# Market projections of cellulose nanomaterial-enabled products — Part 2: Volume estimates

JOHN COWIE, E.M. (TED) BILEK, THEODORE H. WEGNER, AND JO ANNE SHATKIN

**ABSTRACT:** Nanocellulose has enormous potential to provide an important materials platform in numerous product sectors. This study builds on previous work by the same authors in which likely high-volume, low-volume, and novel applications for cellulosic nanomaterials were identified. In particular, this study creates a transparent methodology and estimates the potential annual tonnage requirements for nanocellulose in the previously identified applications in the United States (U.S.). High, average, and low market penetration estimates are provided for each application. Published data sources of materials use in the various applications provide the basis for estimating nanocellulose market size. Annual U.S. market potential for high-volume applications of nanocellulose is estimated at 6 million metric tons, based on current markets and middle market penetration estimates. The largest uses for nanocellulose are projected to be in packaging (2.0 million metric tons), paper (1.5 million metric tons), and plastic film applications (0.7 million metric tons). Cement has a potential nanocellulose market size of over 4 million metric tons on a global basis, but the U.S. market share estimated for cement is 21,000 metric tons, assuming market penetration is initially limited to the ultra-high performance concrete market. Total annual consumption of nanocellulose for low-volume applications is less than 10% of the high-volume applications. Estimates for nanocellulose use in emerging novel applications were not made because these applications generally have yet to come to market. The study found that the majority of the near-term market potential for nanocellulose appears to be in its fibrillar versus crystalline form. Market size estimates exceed three prior estimates for nanocellulose applications, but the methodologies for those studies are not transparent.

***Application:*** This work develops a methodology for estimating market volumes for nanocellulose in high-volume, low-volume, and emerging sector applications and presents initial market estimates. The methodology and estimates may be used for planning and research decision making.

By deconstructing material to the nano scale (between 1 and 100 nm), materials — including cellulose — can be utilized in new ways to provide enhanced or novel properties. The basic structure of plant walls consists of cellulose, the earth's most abundant organic chemical. Research on nanocellulose shows that the material has promise in a number of applications, but evaluations of the size of potential nanocellulose markets are limited. Such information should be of interest to forest products industries from the perspective of both nanocellulose production and of nanocellulose use in its products. Such information should also be of interest to forest owners and land managers planning for resource flows from their forested lands.

Our objective is to undertake a systematic evaluation of potential markets for nanocellulose. First, markets are divided into three groups (high volume, low volume, novel applications); then the potential volume of nanocellulose is estimated based on U.S. market size, anticipated adoption rates, and published literature to derive a total nanocellulose material demand; then this latter estimate is used to predict areas of forestland required to supply the demand for wood fiber, if wood remains the source for the nanocellulose.

This study follows previous work by the same authors [1] in which we identified and described a number of potential markets for nanocellulose and divided those markets into three groups. High volume and low volume uses are likely to exist within the next 5 to 10 years. Novel uses have the potential to become significant but do not have comparable current markets to estimate volumes; they may also have technological hurdles to overcome before they come to market.

Potential market size in this study was estimated by considering applications where cellulose nanomaterials are likely to replace existing materials in products and be used at a certain rate for some fraction of an entire existing market. This market study first estimates the tonnage of cellulose nanomaterials that could be used. Therefore, the applications that are studied in greatest depth are those that are estimated to consume the highest volume of wood to make cellulose nanomaterials. For this study, we assumed that the cellulose nanomaterial-enabled product will be economically competitive with the product it is either enhancing or replacing. The degree to which the new cellulose nanomaterial-enabled product is adopted in a given market is then estimated based on knowledge of the existing product with which it is competing.

This study represents an initial analysis of the potential size and nature of products and markets that may ultimately be positively affected by cellulose nanomaterials. This is not a standalone market study but rather a starting point for a more comprehensive analysis of potential growth of the market for cellulose nanomaterials. Estimates of various potential uses of cellulose nanomaterials are preliminary but are constructed transparently. Thus, they serve as a foundation for updating estimates when better information becomes available. Our goal is to better estimate the future potential for this emerging novel material. The forest products industry and end users will have a vested interest in development and growth of these markets. The potential area of forestland used for the production of wood to make cellulose nanomaterials will be of particular interest to those who manage forestland publicly and privately.

## METHODOLOGY

Although potential market size for a new product or material is a very important marketing metric, a generally acknowledged best method for calculating it does not exist. Unfortunately, different methods may yield varied estimates for several reasons, including variations in how size is measured (tonnage versus dollars), where measurements are taken (shipments from manufacturers versus sales), market definition, and measurement error.

Our approach was to identify a broad range of potential manufacturing markets for cellulose nanomaterials and then classify them according to the volume of cellulose nanomaterial they are likely to consume, as described in Part I of this analysis [1]. For each of these markets, forecasts were made based on specified engineering metrics, current market sizes for existing products, and reasonable penetration rates for cellulosic nanomaterials into those markets.

Although successful forecasting depends on future events that may transform the marketplace, determining potential market size often starts with estimates from recent sales. Potential market size in this study was estimated by taking recent industry volume as the first approximation. Market size was determined from the following information sources: government data, trade association data, and financial data from major corporations. Census data were also used when needed, because they are authoritative figures on production and sales volume for fairly broadly defined product classes in the U.S. Other industry sales volume data were found in trade publications, archives of trade associations, professional society journal articles, and published presentations from professional society meetings. Surveys of product volume and use were not used in this study, because high-quality market data were found in the open literature, and professionals with a stake in the market in question have an incentive to under-report potential size to prevent competitors from entering the market. Consequently, survey data from such professionals were considered suspect and not used in the market size estimates. The companion paper describes the applications considered and the supporting data for their selection [1].

Because this market study was performed for an emerging material not widely used in commercial applications, key information for potential products and markets that might use cellulose nanomaterials were derived from numerous technical presentations, peer reviewed publications, and reports of potential applications. For select applications, estimates of global production were made. When no worldwide data were available, the conversion was made by distributing national figures in proportion to such measures as population and gross domestic production. In summary, market potential estimates reported here were developed from available data and market reports on existing products and their present-time market size.

In the absence of present market size data, corollary or proxy data were used to estimate market size potentials. Data on complementary goods, for example, can serve this purpose; the market potential of automobile body panels for replacement can be estimated from data on the production of cars and light trucks and the average weight of the steel sheet used in their production. As an example, the following section provides a typical estimate for the automotive body market, including rationale and calculation.

### *Example: Automotive body market estimate*

The average weight for unibody vehicles (cars) is 1.57 metric tons (3,471 lb) and for full frame vehicles (light trucks) is 2.08 metric tons (4,584 lb). One-third of the automobile weight is in the body, but only half of that is non-structural where steel can easily be replaced with high-performance composites. The number of vehicles manufactured in the U.S. was 15.8 million (84.1 million globally) in 2012 [2]. Roughly half the vehicles are light trucks and half are cars. Assuming the economics are favorable to replace all of the non-structural steel sheet in the automobile bodies with cellulose nanomaterial composites, then the size of the market is simply half of one-third the weight of the average for two types of vehicles times the number of vehicles produced. The calculation for the weight of the steel is then:

1/3 x 1/2 (1.57 t/vehicle + 2.08 t/vehicle)/2 x 15.8 million vehicles/year = 4.8 x $10^6$ metric tons

The specific strength (strength-to-weight ratio) of fiber-strengthened polymers is on the order of 780 kN m/kg, compared with 250 kN m/kg for sheet steel [3]. The modulus of elasticity is about 200 GPa for steel, compared with about 150 GPa for fiber–polymer composites [3], which limits potential weight reduction to roughly half, because a composite epoxy resin polymer matrix is approximately 65% fiber content. The density of epoxy resin is nearly identical to cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs), 1.5 to 1.6 g/cm$^3$. Therefore, the content of 65% fiber in a 2.4 million metric ton market (half the weight of the 4.8 million metric ton sheet steel market) will be 1.5 million metric tons.

