment is, however, a typical effect of the process. A decrease in mass up to 20% can occur depending on type of process. Most properties of TMT are, in addition to properties of the raw material, affected by the intensity of the thermal treatment process, ie by the temperature and duration of the process.

In general, most thermal treatments, even at mild temperatures, decrease the hygroscopicity of wood, ie its capacity for reabsorption of moisture from the air, but the decreased hygroscopicity can in some cases be recovered by moistening

Table 2. Main changes of properties for thermal-treated wood compared with untreated wood.

<table>
<tr><th>Desirable property changes</th><th>Undesirable property changes</th></tr>
<tr><td>Lower EMC</td><td>Decreased MOR and to some extent MOE</td></tr>
<tr><td>Greater dimensional stability</td><td>Decreased impact strength</td></tr>
<tr><td>Greater durability against decay</td><td>Increased brittleness (complicates eg machining)</td></tr>
<tr><td>Lower thermal conductivity</td><td>Decreased hardness (Brinell hardness)</td></tr>
<tr><td colspan="2" align="center">Lower density</td></tr>
<tr><td colspan="2" align="center">Dark brown color</td></tr>
<tr><td colspan="2" align="center">Characteristic smell</td></tr>
<tr><td colspan="2" align="center">Longer pressing time for gluing</td></tr>
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(Maejima et al 2015). Because of the loss of hygroscopic hemicellulose polymers during thermal treatment, the EMC is decreased. Consequently, the swelling and shrinking of thermal-treated wood are drastically decreased. On average, the EMC is decreased to about half the value of the untreated wood. The hygroscopicity of thermal-treated wood can vary considerably with varying process parameters. Table 3 shows a summary of the effect of thermal treatment on the EMC according to various researchers.

Welzbacher and Rapp (2007) compared different types of industrially thermal-treated products using several different fungi in laboratory tests and in different field and compost conditions. Table 4 shows the weight loss during a CEN (1996) test using three different fungi. The thermal treatment in oil was the most effective, but the effect of the oil in the decay test is not known. Schwarze and Spycher (2005) reported that densified wood posts treated at 180°C were more resistant to colonization and degradation by brown rot fungi. In contrast, results obtained by Welzbacher et al (2008) showed that a very durable-to-durable THM-densified wood is produced only when thermo–mechanical densification is used in combination with OHT. In addition,

Table 3. Decrease in EMC in thermal treatment.

Wood species	Temperature (°C)	Time (h)	Decrease in EMC (%)	Reference
Fagus silvatica	180	4	40	Teichgräber (1966)
	190	2.5	60	Giebeler (1983)
Pinus pinaster	190	8-24	50	Esteves et al (2006)
Pinus sylvestris	220	1-3	50	Anon (2003)
Eucalyptus globulus	190	2-24	50	Esteves et al (2006)
P. sylvestris	Plato		50-60	Tjeerdsma (2006)

Table 4. Weight loss (%) of different species of wood after different thermal treatment processes (Welzbacher and Rapp 2007).

Material		*Postia placenta*	*Coriolus versicolor*	*Coniophora puteana*
Control species				
P. sylvestris L.[a]		31.0	5.1	47.5
P. sylvestris L.[b]		26.2	35.7	60.3
Pseudotsuga menziesii F.		14.0	2.6	27.4
Quercus petrea Liebl.		0.8	14.3	3.9
Thermal-treated wood	Process			
Pices abies (L.) Karst.	Plato	10.0	6.8	3.7
P. sylvestris L.	ThermoWood	16.0	9.0	1.9
Pinus maritima Mill.	Retification	13.3	7.8	12.2
P. sylvestris L.	OHT	7.4	5.6	3.4

[a] Including both sap and heartwood.
[b] Including only sapwood.

Table 5. Decrease in MOR of thermal-treated sawn timber in relation to untreated wood.

Species	Treatment	Process	Decrease in MOR (%)	Reference
Birch (*Betula pendula*)	Vapor, 200°C, 3 h	ThermoWood	43	Johansson and Morén (2006)
Scots pine (*P. sylvestris*)	Oil, 220°C, 4.5 h	OHT	30	Rapp and Sailer (2001)
Eucalyptus (*Eucalyptus globulus*)	Vapor, 200°C, 10 h	Closed system	50	Esteves et al (2006)
Norway spruce (*Picea abies*)	Aqueous environment 8-10 bar, 165°C, 30 min	Plato	31	Boonstra et al (2007)

Skyba et al (2008) found that THM treatment increased the resistance of spruce but not of beech wood to degradation by soft rot fungi.

