Bitumen Beyond Combustion (BBC) Project
Phase 1 Report

Prepared for Alberta Innovates

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Executive Summary

This report summarizes the work performed in Phase 1 of the Bitumen Beyond Combustion (BBC) project. The Project was sponsored by Alberta Innovates and conducted in collaboration with representatives of the Bowman Centre for Sustainable Energy, Canmet Energy, Cenovus, CNRL, Conoco Phillips, InnoTech Alberta, MEG Energy, Shell, and Suncor. Nexen and BASF Canada representatives also provided valuable insights.

The main Project objective is the identification and assessment of the techno-economic potential of Alberta oil sands constituents for producing non-combustion products, i.e., products that are not fuels, such as gasoline, diesel, and heating oil. The aggregate of all product categories should utilize, by the year 2030, at least 500,000 barrels per day (500 k bpd) of bitumen, with any one category utilizing 100 k bbd.

The principal Project drivers, which individually and collectively, enhance and protect the value and profitability of oil sands operations, are:

- diversifying the uses of oil sands constituents, resulting in high-value products that can be made by or in partnership with Alberta's oil sands industry
- accommodating increased oil sands production in Alberta by creating new and/or expanded markets for oil sands constituents and their derived products
- offsetting potential lessening in the demand growth of oil sands constituents and products destined for combustion

The Project differs from and complements other projects (such as partial bitumen upgrading) insofar as it focuses on non-combustion and large-scale end-products from oil sands, rather than intermediates for fuel and petrochemicals production.

The Project provides long-range guidance to the oil sands industry and the governments of Alberta and Canada regarding the use of oil sands for purposes other than combustion products. Special efforts were made to understand the basic science and technology of the products, their markets, and end-of-life issues. Furthermore, products with high near-term success potential were sought.

The following principal conclusions were reached:

1. The organic constituents of oil sands have considerable global market potential as feed-stocks for non-combustion products, with asphalts and carbon fibres (as a replacement for steel) being particularly promising. As shown by Table 1 (next page), other products are also promising and some, like carbon fibre-reinforced wood products and controlled-release fertilizers, are particularly well suited for Alberta since the Province is a bitumen, wood, and fertilizer producer.

Table 1: Estimated global demand for asphaltenes and bitumen by 2030

	Estimated Global Demand (k bpd)	
	Asphaltenes	**Bitumen**
Asphalts	3,600	20,400
Carbon Fibres		
Current uses	5.1	29.2
Steel replacement	6,100	34,600
Vehicle use	190	1,100
Wood composites	287	1,640
Graphene	133	760
Polyurethanes		489
Polycarbonates		122
Controlled-release Fertilizers		105

The global estimates for asphaltene and bitumen demands are based on assumptions that are stated in the report. The assumptions include global market penetration and the oil sands fraction from which the products are produced.

Materials for additive manufacturing (3D printing) were also identified as promising and having potential for high growth rates. However, no reliable prospective market information was available.

2. Asphalts and new asphalt transportation technologies have the potential for major near-term market success, especially because asphalts derived from Alberta bitumen are known for their very high quality.

3. Carbon fibres produced from the asphaltene fraction of bitumen have major mid- to long-term market potential. Competitive, large-scale production technologies remain to be demonstrated and collaborative partnerships with fibre users are essential.

4. Controlled-release fertilizers have mid-term market potential, requiring both new manufacturing technologies and demonstration of crop value under Canadian and international conditions.

5. Graphenes have major long-term potential as a replacement for copper in electric machinery and power distribution. Early collaboration with a wide range of researchers (including researchers at the Canadian National Institute for Nanotechnology, Edmonton) would be fruitful.

6. Large potential markets are only one important criterion for bitumen demand and success. Another critical criterion is price competitiveness and profitability that depend on bitumen cost, bitumen properties, costs of bitumen conversion technologies, and supply-chain costs of bitumen and its derived products. All bitumen-derived products must compete with products made from other feed-stocks, notably conventional crude oil, natural gas, and increasingly bio-products.

7. The present technologies for making the non-combustion products shown in Table 1 are complex, even for conventional feed-stocks that have narrower composition ranges than bitumens. Except for asphalts, bitumens may therefore be disadvantaged, a problem that can only be overcome by better technologies, particularly more advanced separation and chemical conversion processes.

8. There appear to be no basic problems with the re-usability, recyclability, and end-of-life conversions of products listed in Table 1, although data are missing in some cases. For example, little is presently known about these issues for graphenes.

9. The recovery of vanadium from bitumen (for bitumen production rates of 500 k bpd or more) would significantly impact the present global supply of vanadium and therefore its price, unless new markets can be found. Vanadium redox batteries would provide such a market if they can be successfully deployed for storing electricity from intermittent sources, such as solar and wind.

10. The recovery of nickel from bitumen (for bitumen production rates of 500 k bpd or more) would not significantly impact the global nickel market or price.

11. Zircon recovery from froth processing of bitumen would modestly impact the global zircon market.

12. Market opportunities for quartz and clay minerals, produced from open pit oil sands operations, were examined in the past and should be revisited. It might be possible to use fine clays as materials in additive manufacturing.