## ASSUMPTIONS

Market penetration rates were estimated assuming favorable performance, technological readiness, and economics, projected 6 to 10 years forward. The time scale for these achievements is not known with certainty, hence the estimates may be low because market size may be larger in the future, or the economics could change drastically with technological improvements. Two major assumptions made in all calculations are (1) that cellulose nanomaterials can reach the price target of US$4.4/kg to US$11/kg ($2-$5/lb) [4], and (2) that at this price, investments in producing cellulose nanomaterial-enabled products will be of sufficiently high profit and low risk that they will be competitive with exiting investments or new investments to produce products they are targeted to replace.

The calculations were made using the present market size for products that cellulose nanomaterial-enabled materials could potentially replace. No attempt was made to predict growth of markets for individual products, so market size calculations are based on current market size and therefore may be conservative. Also, no attempt was made to estimate the time to attain full market penetration for any product considered. Clearly, some industries can move more quickly with innovations and investments in their respective marketplaces than others.

Although not without uncertainty, using current market size estimates as a basis likely underestimates potential market size at the time of adoption of cellulose nanomaterials introduction if we assume general increases in production for industries where adoption will occur. Although some products may be nearing commercialization, most applications are anticipated in the next 6 to 10 years, pending necessary technical and manufacturing developments that make commercial use of two common types of nanocellulosic material (cellulose nanocrystals [CNCs] and cellulose nanofibers [CNFs]) reliable and competitive with current technologies. Further, some applications under development are for completely novel products that have little or no current market (such as flexible electronic products) and additive manufacturing (also known as 3D printing), for which market volumes were not estimated.

Three estimates were made for the market penetration rate — low, average, and high. The rationale is provided for the penetration rate for each product that was evaluated. Large spreads in low and high estimates are indicative of high uncertainty in profitability and risk associated with investments needed to displace an existing product. Conversely, a low spread in the estimate is indicative of somewhat more (but still limited) confidence in sufficient profitability and acceptable risk to gain a particular market share.

Market potential estimates reported here were developed entirely from available data and market reports on existing products and their current market size. Every potential product cannot possibly be identified and hence was not included in the present analysis of total market size for cellulose nanomaterials.

It is assumed that no unforeseen changes or "black swans" on the horizon in the cellulose nanomaterials marketplace would completely alter predictions in either direction. Some black swans might include an alternative process for manufacturing cellulose nanomaterials less expensively; a mandate from the federal government requiring sustainable renewable materials be used over their alternatives; an increase in risk from environmental, health, and safety considerations; public rejection of nanotechnology products; or discovery of an alternative, cost-effective material possessing phenomenal properties. Any of these would completely alter the predictions presented here.

## ESTIMATES

This market study was performed on a material with near-term potential for commercialization. Because very few cellulose nanomaterial-enabled products exist in the marketplace today, the potential market size for cellulose nanomaterials was determined from complementary goods that are targeted for displacement by cellulose nanomaterial-enhanced products. Total market sizes for new products containing cellulose nanomaterials were estimated from available data pertaining to the existing targeted products.

Three types of estimates are made: high volume–global, high volume–U.S. market, and low volume applications. Several low volume and novel application categories either have no analogous products existing today or have no market data available to support a market size estimate. Therefore, these products exhibit the highest uncertainty in estimates of market size and degree of market penetration, and are not included in the estimates.

### *High volume global applications*

<u>Cement</u>

Annual production of cement on a worldwide basis is 3.3 billion metric tons. Recent research on toughening and strengthening concrete through minute additions of cellulose nanomaterials has shown great promise. A very small addition (0.5 wt%) of cellulose nanomaterial reinforcement is optimal in improving fracture toughness resistance of concrete [5]. Although others have suggested as much as 3% addition by volume [6], a 0.5 wt% addition of cellulose nanomaterials translates into 4.1 million metric tons of cellulose nanomaterials for the huge 3.3 billion metric ton global cement market.

Market penetration can only be estimated based on the mechanical property improvement for the product and its positive environmental attributes. Even though cellulose nanomaterial costs more on a weight basis than the cement it displaces, the strength of concrete is increased by 20% with cellulose nanomaterials, so the addition of cellulose nanomaterials could result in a 17% reduction in material needed, which would offset the added cost of the cellulose nanomaterial addition for the construction industry. Because emissions average 0.83 metric tons of $CO_2$/metric ton of cement produced globally [7], the addition of nanocellulose to cement could result in a reduction of almost 500 million metric tons of carbon emissions/year (assuming 3.3 billion metric tons of $CO_2$ is released). Material reductions may also result because of reduced mass required in multi-story building foundations and lower levels; they would not need to carry as much load because upper levels built with cellulose nanomaterial-enhanced concrete panels would be lighter.

The cement industry is one of two primary industrial producers of carbon dioxide ($CO_2$), creating up to 5% of worldwide anthropogenic emissions of this gas, of which 50% is from the chemical process and 40% from burning fuel [8]. Market resistance may come from construction standards regarding minimum strength levels in the cement, so there would not be an immediate reduction in cement usage until the codes are updated to reflect these mechanical property improvements. Thus, timing is uncertain, although the argument that the benefits create real value is straightforward. At a minimum, nonstructural uses of cement are anticipated to face few barriers to introduction.

Given the uncertainty, it was assumed that over time one can expect to see the global market for cellulose nanomaterials in cement range from 0 to 8.25 million metric tons (50% penetration), with an average estimate of 4.13 million metric tons (25% penetration). Because of the hurdles to change current structural standards, estimates for the U.S. market are based only on the category of ultra-high performance concrete, at an estimated 21,200 metric tons/year, assuming 11% cement in concrete, and 63% of 48 million metric tons per year is structural, again with 0.5% volume as nanocellulose, at a 75% penetration rate. **Table I** presents all the data for potential high volume applications for cellulose nanomaterials.

Automotive body components

Globally, the automotive industry manufactures about 84.1 million cars and light trucks per year. One can expect the market will shift to about 20% cellulose nanomaterial-rein-

| Market and/or Application | U.S. All estimates calculated from current market data | | | | | | Global All estimates calculated from current market data[1] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pessimistic Estimate | | Reasonable Estimate | | Optimistic Estimate | | Pessimistic Estimate | | Reasonable Estimate | | Optimistic Estimate | |
| | % | Metric Tons (thousands) | % | Metric Tons (thousands) | % | Metric Tons (thousands) | % | Metric Tons (thousands) | % | Metric Tons (thousands) | % | Metric Tons (thousands) |
| Packaging coatings | 15 | 855 | 20 | 1140 | 25 | 1425 | 15 | 3958 | 20 | 5278 | 25 | 6297 |
| Replacement for plastic packaging | 1 | 390 | 2.3 | 897 | 4 | 1560 | 1 | 1806 | 2.3 | 4153 | 4 | 7222 |
| Plastic film replacement | 5 | 364 | 10 | 727 | 15 | 1091 | 5 | 1683 | 10 | 3366 | 15 | 5049 |
| Hygiene and absorbent products | 15 | 420 | 25 | 700 | 50 | 1400 | 15 | 1944 | 25 | 3241 | 50 | 6481 |
| Automotive body | 15 | 240 | 20 | 320 | 50 | 800 | 15 | 2700 | 20 | 3573 | 50 | 8950 |
| Textiles for clothing | 25 | 275 | 50 | 550 | 75 | 825 | 25 | 1273 | 50 | 2543 | 75 | 3891 |
| Paper filler | 15 | 310 | 25 | 517 | 35 | 724 | 15 | 1437 | 25 | 2394 | 35 | 3352 |
| Packaging filler | 15 | 310 | 25 | 517 | 35 | 724 | 15 | 1437 | 25 | 2394 | 35 | 3352 |
| Paper coatings | 15 | 351 | 20 | 486 | 25 | 585 | 15 | 1625 | 20 | 2167 | 35 | 2708 |
| Automotive interior | 15 | 81 | 20 | 108 | 25 | 135 | 15 | 420 | 20 | 587 | 25 | 700 |
| Cement | 50 | 14 | 75 | 21 | 100 | 28 | 0 | 0 | 25 | 4130 | 50 | 8250 |
| **TOTALS** | — | **3,610** | — | **5,966** | | **9,297** | — | **18,283** | | **32,829** | — | **56,481** |