It is well known that changes in the cell wall chemistry, such as changes in the hemicelluloses and lignin structures, cellulose depolymerization, and increased crystallinity, affect the strength properties of thermal-treated wood (Schneider 1971). Bending strength, which is a combination of tensile stress, compressive stress, and shear stress, is commonly used to compare mechanical properties of different processes. Table 5 presents a summary of data on bending strength changes (modulus of rupture [MOR]) in thermal-treated timber from different processes and of different species. In general, there is only a small change in modulus of elasticity (MOE) but a major decrease in MOR independent of process or species. In some cases, even an increase in MOE is reported. Boonstra et al (2007) tested scots pine timber from the Plato process and got an increase in MOE of 10%, whereas MOR showed a decrease of 3% compared with untreated timber. For structural timber of scots pine and norway spruce with cross-sectional dimensions of 45 × 145 mm and treated in the ThermoWood process, Bengtsson et al (2002) found decreased bending strength of up to 50% but only minor MOE changes.

Impact bending strength is decreased considerably for all thermal treatment processes and is a consequence of the increased brittleness. Impact bending strength can be decreased up to 50% compared with untreated wood, but an 80% decrease has been reported by Hanger et al (2002).

There is no major difference in health and safety considerations for TMT compared with untreated wood. A typical detectable difference is the smell of the material and the dust generated in the processing. TMT has a smoke-like smell, which comes from chemical compounds, mainly furfurals, which develop during processing. TMT waste can be handled similar to any other untreated wood waste, eg burned or pelletized and briquetted if a mixture with normal sawdust is used.

Gluability is not changed to any great extent because of thermal treatment, and TMT can be glued with many industrial adhesives. The hydrophobic wood surface causes lower penetration of the solvents from the adhesive into the wood material, which may cause a need of increased pressing times.

Decreased MC of TMT improves its stability, which in turn decreases cracking and flaking of the surface coating in changing weather conditions. To prevent color changes and surface shakes, a surface treatment against UV radiation is recommended. Normal painting processes are in general not problematic, but when electrostatic painting is used, moisturizing is required. To prevent color changes, the treatment substance should contain pigment, which usually results in a slightly darker appearance.

ENVIRONMENTAL IMPACTS OF THERMALLY MODIFIED WOOD

Awareness of climate change and its potentially disastrous consequences are stimulating a transformation toward sustainable development, with increasing economic efficiency, protection and restoration of ecological systems, and improvement of human welfare. Wood as a renewable biological raw material in numerous applications is therefore gaining in importance. This presents an opportunity for the forest-based sector to become a leader in achieving the global target of decreased CO_2 emissions with innovative production technologies, decreased energy consumption, increased wood products recycling, and the reuse and refining of side-streams (eg by utilizing by-products). The systematic evaluation of material databases shows that, in spite of the major achievements made in material science, timber as a structural material can hardly be outperformed by any other materials, that it even remains the first choice as far as plate bending is concerned, even outperforming carbon fiber composites, and that it is undisputedly unrivalled in terms of cost and environmental performance. These results show that timber is a high-performance material for structures, playing an essential role in construction and lightweight design. Several of the species used by industry have deficiencies related to poor resistance to biological degradation and low shape stability, which previously could be decreased by preservation with more or less toxic substances, which today are forbidden to use in many countries and regions. Consequently, there has been renewed interest in developing thermal processes in recent years.

Thermal processing will be implemented to improve the intrinsic properties of wood and to obtain the form and functionality desired by architects, designers, and engineers. Great performance at low weight and low price creates a considerable market potential for thermal-treated timber products that can replace energy-intensive materials and methods of construction and reveals a great potential in construction, architecture, light-weight construction, and furniture manufacture. Different modification processes and parameters yield modified wood with different properties suitable for a variety of product lines. However, they also have different environmental impacts, which are consequently transferred into the materials and final products. Interactive assessment of process parameters, product properties, and environmental impacts should be used to aid development of innovative modification processes and manufacturing technologies. Recycling, upcycling, the cradle-to-cradle paradigm, and end-of-life disposal options need to be integrated in a fully developed industrial ecology for modified wood processes. New advances in wood-based material processing should support and promote efficient product reuse, recycling and end-of-life use, and a low-carbon economy.