13. All oil sands extraction and conversion processes are energy intensive. Sources of clean energy are integral to the successful conversion of oil sands constituents into non-combustion products.

The conclusions regarding non-combustion products from oil sands, their production technologies, and markets should be viewed as preliminary, with all estimates being approximate. Other products may also be added. These issues will be addressed in Phase 2 of the BBC project, with the assistance of a contractor identified through an open Request for Proposal.

The primary conclusion is that the market potential for growth of existing and new non-combustion products from oil sands is sound, reaching the target potential of 100 k bpd per product category and 500 k bpd in aggregate. Due to the scale of oil sands production, the markets are primarily global in extent. Reaching the market potential is complex, posing important technical, transportation, and marketing challenges.

THE CHALLENGE

Alberta's oil sands, one of the world's largest deposits of fossil hydrocarbons, currently produce approximately 2.5 million bpd* of bitumen, with production expected to rise to 3.5 million bpd by 2030. Most bitumen, like other types of petroleum, is primarily used for making combustion products, especially fuels such as gasoline, diesel, and heating oil.

The objective of the Bitumen Beyond Combustion (BBC) Project is the identification and assessment of the techno-economic potential of Alberta oil sands constituents for making non-combustion products. The aggregate of all product categories should utilize at least 500 k bpd of bitumen, with any one product category utilizing 100 k bbd.

The principal drivers for the project are:

- diversifying the uses of oil sands constituents, resulting in high-value products that can be made by or in partnership with Alberta's oil sands industry
- accommodating increased oil sands production in Alberta by creating new and/or expanded markets for oil sands constituents and their derived products
- offsetting potential lessening in the demand growth of oil sands constituents and products destined for combustion

Individually and collectively, these drivers protect and enhance the value and profitability of oil sands operations.

The BBC Project is designed to provide long-range guidance to the oil sands industry and the governments of Alberta and Canada. Efforts were also made to identify products that have near-term success potential.

Specific project objectives are given in the Comprehensive WANT Statement (see Attachment 1) and include:

- the identification and characterization of major organic and inorganic oil sands constituents and their potential uses other than fuels, together with high-level information on the technologies (including their costs, energy requirements, and environmental impacts) for making the non-combustion products, and the long-term disposal issues of the products
- the preparation of a Request for Proposals (RFP) and selection of a contractor to perform a detailed market and technical analysis on oil sands constituents for producing non-combustion products
- oversight of the work performed by the contractor.

The price of oil, manufacturing and transportation costs, competitiveness with other products and safety, regulatory, environmental, and social issues are all critically important for the commercial viability and success of oil sands products. In Phase 1,

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* bpd = barrels per day

these issues are only addressed qualitatively; they will be examined more closely in the next phase.

For users of oil sands constituents, the competitiveness and profitability of their products are paramount, with the volume of constituents used having lesser importance. High-value products can be very attractive even though their volumes are small. Small volume products are not the focus of the BBC project, which is aimed at the entire oils sands sector. High value, small volume products could be the objective of another project.

The objective of the BBC Project is different from, but complements, other work focused on partial upgrading of bitumen, including the conversion of bitumen into fluids that can be transported by pipelines or chemical intermediates, such as monomers (see, for example, Muse Stancil[1] and McCann et al.[2]). The BBC Project identifies and assesses primarily end-products that can be made from oil sands constituents on a large scale.

Note: Highlights in the report have been identified by placing red markers in the margin.

CONCEPTUAL FRAMEWORK

The conceptual framework to address the BBC Project objectives consists of three components:

- The high-level *flowsheet* shown in Figure 1

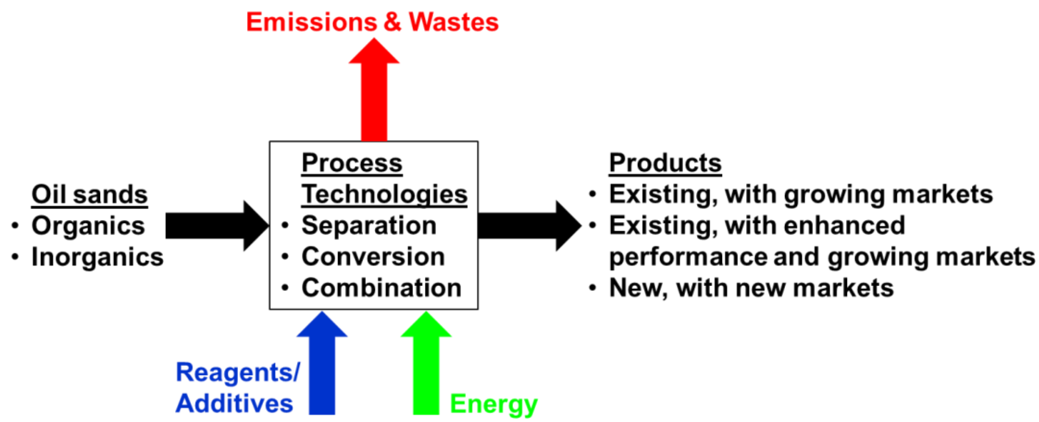

Figure 1: Conceptual flowsheet for addressing the Project Objectives

The organic and inorganic oil sands constituents are envisioned to be processed into non-combustion products or become components of non-combustion products, such