[1] Global estimates based on gross domestic product (GDP), except where noted in the text (cement, automotive applications, and plastic packaging).

***I. Potential applications for high volume cellulose nanomaterials.***

forced composite body components, ranging from a low of 2.7 million metric tons (15% penetration) to 9.0 million metric tons (50% penetration), with an average estimate of 3.6 million metric tons (20% penetration).

Automotive interior

Annual production of cars and light trucks in the world is 84.1 million vehicles. One can expect the market will shift to nearly all cellulose nanomaterial-reinforced composite interior components, ranging from a low of 420,000 metric tons (15% penetration) to 700,000 metric tons (25% penetration), with an average estimate of 587,000 metric tons (20% penetration).

Replacement for plastic packaging

Annual production of plastic packaging on a global basis is 78 million metric tons. CNFs could conceivably replace flexible plastic packaging (22.5 million metric tons); a 30 wt% addition of CNFs to strengthen rigid plastic packaging could lead to thinner, lighter-weight bottles and containers [9,10].

Bio-plastics could become significant drivers as packaging market demand gradually shifts from biodegradable and compostable polymers towards bio-packaging based on renewable and sustainable materials. By 2020, bio-plastics are expected to reach 884,000 metric tons per year [11]. The market penetration of bio-plastics, and as a result the potential market as additives to bio-plastics, is not as favorable as for other products and markets. The feedstock for polymers (natural gas) is relatively inexpensive and is expected to remain so into the foreseeable future. Environmentally conscious consumers may represent the most significant market for bio-plastics and cellulose nanomaterials. This may be driven by OEM supply chains seeking to differentiate themselves on the basis of renewability, or by governmental bans on certain categories. Here, a fairly low adoption rate of 4.1 million metric tons (2.3% penetration) is estimated. The low estimate is 1.8 million metric tons (1% penetration), and the high estimate is 7.2 million metric tons (4% penetration).

### *High volume U.S. market applications*

Packaging coatings

Annual production of paper-based packaging in the United States is 82 million metric tons [12]. Research at UPM reveals that a 3 g/m² coating of CNF will permit less use of nanoclays, resulting in weight reduction of the paper by as much as 12.5 g/m² [13], while maintaining the paper's strength. UPM is looking to use cellulose nanomaterials at the wet end of the paper machine to improve strength properties and to replace synthetic binders in paper coatings [14]. Research performed at the University of Maine confirms that the 3 g/m² CNF works well. Applying 3 g/m² to both sides of the entire current U.S. production of paperboard results in the usage of approximately 5.7 million metric tons of cellulose nanomaterials.

Market penetration can be estimated based on the reduction in paperboard weight, which is an advantage for use as shipping containers, and a potential reduction in cost. Strengthening with cellulose nanomaterials is a low-cost solution to reduce weight (through reduced thickness) to help customers reduce shipping costs. Given an improvement in both cost and performance, one could expect a large percentage of the market to shift toward this technological advancement.

Although we anticipate the paperboard market will move toward nearly full adoption of cellulose nanomaterial coatings, it is assumed the market for cellulose-nanomaterial-coated paperboard may range from a low of 855,000 metric tons (15% penetration) to 1.425 million metric tons (25% penetration), with an average estimate of 1.14 million metric tons (20% penetration).

Paper coatings

Annual production of coated paper in the United States is 34 million metric tons [12]. By adding a coating of cellulose nanomaterials to the surface of paper, substantially more clay can be packed into this nano-layer, thereby permitting use of less pulp/cellulose in the paper thickness, which reduces cost while maintaining the paper's properties and appearance. This results in approximately 3.4 million metric tons of cellulose nanomaterials being used if the entire market converts to this technological advancement. Lower cost of the final product will shift the market, resulting in an estimate ranging from a low of 351,000 metric tons (15% penetration) to 585,000 metric tons (25% penetration), with an average estimate of 468,000 metric tons (20% penetration).

Paper filler

As stated previously, annual production of coated paper in the United States is 34 million metric tons. Research indicates that 2% to 10% addition of CNF as filler will significantly strengthen and toughen paper by 50% to 90% [15]. If the entire market shifted to CNF filler, one can expect to use 2 million metric tons of cellulose nanomaterials. This cellulose nanomaterial filler technology represents a relatively low-cost solution to increasing the strength of paper with small additions of CNF. It is reasonable to expect that the filler toughening technology will be adopted by a large percentage of the market. This translates to a range of cellulose nanomaterial usage from a low of 310,000 metric tons (15%) to 724,000 metric tons (35% penetration), with an average estimate of 517,000 metric tons (25% penetration).

Packaging filler

As stated previously, annual production of paperboard in the United States is 82 million metric tons; and as stated previously, addition of 2% to 10% CNF as filler will significantly strengthen and toughen paper. If the entire market shifted to CNF filler, this would require 2 million metric tons of cellulose nanomaterials. This cellulose nanomaterial filler technology represents a relatively low cost solution to increasing strength of paperboard with small additions of CNF. It is anticipated that filler toughening technology will be adopted by a large percentage of the market. Here, a range of cellulose nanomaterials usage from a low of 310,000 metric tons (15% penetration) to 724,000 metric tons (35% penetration), with an average of 517,000 metric tons (25% penetration), is estimated.

Replacement for plastic packaging

Regulatory bans are creating demand for plastic alternatives, such as the recent bans in the U.S. of polystyrene in San Jose, CA, or the ban in San Francisco, CA, on plastic shopping bags. We assume low adoption rates of 390,000 metric tons (1% penetration) to 1.56 million metric tons (4% penetration), with a referenced average estimate of 897,000 metric tons (2.3% penetration) [11]. Although retailers may drive demand further, it is still uncertain how widespread the request for plastic alternatives will become.

Plastic film replacement

Annual production of plastic film on a global basis is about 7.3 million metric tons. Based on expected performance properties, all plastic film could be replaced by CNF [16]. Plastic films are being developed that will allow food items to stay fresher longer. These films are packed with silicate nanoparticles to reduce the flow of oxygen into the package and the leaking of moisture from the package [17]. Feedstock for polymers (natural gas) is relatively inexpensive and is expected to remain so in the near term. Environmentally conscience consumers may drive the market for bio-plastics. Estimates of cellulose nanomaterials usage range from a low of 364,000 metric tons (5% penetration) to 1.091 million metric tons (15% penetration), with an average estimate of 727,000 metric tons (10% penetration).

Hygiene and absorbent products (disposable diapers)

The market size for disposable diapers and incontinence pads is 98 billion units per year [18], or 2.8 million metric tons of absorbent material. Cellulose nanomaterials are naturally absorbent, holding several times their weight in water, and could replace absorbent materials in these products.