The low-carbon economy aims to mitigate climate change and promote sustainable development by decreasing energy consumption, pollution, and emissions while increasing performance. This goal is especially stated within the EU. Therefore, research into thermally based timber processing and the resultant products must place more emphasis on the interactive assessment of process parameters, developed product properties, and environmental impacts. Energy consumption contributes considerably to the environmental impact of thermally treated wood. However, the improved properties during the use phase might decrease the environmental impact of the thermally based timber processing. To achieve sustainable development, certain criteria within a framework of economic, environmental, and social systems must also be followed. The effective use of wood throughout its whole value chain from forest management, through multiple use cycles, and end-of-life disposal can lead to truly sustainable development. This is especially true for the cascading use of wood—sequential use of a certain resource for different purposes (Höglemeier et al 2013). Therefore, to contribute to the low-carbon economy, thermal wood processing should implement the following:

1. Establish a baseline of environmental impacts. Identify and quantify the environmental loads involved, ie the energy and raw materials used and the emissions and waste released. Then evaluate the potential environmental impacts of these loads, which should be followed by an assessment of the opportunities available to bring about environmental improvement.
2. Decrease emissions by redesigning existing technologies.

3. Demonstrate a manufacturer's commitment to sustainability and showcase the manufacturer's willingness to go above and beyond. Therefore, product category rules, which include the requirements for environmental products declarations (EPD) for thermally processed wood, should be defined in an internationally accepted manner based on an open, transparent, and participatory process. Furthermore, EPD in which relevant, verified, and comparable information about the environmental impact of products resulting from thermal processing of wood should be acquired. The EPD can then be used as proof of environmental claims in the public procurement arena.
4. Develop an "upgrading" concept for recovered products resulting from the thermal processing of wood as a source of clean and reliable secondary wooden products for the industry. This will further strengthen TMT market competitiveness and sustainability and mitigate climate change by longer storage of captured carbon in wooden materials.

Development of new building materials should consider human well-being and should go beyond achieving minimal environmental impacts. The sustainable design principles that emphasize decreasing environmental impact of building construction, location, and utilization do so by their material choice, site choice, and energy use across all phases of the building's lifetime. These principles should be performed together with the restorative environmental design (RED) paradigm, which brings together the ideas of sustainable design and biophilic design (Kellert 2008; Derr and Kellert 2013). RED attempts to promote a stronger connection between building occupants and nature. Derr and Kellert (2013) believe RED is the next evolution of "green" design, which offers an opportunity for increased wood use. Wood that is harvested from healthy, well-managed forests is a renewable material that provides carbon storage and satisfies both general tenets of the RED paradigm, sustainability and a connection to nature, making it an ideal material for RED. It is also possible to emphasize the aspects of wood that people recognize as natural, such as grain patterns and color providing building occupants with a connection to nature (Nyrud and Bringlimark 2010). Any modifications to wood should minimize changes that decrease its apparent naturalness (Burnard and Kutnar 2014, 2015). To successfully integrate TMT wood into RED practices, it must have minimal environmental impacts (or positively affect the environment) and be a recognizable element of nature.

CONCLUSION

Thermal treatment of wood is an innovative process currently being implemented in industrial applications. Although many technical aspects of thermal treatment are well known, the fundamental influence of the process on product performance, the environment, and end-of-life scenarios remains unknown. Several studies have dealt with LCA of forests and primary wood products, but most of these tend to be cradle to gate and there is still a lack of data for the whole value chain. The number of LCA studies in the wood sector is relatively limited, and these studies are geographically distributed and use a variety of databases and impact assessment protocols. Comparison among different production processes is not possible given the lack of available information, different system boundaries, and different assessment criteria. A comparison of different production methods using common calculation rules is clearly required. This requires an integrated approach. It is essential to integrate interactive assessment of process parameters, developed product properties, and environmental impacts. To optimize modification processing to minimize environmental impacts, much more information must be gathered about all process-related factors affecting the environment (volatile organic compounds, energy use, end-of-life use, etc.). This study clearly shows that such data are missing or at least are not documented in a systematic and transparent way. Research in the future should investigate and characterize the relationships among thermal modification processing, product properties, and the associated environmental impacts. This will require analysis of the whole value chain, from forest through processing, installation, in-service use, end of life, second and third life (cascading), and ultimately incineration with energy recovery.

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