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[1] Muse Stancil Canadian Heavy Oil Crude Competitiveness Study Phase 2, http://www.ai-ees.ca/wp-content/uploads/2016/04/canadian_heavy_crude_oil_competitiveness_study_executive_summary_final.pdf

[2] McCann at al., Petrochemicals from Oil Sands, http://www.energy.alberta.ca/EnergyProcessing/pdfs/Petrochemicals_From_Oil_Sands.pdf (July 2002)

as carbon fibres in composites. The primary technologies are separation, chemical conversion, and physical combination processes.

The importance of environmental and social impacts (including impacts on indigenous communities) associated with producing and transporting oil sands constituents as well as transporting and utilizing the conversion products are well recognized, but fall outside the scope of Phase I of the BBC Project. They are therefore not reflected in Figure 1, but will be addressed in future.

All processes require energy and that energy is ideally derived from sources which minimize the emission of greenhouse gases (GHGs) and wastes. However, combustion of natural gas or a portion of the organic components of the oil sands are well-established energy sources in the oil sands and petrochemical industries; they may remain the preferred energy source even though GHGs are created.

- The *mind map* of non-combustion products shown in Figure 2

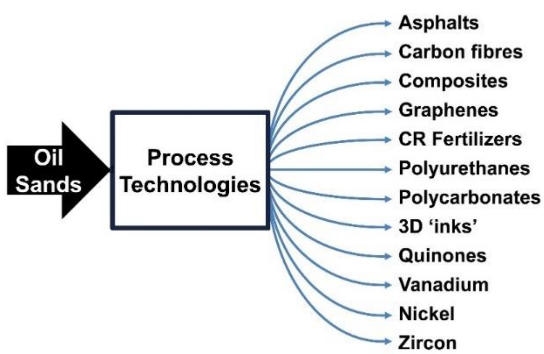

Figure 2: Mind map of non-combustion product categories

The products shown in Figure 2 should be viewed as categories, with each category including chemicals of a similar nature. The non-combustion products include:

- Existing products with major market growth potential. An example is conventional asphalt obtained from oil sands bitumen
- Existing products whose market potential can be increased due to enhanced performance characteristics. Examples are asphalts with superior properties and/or greater ease of shipment over greater distances than conventional asphalts
- New products with high market potential that are superior in terms of performance and / or cost to other products or which address new market opportunities. Examples include carbon fibres as replacement for steel, and vanadium in redox flow batteries

Figure 2 shows non-combustion products that have been identified thus far. The list is not exhaustive and other products can be added in future.

The figure is an extension of the mind map developed by the Bowman Centre for Sustainable Energy[3].

- The combined *Strengths, Weaknesses, Opportunities, Threats (SWOT) matrix* for product categories shown in Figure 3

PRODUCT	STRENGTHS	WEAKNESSES

	OPPORTUNITIES	THREATS

Figure 3: Combined SWOT matrix

For each product category, the principal strengths, weaknesses, opportunities, and threats of each product category are shown on page 48.

SCALE

A key challenge of the BBC Project is product scale, i.e., the identification of products that can be made competitively and on scales that are meaningful to the oil sands industry. For the BBC Project, 100 k bpd bitumen equivalent was selected for each product category, with an aggregate of 500 k bpd of all product categories.

The challenge of scale becomes clear by considering the current production of non-combustion products from petroleum and the per capita consumption of bitumen. Details are given in Attachment 2.

In essence, approximately 95% of US petroleum refinery inputs (16.4 million bpd, including bitumen from oil sands) are used for making combustion products. Only 5% (860 k bpd) of the inputs go to petrochemicals. Globally, refinery inputs are in the 80 to 90 million bpd range and the percentages for petrochemicals are similar. The BBC

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[3] Personal Communication, Don Wood, Bowman Centre for Sustainable Energy (2017)

objectives of 100 and 500 k bpd therefore represent substantial fractions of current and projected petrochemicals production.

The BBC objectives may also be expressed on a per capita basis for Canada, North America, and the world. For 500 k bpd, they amount to bitumen demands of 2.2, 0.2, and 0.01 L per person per day (in 2015), respectively. These are considerable consumption rates and, at present, only the demand for fuels (not petrochemicals or other materials) derived from petroleum approximates these demands.

Addressing the Challenge of Scale

The challenge of scale can be addressed by focusing on product sectors that are large, growing, essential, and economically strong. The following sectors have the potential of meeting these characteristics:

- materials (including materials for construction and transportation)
- food
- energy support
- personal care

Due to increases in population, changing age demographics, and growing prosperity, the demand for more and different housing and work spaces will grow. As shown by Figure 4, the global and Canadian populations are increasing and aging. Both changes create demands for additional and different forms of spaces which will, in turn, lead to major new demands for construction and refurbishment materials.