Because there is strong consumer preference for biodegradable diapers over non-biodegradable diapers, especially in Europe and the U.S., significant penetration of this market by cellulose nanomaterials to safer and more sustainable absorbent diapers can be expected. A range of cellulose nanomaterial adoption in the United States from 420,000 metric tons (15% penetration) to 1.4 million metric tons (50% penetration), with an average of 700,000 metric tons (25% penetration), is estimated.

Textiles for clothing

Annual production of cotton and rayon for clothing applications on a global basis is currently 22 million metric tons. Rayon is made from cellulose and is a replacement for cotton fiber. Cotton prices are high due to shortage of land for growing cotton coupled with an ever-increasing global population. No reference was found to support the usage of cellulose nanomaterials in textiles, but an estimate of 5 wt% addition to the fabric would yield a total potential market size for cellulose nanomaterials of 1.1 million metric tons.

Some understanding of trends in textiles used in clothing is necessary to estimate the market penetration rate. Cotton is rapidly losing market share to other materials, mostly to rayon and polyester. Rayon is more breathable than cotton but weaker. Strengthening the weak rayon fibers with cellulose nanomaterials would improve overall strength and wear resistance.

The market penetration rate of cellulose nanomaterial usage is assumed to be in the range from a low of 275,000 metric tons (25% penetration) to 825,000 metric tons (75% penetration), with a conservative average estimate of 550,000 metric tons (50% penetration). This does not account for specialty applications, such as for military, sporting goods, high-fashion use and upholstery, where strength and optical properties may increase market share. These would be anticipated to be low volume applications.

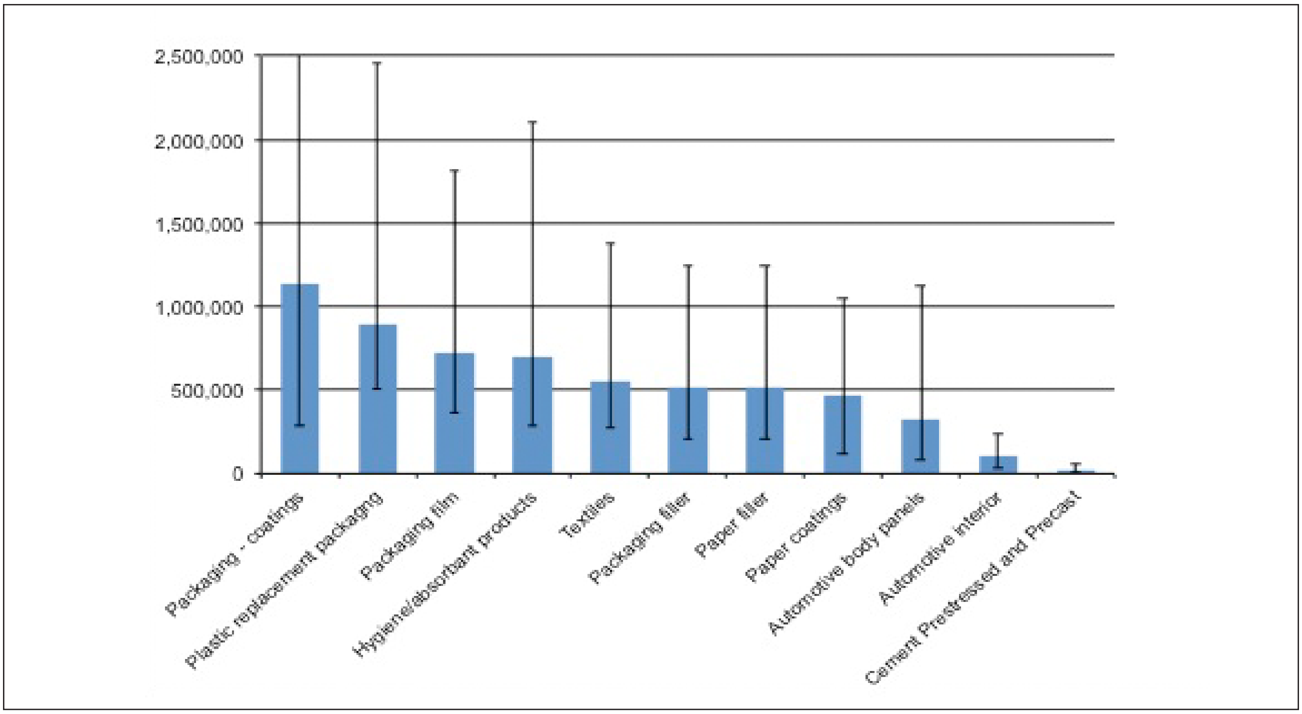
Automotive body components

About 15.8 million cars and light trucks are manufactured in the U.S. each year. Approximately one-third of the automobile weight is in body components. Given that the average vehicle weight is a little over two tons, total U.S. market for automotive body components is 9.7 million metric tons. A major effort is currently underway with automotive manufacturers at Oak Ridge National Laboratory that is leading toward replacement of steel body and frame components with carbon fiber composites to lighten the vehicles and increase fleet fuel mileage [19]. The driving force is the recent raising of the federal fuel efficiency standard to 4.32 L/100 km (54.5 miles/gallon) by 2025 [20]. High feedstock cost and manufacturing issues with carbon fiber composites need to be resolved before full manufacturing implementation by automobile manufacturers.

An alternative material for lightweight body components is cellulose nanomaterial-reinforced composites. Given the probable cost advantage of cellulose nanomaterials over carbon fiber, cellulose nanomaterial-reinforced composites may soon be used for automotive body parts. The U.S. market for cellulose nanomaterial-reinforced composite body components may range from a low of 240,000 metric tons (15%) to 800,000 metric tons (50% penetration), with an average estimate of 320,000 metric tons (20% penetration).

Automotive interiors

In addition to automotive body components, about 825,000 metric tons of plastic is used in car and light truck interiors in the U.S. each year. In a typical epoxy resin polymer matrix composite, the fiber content is approximately 65% by weight. Because the density of epoxy resin is nearly identical to both CNFs and CNCs [3] (i.e., 1.5 to 1.6 g/cm$^3$), total fiber content in a 0.825 million metric ton market is 0.54 million metric tons.




***1. Annual U.S. tonnage estimates for nanocellulose.***

The new federal fuel efficiency standard is an incentive to replace heavier materials with lightweight composites. In addition, there is a move toward more renewable and sustainable materials. In 1997, the European Commission proposed a Directive that aims to make vehicle dismantling and recycling more environmentally friendly by setting clear targets for the recycling of vehicles. In 2000, this legislation was officially adopted by the European Parliament and Council [21], and this proposal inches forward in the European Union. Automobile manufacturers prefer to source their parts on a global basis. Given these two incentives, one can expect a complete market replacement of interior components with high-strength, lightweight composites.

It is assumed the market will shift toward all cellulose nanomaterial-reinforced composite interior components, ranging from a low of 81,000 metric tons (15% penetration) to 135,000 metric tons (25% penetration), with a conservative average estimate of 108,000 metric tons (20% penetration).

Prestressed and precast concrete

This concrete market is a subset of the construction cement market. We give it special attention because this segment, representing the high end of the concrete market, is anticipated to move quickly toward the high-strength addition of cellulose nanomaterials. About 11% of cement is used for these high-strength concrete products [22], which translates to 8 million metric tons of cement. Given that a 0.5 wt% addition of cellulose nanomaterials reinforcement to cement is optimal in improving fracture properties of ultra-high performance concrete (UHPC) [23], then the total size of this market for cellulose nanomaterials is 28,400 metric tons/year. However, one could expect this entire market segment to quickly use cellulose nanomaterials because they would substantially improve performance characteristics of the final product. Additionally, the amount of CNFs will not substantially increase the cost of the concrete, because the cost of UHPC is 10 times greater than that of conventional concrete. For this subset of the market, we estimate 21,200 metric tons/year at a 75% adoption rate, with a low of 14,200 metric tons/year (50%) and a high of 28,400 metric tons/year (100%).

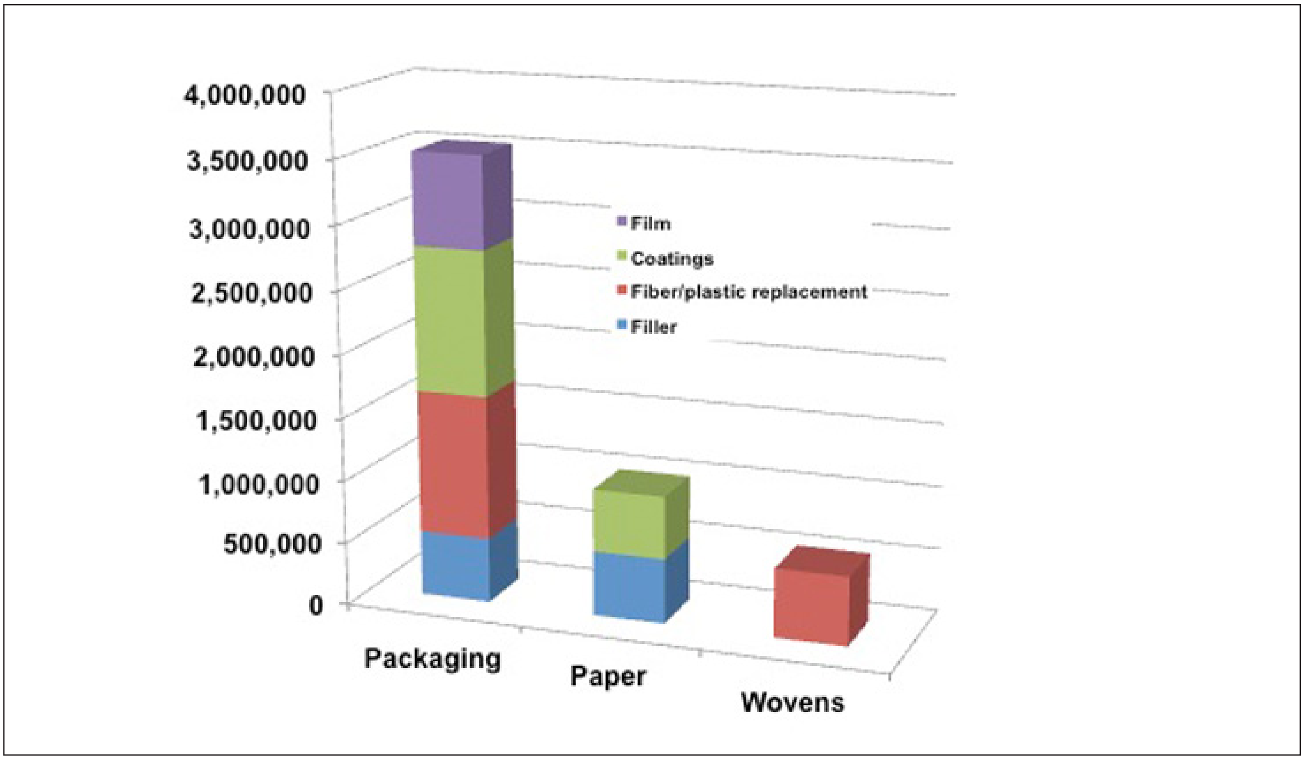
### *Summary of high volume cellulose nanomaterials consumption estimates*

Estimated volume of nanocellulose in the high volume categories totals about 6 million metric tons for the U.S. market annually, not accounting for any market growth over time (Table I). These values are converted to global estimates of about 33 million metric tons based on a GDP conversion. Although not exact in each category (e.g., automobile rates per capita are higher in the U.S. than elsewhere), these global estimates are indicators of a possible market size overall. **Figure 1** shows the relative contributions of different applications. Projections for the forest products sectors are shown in **Fig. 2**.

### *Low volume applications*

Gypsum wallboard facing

Annual production of gypsum wallboard facing (a paper product) in the United States is currently 895,000 metric tons [12].




***2. Annual tonnage estimates by forest products subsector.***

A 2% to 10% CNF filler will significantly strengthen and toughen paper by 50% to 90% [15]. Cellulose nanomaterials as a coating would also aid in mold, mildew, and moisture resistance. For a 30-g/m$^2$ coating of CNF, total market size for cellulose nanomaterials is 0.022 million metric tons. Given that savings due to reduction in fiber needed per unit area is greater than the added assumed expense of the cellulose nanomaterials [24], one can expect the market will shift to a large percentage of cellulose nanomaterial-reinforced gypsum wallboard facing, ranging from a low of 5,500 metric tons (25%) to a high of 16,500 metric tons (75% penetration), with an average estimate of 11,000 metric tons (50% penetration). **Table II** provides details on the estimated range of consumption for each low volume product enhanced by cellulosic nanomaterials.

<u>Insulation in construction applications</u>

The construction industry uses 23.1 billion square meters of R-1 insulation value per year [25]. Aerogel foams are 5 to 10 times more insulating than fiberglass per unit volume [26,27]. However, their density is exceptionally low (40 kg/m$^3$) because they are mostly composed of air. Although the existing insulation market is enormous, given aerogel's low density and super-insulating properties per unit volume, the total market for aerogel insulation is estimated to be 2.4 million metric tons.

The cost comparison of fiberglass insulation with cellulose nanomaterials aerogels is unknown. Cellulose nanomaterial aerogels may be more cost competitive with foam insulation. Fiberglass controls approximately 85% of the U.S. home insulation market, whereas cellulose is currently 10% and spray polyurethane foam (SPF) is a little less than 5% [28]. Given the very low cost of fiberglass insulation, we estimate only a small percentage of cellulose nanomaterial aerogel insulation market penetration, ranging from a low of 48,000 metric tons (2% penetration) to 168,000 metric tons (7% penetration), with a conservative average estimate of 120,000 metric tons (5% penetration).

<u>Aerospace structural components</u>

Approximately 1,500 commercial aircraft are produced each year. Given this relatively low number, the total market size for all structural composites is 8,800 metric tons [29]. As economic conditions improve and new programs come online, aircraft component manufacturers are ramping up composites production to meet airline demand. With roughly 65% of the composite made from reinforcing fiber, the potential market size for cellulose nanomaterials is currently 5,750 metric tons. Given that CNF-reinforced composites will compete directly with ultra-high strength carbon fiber-reinforced composites in the direct replacement of aluminum alloy sheet, full market penetration is not anticipated. The market size may range from 575 metric tons (10% penetration) to 2,900 metric tons (50% penetration), with an average estimate of 1,700 metric tons (30% penetration) per year.