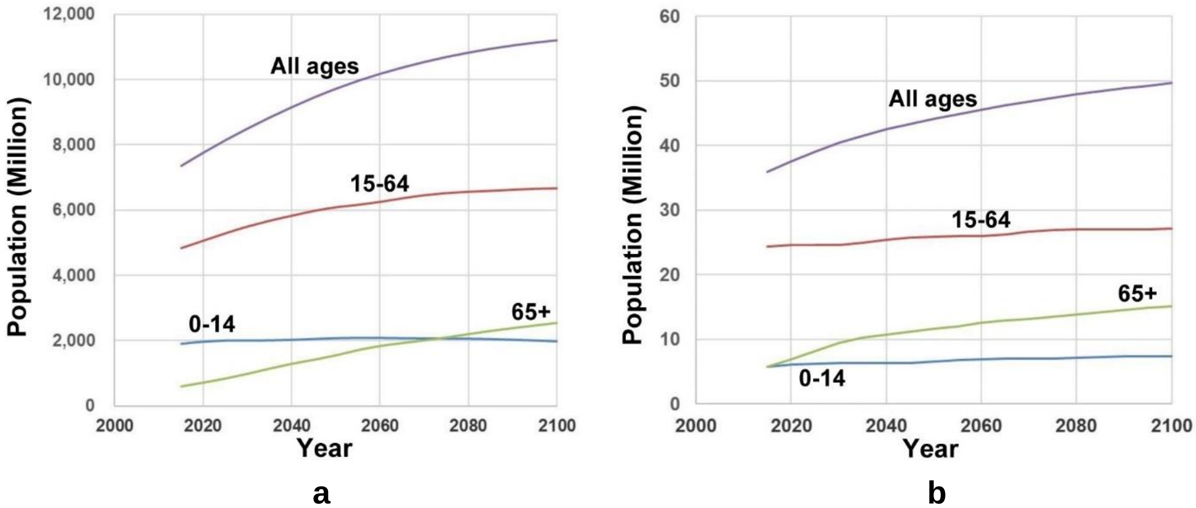

Figure 4: Population projections for the world (a) and Canada (b) to the year 2100[4]

A basic mathematical model, developed on the assumptions that the volume of construction materials must provide for enclosed living and working spaces with a floor area of 100 m^2 per person and that each additional member of the population requires this space at least once in his or her lifetime, translates into the bitumen demand estimates shown in Table 2. The demands are substantial, but it needs to be recognized that not all citizens are able to afford the additional space, especially at present when global incomes are still low. Nevertheless, the demands and hence the potential for bitumen uses are greatest in the near term when populations are growing most rapidly.

Furthermore, it is essential to recognize that the estimates are approximate and will need to be refined in the subsequent phase of the Project.

[4] United Nations Population Division, World Population Prospects: The 2015 Revision, File POP/8-1: Total population 1950 - 2100

Table 2: Approximate estimates of bitumen demand associated with needs for housing and work for the period of 2015 to 2050

Period			Canada (k bpd)	World (k bpd)
2015	to	2020	183	45,100
2020	to	2025	162	42,300
2025	to	2030	146	39,600
2030	to	2035	124	37,300
2035	to	2040	106	35,100
2040	to	2045	95	33,700
2045	to	2050	88	19,900

The 'energy support sector' includes electric power generation (by means other than fossil fuel combustion), transmission, and storage.

The potential of the food sector for oil sands products is likely the least well understood sector at present. Specialty fertilizers, which have the potential of contributing to more effective food production, are addressed in the section on Controlled-release Fertilizers. However, there is also the possibility of converting bitumen into proteins. Considerable work was undertaken in the 1960s and 1970s on the production of single cell organisms using conventional petroleum as a growth medium[5],[6]. This work did not translate into commercial success, but should be reviewed and revisited in light of the major advances that have occurred in cellular and molecular biology since that time. New approaches may therefore be available now.

The public acceptance of human food derived from bitumen is likely low, but animal feed is a possibility and deserves attention. Personal care products (e.g., lotions, cosmetics, and cleansings agents) may pose similar opportunities and challenges to foods.

[5] Norris, JR Animal Protein from unusual substrates including petroleum and methane, Adv Sci, 1968 Dec 25 (124) 143-150
[6] Walker, T Protein from Petroleum, Nut & Food Sci, **72**(2), 20-23 (1972)

ORGANIC OIL SANDS CONSTITUENTS AND THEIR POTENTIAL FOR NON-COMBUSTION PRODUCTS

Alberta's proven bitumen reserves total approximately 170 billion bbl, with the current production averaging 2.5 million bpd, and expected to rise to 3.5 million bpd, by 2030.

Table 3: lists constituents of the organic (bitumen) fraction of oil sands, as given by O.P. Strausz and E.M. Lown. Similar data were reported by Banerjee[7].

Table 3: Composition of Alberta oil sands bitumen[8]

Elemental Composition		
Carbon	83.1 ±0.5	wt%
Hydrogen	10.3 ±0.3	wt%
Nitrogen	0.4 ±0.1	wt%
Oxygen	1.1 ±0.3	wt%
Sulphur	4.6 ±0.5	wt%
Vanadium	139 ±19	ppmw
Nickel	66.3 ±8	ppmw
Titanium	<100	ppmw
Zirconium	<7	ppmw
Aluminum	<1,000	ppmw
Iron	<200	ppmw
Organic Fractions		
Saturates	15 – 21	wt%
Aromatics	18 – 19	wt%
Resins (polars)	44 – 48	wt%
Asphaltenes	14 – 20	wt%

Industrial experience has shown that vanadium and nickel concentrations are typically somewhat higher, averaging 200 and 80 ppmw, respectively.

7 D.K. Banerjee, Oil sands, heavy oil, and bitumen: from recovery to refinery, PennWell Corp. (2012)
8 O.P. Strausz and E.M. Lown, *The Chemistry of Alberta Oil Sands, Bitumens and Heavy Oils*, Alberta Energy Research Institute (2003)

POTENTIAL PRODUCTS FROM ORGANIC OIL SANDS CONSTITUENTS

The mind map (Figure 2) provides a summary of major potential non-combustion products. In the following sections, details are provided on most of these products.

ASPHALTS – EXISTING PRODUCTS WITH GROWING MARKETS

In 2015, global demand for conventional or primary asphalt was 725 million bbl (or just under 2 million bpd), of which 31% (616,000 bpd) arose in North America[9]. In 2012, primary asphalt sales in Canada were 53,000 bpd[10]. StatsCan does not provide more recent information.

The global and North American demand increases are estimated to be 4% per annum, resulting in the demand projections shown in Table 4. The increases in asphalt demand are approximately 1.6 and 0.5 million bpd in the world and North America, respectively.

Table 4: Primary asphalt and associated bitumen demand projections to 2030, assuming 4% compound annual growth

Year	Global Demand (k bpd)		North American Demand (k bpd)	
	Asphalt	Bitumen	Asphalt	Bitumen
2015	2,000	11,400	600	3,500
2020	2,400	13,800	700	4,300
2025	2,900	16,800	900	5,200
2030	3,600	20,400	1,100	6,300

Since bitumen contains approximately 17.5% asphaltenes, the main constituent of asphalts, the total demands for bitumen are considerably higher and the corresponding data are also shown in Table 4.

Asphalts therefore have the potential of meeting and exceeding the targets of the BBC Project. It is understood that most asphalts will continue to be made from conventional petroleum.

Reaching North American and overseas markets will require the transportation of Alberta asphalt over long distances, which represents technical, logistical, and cost challenges.

Alberta bitumens are excellent proven feed-stocks for asphalts, but the extensive use of certain additives (such as used motor oil residues with significant metal content) reduce their effectiveness, resulting in premature road problems and even failures. Recent consultations with Prof. Simon Hesp (Queen's University, Kingston, ON) have confirmed that this problem exists, particularly in Ontario.

9 http://www.freedoniagroup.com/brochure/28xx/2847smwe.pdf
10 http://www.statcan.gc.ca/pub/45-004-x/2013004/t014-eng.pdf

Transportation of Molten Asphalt

In North America, basic rail infrastructure exists to transport asphalt from Alberta in molten form[11]. Marine shipment of molten asphalts has also become a recent reality. For example, Sargent Marine (SM) operates several asphalt tankers certified by Bureau Veritas[12]. They maintain asphalt temperatures up to 170^{o}C and have a capacity of 35,666 m^3 (250,000 bbl).

Figure 5: Rail and marine transportation of molten asphalt

Transportation costs by sea and/or rail should be determined as part of the Phase 2 of the BBC Project.

Transportation of Solid Asphalts

Transportation of molten asphalt is inherently complex, requiring sophisticated storage, handling, transportation, and safety measures as well as specially trained personnel. Such provisions are often unavailable (especially at remote locations in developing countries) and they are associated with considerable costs, significantly reducing the net-back to oils sands operators.

An alternative to handling asphalt in molten form is storage and transportation in solid form, as pellets, rods, cubes, or rectangular parallelepipeds. The latter are similar in shape to 2"x4" lumber. All solid forms of asphalts have to be modified to reduce their 'stickiness' under ambient conditions and, preferably, be encased in a material that prevents adhesion. The casement material should be selected so that it can be blended with the asphalt upon melting and enhance its properties. A summary of pellet and casement technologies, together with their providers, is given in the white paper 'Asphalt

[11] http://www.gatx.com/wps/wcm/connect/GATX/GATX_SITE/Home/Rail+North+America/Products/Equipment+Types/Tank/General+Service/

[12] http://fairplay.ihs.com/commerce/article/4261651/bv-classes-world-s-largest-specially-built-asphalt-carrier

Pellets: An Alternative Delivery System for Asphalt Products'[13]. Recent work by CN and Innotech Alberta on Cana-Pux (a semi-solid form of bitumen) may also be relevant[14].