<u>Aerospace OEM interiors and aftermarket interiors</u>

Approximately 15,000 metric tons of composite materials are

| Market and/or Application | U.S. All estimates calculated from current market data | | | | | | Global All estimates calculated from current market data[2] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pessimistic Estimate | | Reasonable Estimate | | Optimistic Estimate | | Pessimistic Estimate | | Reasonable Estimate | | Optimistic Estimate | |
| | % | Metric Tons (thousands) | % | Metric Tons (thousands) | % | Metric Tons (thousands) | % | Metric Tons (thousands) | % | Metric Tons (thousands) | % | Metric Tons (thousands) |
| Wallboard facing | 25 | 5.5 | 50 | 11.0 | 75 | 16.5 | 25 | 25 | 50 | 51 | 75 | 76 |
| Insulation | 2 | 48 | 5 | 120 | 7 | 168 | 2 | 222 | 5 | 556 | 7 | 778 |
| Aerospace structure | 10 | 0.6 | 30 | 1.7 | 50 | 2.9 | 10 | 3 | 30 | 8 | 50 | 13 |
| Aerospace interiors | 50 | 5 | 75 | 7 | 100 | 10 | 50 | 23 | 75 | 32 | 100 | 46 |
| Aerogels for the oil and gas industry | 25 | 150 | 50 | 300 | 75 | 450 | 25 | 694 | 50 | 1389 | 75 | 2083 |
| Architectural paint | 10 | 5 | 25 | 12 | 40 | 20 | 10 | 23 | 25 | 56 | 40 | 93 |
| Special purpose paint | 50 | 12 | 75 | 18 | 75 | 24 | 50 | 56 | 75 | 83 | 75 | 111 |
| Paint for OEM applications | 50 | 6 | 75 | 12 | 100 | 18 | 50 | 28 | 75 | 56 | 100 | 81 |
| **TOTALS** | — | **230** | — | **480** | — | **710** | — | **1,075** | — | **2,230** | **35** | **3352** |
| [2]Global estimates are scaled up on the basis of GDP. | | | | | | | | | | | | |

***II. Potential applications for low volume cellulose nanomaterials.***

being used in both new aircraft and retrofitted aircraft in replacing aluminum alloy parts. The retrofitting market is actually twice as large as the new aircraft market. The potential market for cellulose nanomaterials is 9,800 metric tons because existing aircraft could benefit from these lighter materials [29]. Given that CNF-reinforced composites will compete directly with relatively more expensive but stronger carbon fiber-reinforced composites, market penetration will most likely be high as interior cost is a larger driver than ultra-high strength. As a result, market size is estimated to range from 5,000 metric tons (50% penetration) to 10,000 metric tons (100% penetration), with a most likely estimate of 7,000 metric tons (75%).

<u>Aerogels for the oil and gas industry</u>

Cellulose nanomaterials can be used as fracturing fluid in oil recovery applications [30]. Aerogels are ultra-lightweight sponge and will effectively clean up spills of all kinds of oils and solvents, such as gas fracking liquids, and allow for absorbed oil to be recovered for use. Aerogels are super light, composed of about 96% air, 2% polymer, and cellulose nanomaterials. Chemically, aerogels made with cellulose nanomaterials hate water and love oil — the perfect combination. Current market size for aerogels in this industry is 608,000 metric tons. Cellulose nanomaterial aerogels may prove to be a perfect replacement for silica aerogels in the oil and gas industry, because they have equal or better performance at a fraction of the likely silica nanomaterials price. Given these advantages, a relatively large percentage of cellulose nanomaterials adoption in the aerogel market is expected, ranging from a low of 150,000 metric tons (25%) to 450,000 metric tons (75% penetration), with an average estimate of 300,000 metric tons (50% penetration). While other uses in the oil and gas industry may be developed (e.g., viscosity modifier), estimates for these applications were not identified.

<u>Paint</u>

Three classes of paint are considered: architectural, special purpose coatings, and product coating for OEM applications [31].

Architectural paints account for 2.494 trillion liters (659 billion gallons) per year of the overall paint and coating market [31], including flat, semi-gloss/enamel, primers, clears/sealers/varnish, stains, sealers, and deck and floor. A 2% by weight addition of cellulose nanomaterials enhances viscosity and flow characteristics of the paint [10]. As a result, total potential market size for cellulose nanomaterials is anticipated to be 48,000 metric tons. Given that these paints have price pressure to stay low for consumer acceptance, we can expect a market range from a low of 5,000 metric tons (10% penetration) to 20,000 metric tons (40% penetration), with an average estimate of 12,000 metric tons (25% penetration).

Special purpose coatings markets include aerosols, arts and crafts, automotive and machinery refinishing, bridge maintenance, high-performance maintenance, metallics, multicolored, roof, swimming pool, and traffic marking. These coatings account for 658 billion liters (174 billion gallons) per year. As a result, total potential market size for cellulose nanomaterials is estimated at 24,000 metric tons. Given that these are higher-end paints with less price pressure, we can expect a high market, ranging from a low of 12,000 metric tons (50% penetration) to 24,000 metric tons (100% penetration), with an average estimate of 18,000 metric tons (75% penetration).

Product coating for OEM application paints consist of powder coatings, automotive, wood furniture/fixtures, nonwood furniture/fixtures and business equipment, other OEM products, coil sheet and strip, containers and closures, machinery and equipment, paper film and foil, heavy duty trucks and buses. These coatings account for 1.234 trillion liters (326 billion gallons) per year. As a result, the total potential market size for cellulose nanomaterials is only 24,000 metric tons. Given that these paints are higher-end paints with less price pressure, we can expect a high market range from a low of 6,000 metric tons (50% penetration) to 18,000 metric tons (100% penetration), with an average estimate of 12,000 metric tons (75% penetration).

### *Summary of low volume cellulose nanomaterials consumption estimates*

Low volume applications for cellulose nanomaterials are forecast to be about 480,000 metric tons annually in the U.S. and 1.75 million metric tons globally (Table II). Our forecasts are bracketed in wide ranges, with both our U.S. and world averages falling within about ±50%. Even at the high range, our estimates show that these low volume applications are not anticipated to account for relatively large volumes of cellulose nanomaterials.

### *Other low volume and novel applications*

A number of other proposed applications for CNC and CNF are excluded from this market size estimate due to lack of information about market size or potential. These are described in the companion paper [1] and include air and water filtration, industrial viscosity modifiers, sensors, cosmetics, drug delivery, electronics applications (including organic LEDs, recyclable and printed electronics, recyclable photovoltaic cells, flexible electronics), additive manufacturing (3D printing), bone and tissue scaffolding, and modified thermoset adhesives. Either these applications have no existing analogous products or no market data were identified to support a market size estimate. Therefore, these products exhibit the highest uncertainty in estimates of market size and degree of market penetration. No estimates were made in this category, but they represent several potential large markets currently under exploration by research groups in North America and elsewhere.

### *Impact on forestland in the U.S.*

The issues of forest health and wildfires in North America make it useful to estimate how much forestland might be affected by the production of approximately 6.4 million metric tons of cellulose nanomaterials. To make such an estimate, the amount of wood per unit area must be approximated.

Forests can be classified in different ways and to different degrees of specificity. In fact, the United Nations World Conservation Monitoring lists 26 forest categories [32]. However, three categories of forests are considered relevant for harvested biomass: plantation grown trees, stands of trees in natural forests, and forest biomass from forest restoration operations. Here, we estimate the potential impact on wood supply resulting from an increase in wood harvested for these new products and markets, recognizing that many additional potential sources of woody biomass are not forest lands.

A number of co-products are typically generated when wood is made into the primary products of pulp, paper, and structural wood products. Therefore, in estimating affected forestland, we assumed that cellulosic nanomaterials would be produced in addition to current forest products without any raw material use synergies. Using this method provides a maximum area that would need to be harvested per year in locations where wood, transport, and other infrastructure costs are low.