A detailed review of current applied asphalt research should be undertaken but is beyond the scope of this interim report.

ASPHALTS WITH ENHANCED PERFORMANCE AND GROWING MARKETS

Although asphalt markets are large and growing, and asphalts derived from Alberta bitumen have excellent properties compared with asphalts from other sources, there is still a need for continuous improvement to maintain their competitive edge.

Extensive work has been done on the use of additives, including elastomeric polymers such as SBS (styrene-butadiene-styrene block copolymers) and SBR (styrene-butadiene-rubber latex). Success has been limited since the functional improvements usually do not offset the increased costs. However, advances seem possible.

The addition of fibrous materials, including carbon fibres, can improve the mechanical properties of asphalts in road and other applications. Recent attempts of incorporating carbon nanotubes have shown promising results[15], but their long-term service effectiveness remains to be proven, especially under extreme climatic conditions. The addition of carbon fibres to Alberta asphalts would provide a large and local market for such fibres.

Reuse and Recyclability of Asphalts

Reuse and recycling of asphalts are widely practiced. While environmental issues can arise during reclaiming and re-laying of asphalts, technologies are available to address them. Asphalt additives may, however, pose problems and have to be evaluated on a case by case basis.

CARBONS

As indicated in Table 3, the carbon content of bitumen exceeds 80 wt%. Bitumen is therefore a large and excellent source of pure carbon. Since carbon occurs in different allotropic forms, some of which have been discovered only recently and have highly desirable properties, interest in carbon allotropes has grown rapidly. The following is a high-level overview relevant to the objectives of the BBC Project.

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13 http://www.rockymountainasphalt.com/Asphalt%20Pellet%20white%20paper.pdf

14 http://www.theglobeandmail.com/news/national/cn-develops-technology-that-could-make-bitumen-transportation-safer/article34082304/

15 S.G. Jahromi, Int. J. Sus. Const. Eng. And Techn., 6(1) 57- 66 (2015) http://penerbit.uthm.edu.my/ojs/index.php/IJSCET/article/viewFile/1183/808

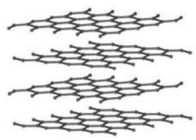
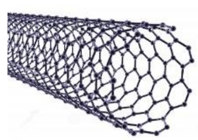
Carbon Allotropes

Table 5 lists carbon allotropes (together with their important properties) that have potential for large-scale uses. Diamond, lonsdaleite, fullerenes, and amorphous carbon (occurring primarily in coal) have therefore been omitted from the table.

It is clear that graphene and carbon nanotubes are significantly stronger and more conductive than widely used metals, such as copper and steel. This superiority becomes even more pronounced when density is taken into account, for example, in motor vehicles and load bearing structures. Both graphene and carbon nanotubes therefore have the potential of playing important roles in the transportation and construction sectors.

To date, it has been difficult to manufacture pure graphene and carbon nanotubes in sufficient quantities and at a price suitable for large-scale use. However, major efforts are underway to do so and represent key objectives of Canada's National Institute for Nanotechnology (a unit of the National Research Council of Canada, headquartered in Edmonton, AB and funded at approximately $35 million per year) and the Graphene Flagship Program funded by the European Commission. The latter has a budget of €1 billion over ten years, starting in 2013.

Table 5: Carbon allotropes that could be produced from oil sands with potential large-scale uses. Copper, steel, and carbon fibre values are provided for comparison purposes.

Allotrope	Atomic Arrangement	Density (Mg/m^3)	Tensile Strength (MPa)	Young's Modulus (GPa)	Electrical Conductivity[16] (S/m)	Thermal Conductivity (W/m K)
Graphite Multiple layers of C_6 hexagonal rings		1.6 - 2.5[17]	4.8 to 76 [18]	4.1 - 27.6	3.30×10^2 - 3.00×10^5	0.6 to 5.2 [19]
Graphene Single layers of C_6 hexagonal rings		NA	>100,000 [20]	~1,000 [21]	10^8	3,080 - 5,150 [22]
Carbon nanotubes Graphene folded into single and multi-walled tubes[23]		1.3 to 1.4	~ 30,000 [24]	~1,000	10^7	2,000
Copper		8.92	220	117	5.96×10^7	386
Steel		7.8	400 – 2,700	200	6.99×10^6	36 – 54
Carbon Fibres[25]		1.75	3,400 – 6,000	240 - 400		

Carbon Fibres

In contrast to carbon nanotubes and graphene, carbon fibres have already seen diverse and growing use, albeit primarily for high-value applications where performance considerations, rather than costs, are paramount.

A comprehensive and recent review of carbon fibres is provided by Soo-Jin Park[26].