Because raw materials for cellulosic nanomaterials could come from a range of forest management regimes, three potential sources were selected that span a wide range: plantation grown trees, stands of trees in natural forests, and forest biomass from forest restoration operations. The amount of forestland required was calculated under each scenario, assuming all raw materials came only from that selected forest management regime. In practice, raw materials could come from all three sources, as well as others, including non-timber biomass grown on agricultural lands and industrial residues. To estimate the forest area that would be potentially impacted by this market, we need to make some assumptions about quantity of wood per unit area. Here we assume that an average natural forest contains 92 metric tons/ha of live (green) tree biomass, managed plantations contain 470 metric tons/ha of green wood, and forest restoration areas contain 22 metric tons/ha of green wood. Further, we assume yield of 40% and 50% wet-to-dry conversion ratio. The maximum forest areas required for the nanocellulose volume estimates are 69,000 ha (176,000 acres) for plantation grown trees; 352,000 ha (906,000 acres) for trees from natural forests; and 1.493 million ha (3.84 million acres) for forest biomass from forest restoration operations.

## CONCLUSION AND DISCUSSION

Numerous existing products could be improved with the addition of cellulose nanomaterials. Countless new products may also be made possible with this novel nanomaterial. This study focused on estimates of market size and penetration for the largest potential products for cellulose nanomaterials for the U.S. market. Novel products currently being developed in research centers around the world could develop into much larger markets for cellulose nanomaterials, but we were unable to locate adequate data to make sound estimates and so did not include them in the calculated market sizes.

As shown in the figures, products with the largest calculated potential for cellulose nanomaterials in the United States, in order of greatest to least, are in packaging, hygiene, textiles, and the paper industry. Packaging applications may account for 1.7 million metric tons of cellulose nanomaterials annually, automotive applications for 0.43 million metric tons, and paper applications for nearly 1 million metric tons. Cement has a potential market size for cellulose nanomaterials of over 4 million metric tons/year on a global basis. The cement market has huge implications for cellulose nanomaterials, but the U.S. market share for cement is less than 3% of the total world market.

The total U.S. market potential for all applications of cellulose nanomaterials is approximately 6.5 million metric tons on an annual basis. Using the share of GDP (U.S. GDP is 21.6% of total world GDP) [33] as a proxy for estimating potential worldwide consumption, potential worldwide consumption of cellulosic nanomaterials is estimated to be 35 million metric tons annually.

Packaging and paper companies are very close to commercializing cellulose nanomaterial-enhanced products, and therefore these large new markets should develop rapidly. Within a few years, the expected U.S. market for cellulose nanomaterials in these sectors should be growing rapidly towards the 6.5 million metric tons estimated as full market maturity. Other applications for cellulose nanomaterials are not as close to commercialization; an important gap is estimating the time to market, which would be a critical topic for a follow-on study.

In an effort to understand how cellulose nanomaterials will ultimately impact the forest products industry as a whole, and more particularly how it will impact forest management in the United States, the potential application of cellulose nanomaterials can be converted to hectares of forest that will be harvested. The amount of forestland required annually was calculated for three scenarios assuming all the raw material came only from that selected forest management regime. The maximum forest areas calculated were 69,000 ha for plantation-grown trees; 352,000 ha for trees from natural forests; and 1.493 million ha for forest biomass from forest restoration operations.

The market size estimate of this study is far greater than those predicted by the three previously published studies on cellulose nanomaterials. A report by Future Markets Inc. estimates market size for cellulose nanomaterials at 21 metric tons by 2017 [34]. A second version of the same report put the market size at 770 metric tons by 2017 [35]. An independent report by ArboraNano and FPInnovations puts the same market for cellulose nanomaterials at 145,000 metric tons, but without indicating a time-frame [36]. The largest predictions for cellulose nanomaterials markets were, from greatest to least: manufactured textiles, natural textiles, films and barriers, excipients, paints and coatings, composites, and paper. The ArboraNano and FPInnovations assessment compares very favorably with this study, assuming their timeframe is before the market reaches saturation level. The ArboraNano and FPInnovations calculations used a constant market penetration of only 5%. If greater acceptance by the marketplace raised penetration rate, their market size for nanocellulose could approach volumes in the millions of metric tons/year range.

This study is a first-cut assessment of market size. Additional effort is required to establish projected production cost of cellulose nanomaterials. Another useful parameter that needs evaluation is a reliable estimate of the time it would take to attain full market penetration for each potential application, which is a function of cost, technical feasibility, level of risk adoption in the sector, and competitive advantage. Market size of several novel products enabled by cellulose nanomaterials could not be evaluated using just existing market size, because these products do not displace existing products. Usage of cellulose nanomaterials in these novel applications could potentially be quite large and requires more in-depth analysis.

Markets for nanotechnology and nanocellulose will continue to develop and evolve. As they do, market demand estimates will change. Here, we provide a systematic and transparent analysis of those markets that can be updated as better information becomes available. In the meantime, we hope that these estimates can provide a foundation for both market and forest planning so that the forest industry and forest owners and managers can better adapt to this new and exciting technology, and adopters and end users can further explore market viability.

## SOURCES OF UNCERTAINTY

The single largest source of uncertainty in this study is the assumption that cellulose nanomaterials will be economically viable in each of the targeted markets. Manufacturing cellulose nanomaterials at a cost of $4.4 to $11 per kg ($2 to $5 per pound) needs to be proven through a more thorough investigation. A thorough market size assessment is essential to fully understanding the economics of the manufacturing process. In fact, there are a few different methods for manufacturing cellulose nanomaterials, with the acid hydrolysis technique and ultra-fine grinding being the two most frequently used methods. The economics of both of these processes need to be better understood. Further, because of proprietary developments, it remains unclear whether new techniques or innovations may affect the economics of cellulose nanomaterials production.

The degree of market penetration is the second largest source of uncertainty. Market penetration estimates are based on our knowledge of existing products. To assess degree of acceptance first by manufacturers and then by end users, a variety of factors must be considered, including the cost of adding cellulose nanomaterials as a percentage of total cost, performance enhancement (significant or small), manufacturing requirements, government regulation mandating that products meet a new target (such as automobile fuel economy), threat from competitors having a better product, consumer perceptions of new products (negative or positive), and external costs driving the need for improvements (such as rising jet fuel cost). Rollout will likely be slow because of performance and use questions. Using these factors, three different scenarios were developed: incomplete acceptance (pessimistic), reasonable market penetration (realistic), and ultimate or ideal market conditions (optimistic). A large spread in market size from these three scenarios is indicative of relatively high uncertainty. Conversely, a tight spread indicates a higher degree of certainty.

Existing products displaced by "new and improved" products can be more accurately evaluated. Making realistic quantitative predictions is more difficult for products that can be considered "game changers" because they create entirely new markets. Novel applications mentioned here (and detailed in the companion article [1]) represent possible large volume needs of cellulose nanomaterials but may not materialize. The uncertainty is immense for predicting the absolute size of the market for nanocellulose. Further, several low-volume applications were also not estimated, because of the difficulty in identifying appropriate market volumes. These categories represent potentially greater market size than is estimated here. **TJ**

## ACKNOWLEDGEMENTS

This work was partially funded by the U.S. Forest Products Laboratory with in-kind contributions from all authors.