Unlike graphite, where layers of hexagonal molecules of carbon lie approximately parallel to each other, thereby giving graphite its soft and lubricating characteristics, carbon fibres

16 https://en.wikipedia.org/wiki/Electrical_resistivity_and_conductivity#Resistivity_and_conductivity_of_various_materials
17 http://www.azom.com/properties.aspx?ArticleID=516
18 http://www.azom.com/properties.aspx?ArticleID=516
19 http://www.azom.com/properties.aspx?ArticleID=516
20 L. Martiradonna et al. Nature Materials 13, 223 (2014)
21 F. Memarian, A. Fereidoon, M.D. Ganji, Superlattices and Microstructures, 85, 348-356 (2015)
22 Gosh et al., Appl. Phys. Letters, 92, 151911 (2008)
23 http://www.pa.msu.edu/cmp/csc/ntproperties/quickfacts.html
24 M.-F. Yu et al., Phys. Rev. Lett, 84, 5552 (2000)
25 http://www.chm.bris.ac.uk/webprojects2002/mjames/chemistry.html
26 Soo-Jin Park, Carbon Fibers, Springer Series in Material Science, **210** (2015)

consist of layers of hexagonal carbon molecules that are folded and interlocked. The interlocking prevents slippage of the layers over each other, without impairing the strength and density of the fibres. Figure 6 is a schematic portrayal of folded graphene layers in carbon fibres.

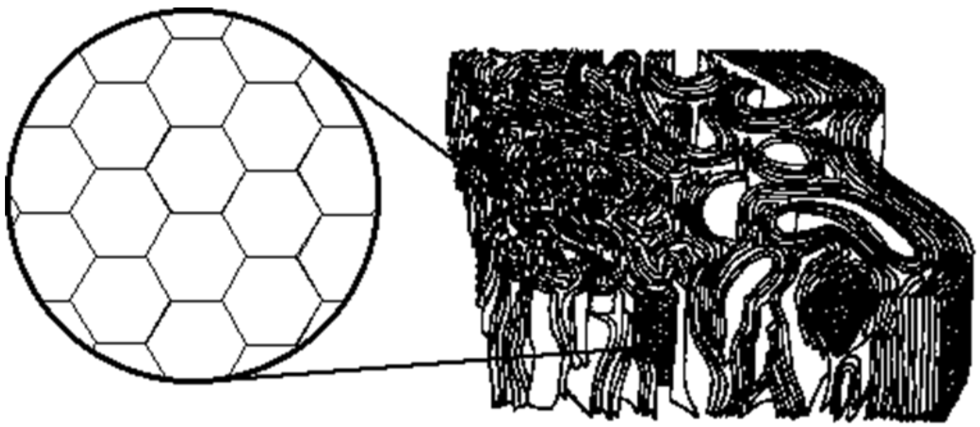
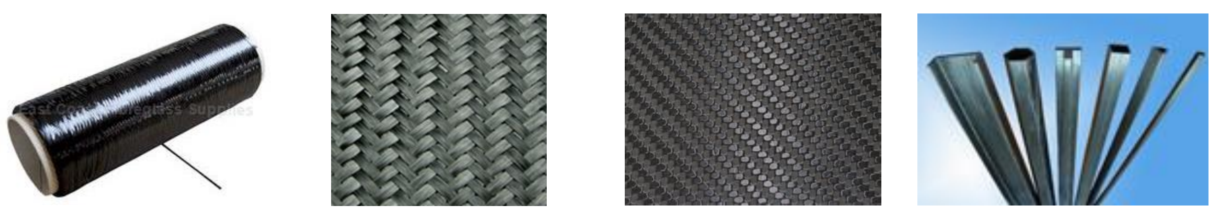


Figure 6: Schematic of carbon fibres comprised of folded graphite layers, consisting of hexagonal carbon rings[27]

The fibres, typically ranging from 5 to 10 μm in diameter, are spun into threads and woven into fabrics or otherwise assembled in regular patterns. They are usually held together by resins, creating a fibre-reinforced composite matrix. Figure 7 shows examples of carbon fibres and fibre products.



a b c d

Figure 7: Carbon fibres and composites (a) spun filaments, (b) filaments woven into fabrics (c) impregnated fibre fabrics, (d) solid shapes composed of fibres

[27] Matthew James, http://www.chm.bris.ac.uk/webprojects2002/mjames/chemistry.html

Carbon Fibre Market – Demand Perspective

Detailed and current information on the global and regional markets for carbon fibres and products requires access to trade publications that are only available at considerable cost. However, Figure 8 provides a reasonable summary. Summary insights include:

- In 2015, the global carbon fibre demand was estimated to be 59,000 t. Assuming that the fibres are pure carbon, this translates into an asphaltene demand of 70,355 t/y or approximately 1,200 bpd*. The corresponding bitumen demand follows from the fact that bitumen contains about 17.5% asphaltenes, the primary feedstock for carbon fibres. These estimates do not account for any process inefficiencies or energy requirements to produce the carbon fibres.

- The projected annual growth rate for carbon fibres is expected to vary from 8.1 to 15.1%[28]. Assuming a growth rate of 10% per year, the carbon fibre demands and corresponding asphaltene and bitumen demands are shown in Table 6.