## LITERATURE CITED

1. Shatkin J.A., Bilek, E.M., Wegner, T., et al., *TAPPI J.* 13(5): 9(2014).
2. Blain, P., "2013 Geneva Motor Show OICA Press Conference," 83e SALON INTERNATIONAL DE L'AUTO & ACCESSORIES, Geneva, 6 March 2013. Available [Online] http://oica.net/wp-content/uploads/pc-oica-geneve-2013-v3b.pdf>[13June2014].
3. Das, S., "The cost of automotive polymer composites: A review and assessment of DOE's lightweight materials composites research," ORNL/TM-2000/283, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 2001, pp. 7-18.
4. Wegner, T., *Nanocellulose Competitive Analysis* (unpublished), USDA Forest Products Laboratory, Madison, WI, USA, 2013.
5. Stephenson, K.M., "Characterizing the behavior and properties of nano cellulose reinforced ultra high performance concrete," Ph.D. dissertation, University of Maine, Orono, ME, USA, 2011.
6. Wegner, T., USDA Forest Products Laboratory, Madison, WI, personal communication.
7. IEA, "Tracking industrial efficiency and CO2 emissions," International Energy Agency, Paris, France, 2007, p. 6.
8. WBCSD, "The cement sustainability initiative: Progress report," World Business Council for Sustainable Development, Geneva, Switzerland, 2002. Available [Online] http://www.wbcsdcement.org/pdf/csi.pdf>[11June2014].
9. Kiziltas, A., Gardner, D.J., Han, Y., et al., *Wood Fiber Sci.* 42(2): 165(2010).
10. Forsström, U., "From nanocellulose science toward applications: Status update from Finland," *Int. Conf. Nanotechnol. Renewable Mater.*, TAPPI PRESS, Atlanta, GA, USA, 2012, Session 24.
11. PIRA, "The future of bio-plastics for packaging to 2020: Market forecasts," Smithers Pira Market Intelligence, Leatherhead, UK, 2011, p. 125.
12. AF&PA, "2011 Statistical Summary, Paper, Paperboard, Pulp," American Forest & Paper Association, Washington, DC, USA, 2012, pp. 3-19.
13. Bilodeau, M. and Bousfield, D., "Potential applications of nanofillibrated cellulose in printing and writing papers," *Int. Conf. Nanotechnol. Renewable Mater.*, TAPPI PRESS, Atlanta, GA, USA, 2012, Session 9.
14. Walker, C., *Paper360°* 7(1): 8(2012).
15. Berglund, L.A., and Peijs, T., *MRS Bull.* 35(3): 201(2010).
16. Bilodeau, M., University of Maine, Orono, personal communications.
17. Larsson, K., Berglund, L.A., Ankerfors, M., et al., *J. Appl. Polym. Sci.* 125(3): 2460(2012).
18. Richer, C., "The diaper industry in the next 25 years," *Insight 2005.* Available [Online] http://www.disposablediaper.net/files/Diapernextyears.ppt>[11June2014].
19. Eberle, C., "ORNL carbon fiber R&D update," *Oak Ridge Carbon Fiber Composites Consortium*, Oak Ridge National Laboratory, Oak Ridge, TN, USA, April 2012. Available [Online] http://www.cfcomposites.org/PDF/cliff_day1.pdf>[11June2014].
20. The White House, Office of the Press Secretary, "President Obama Announces Historic 54.5 mpg Fuel Efficiency Standard," 29 July 2011. Available [Online] http://www.whitehouse.gov/the-press-office/2011/07/29/president-obama-announces-historic-545-mpg-fuel-efficiency-standard>[11June2014].
21. EUR-Lex, "Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles." Available [Online] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2000L0053:20050701:EN:PDF>[11June 2014].
22. Krause, K., "Precast/prestressed market share analysis 2008," Precast/Prestressed Concrete Institute, Chicago, IL, 2008.
23. Stephenson, K.M., "Characterizing the behavior and properties of nano cellulose reinforced ultra high performance concrete," Ph.D. dissertation, University of Maine, 2011.
24. Bergroth, K., "Consumer and market needs," *SUNPAP Workshop*, VTT, Espoo, Finland, 2011. Available [Online] http://sunpap.vtt.fi/pdf/2_sunpap_wp1_presentation%20_%20bergroth.pdf>[11June2014].
25. Freedonia, "World insulation to 2016 — demand and sales forecasts, market share, market size, market leaders," Study #2956, Freedonia Group, Cleveland, OH, USA, 2012, pp. 48-50 and pp. 99-105.
26. ACS, "New space-age insulating material for homes, clothing and other everyday uses," American Chemical Society, press release, 19 August 2012. Available [Online] http://www.acs.org/content/acs/en/pressroom/newsreleases/2012/august/new-space-age-insulating-material-for-homes-clothing-and-other-everyday-uses.html>[11June2014]/

27. Savolainen, A., Mikkonen, H., Forssell, P., et al., "Potential of wood fibers and nanoparticles in light-weight foams," *Int. Conf. Nanotechnol. For. Prod. Ind.*, TAPPI PRESS, Atlanta, 2010.
28. Spaulding, H., "Expansion of spray polyurethane foam," *Residential Pros.com*, Cygnus Business Media, 18 October 2010. Available [Online] http://www.forresidentialpros.com/article/10348490/the-expansion-of-spf>[11June2014].
29. Red, C., "Composites in aircraft interiors, 2012-2022," *High Performance Composites*, September 2012. Available [Online] http://www.compositesworld.com/articles/composites-in-aircraft-interiors-2012-2022>[11June2014].
30. Laukkanen, A., Teirfolk,J-E., Salmela, J., et al., U.S. pat. 20130035263 (Feb. 7, 2013).
31. U.S. Census Bureau, "Paint, varnish, and lacquer—fourth quarter 2010," MQ325F(10)-4, Department of Commerce, Census Bureau, Manufacturing and Construction Division, Washington, DC, 2011. Available [Online] http://www.census.gov/manufacturing/cir/historical_data/mq325f/mq325f104.xls>[11June2014].
32. Jenkins, M.D., and Groombridge, B., *World Atlas of Biodiversity: Earth's Living Resources in the 21st Century*, World Conservation Monitoring Centre, United Nations Environment Programme, University of California Press, Oakland, CA, USA, 2007, Chap. 1.
33. United Nations, "United Nations GDP statistics," 2013. Available [Online] http://unstats.un.org/unsd/snaama/dnltransfer.asp?fID=2>[11June2014].
34. Future Markets (2012a), "The global market for nanocellulose 2017, February 2012," Future Markets Inc. Technology Report No. 60, 1st edn., 2012, Chap. 8.
35. Future Markets (2012b), "The global market for nanocellulose 2017, October 2012," Future Markets Inc. Technology Report No. 60, 2nd edn., 2012, Chap. 8.
36. Crotogino, R., "The economic impact of nanocellulose," *Int. Symp. Assessing Econ. Impact Nanotechnol.*, Nano.gov, Washington, DC, 2012. Available [Online] http://nano.gov/sites/default/files/materials_-_crotogino.pdf>[11June2014].


## ABOUT THE AUTHORS

We chose to study this topic because the industry needs to know what the market potential is for nanocellulose, and also needs a rational approach to estimating that potential, which doesn't exist.

The available market studies for nanocellulose do not disclose how estimates were made, so we sought to provide a transparent methodology as a foundation for future work.

This research was challenging in that we made a number of assumptions about market adoption rates. We sought input from experts to ground truth these adoption rates.

It was surprising to discover the breadth of potential applications and possible volumes for nanocelluloses, and mill owners may want to look at how they can take advantage of this emerging nanocellulose market. Next, we will take a number of steps to refine the analysis and tailor it to the available types of nanocellulose.

*Cowie*

*Bilek*

*Wegner*

*Shatkin*

*Cowie is president, Cowie & Company, in Derwood, MD, USA. Bilek is economist and Wegner is assistant director with the U.S. Department of Agriculture, U.S. Forest Service, Forest Products Laboratory, in Madison, WI, USA. Shatkin is president, Vireo Advisors, in Boston, MA, USA. Email Shatkin at jashatkin@gmail.com.*