Table 6: Global carbon fibre demand and corresponding bitumen requirements

Year	**Carbon Fibre Demand** t/y	**Asphaltene Demand** k bpd	**Bitumen Demand** k bpd
2015	59,000	1.2	7.0
2020	95,000	2.0	11.3
2025	153,000	3.2	18.1
2030	246,500	5.1	29.2

* The asphaltene fraction of bitumen is taken as the representative precursor of carbon fibres. It is recognized that this is a simplification since other pitch constituents also contribute to fibre formation

28 REINFORCED plastics, p 38 – 45 (Nov/Dec 2014)

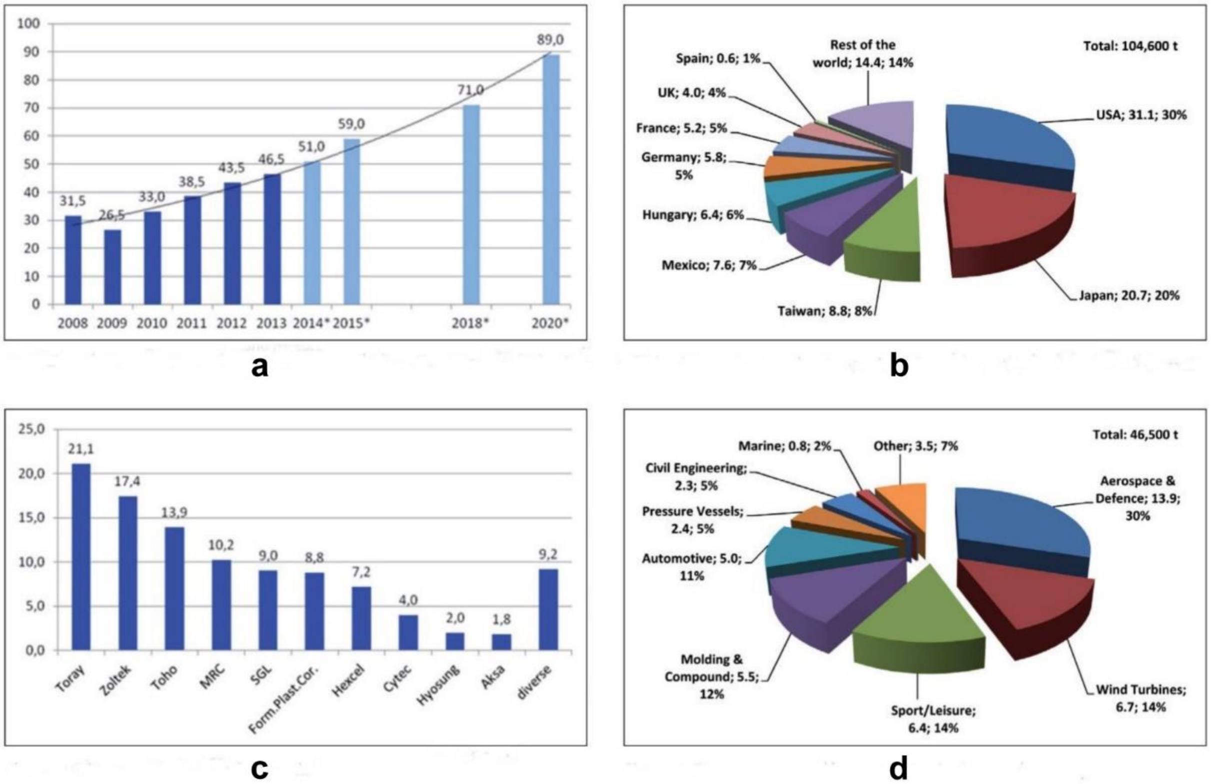


Figure 8: (a) Global demand for carbon fibre in thousands of tonnes (* denotes estimates); (b) Annual carbon fibre production capacity by country in thousands of tonnes for 2013; (c) Carbon fibre production capacities by manufacturer in thousands of tonnes for 2013; (d) Global carbon fibre demand by application in thousands of tonnes in 2013[29]

Given the global market outlook for carbon fibres, the demand for bitumen is and will remain small to 2030, in relationship to the BBC project target of 100 k bpd. To address this target therefore requires different ideas. Five such ideas are presented below.

Carbon Fibres as Steel Replacement – Existing Products with Growth Potential

Given the outstanding corrosion resistance and strength-to-weight characteristics of carbon fibres, over time and with appropriate promotional efforts and cost reductions, they could replace 10% of steel uses. Primary opportunities for such replacement exist in the transportation and construction sectors.

[29] REINFORCED plastics, p 38 – 45 (Nov/Dec 2014) http://www.materialstoday.com/carbon-fiber/features/carbon-fibre-reinforced-plastics-market-continues/

Table 7 provides estimates of the asphaltene and bitumen requirements if steel production would increase by 4% per annum and 10% of such steel production is replaced by carbon fibres.

Table 7: Asphaltene and bitumen requirements resulting from carbon fibres replacing 10% of steel production globally and in Canada (assuming steel production grows annually by 4%)

Year	World			Canada		
	Steel Production B t	**Asphaltene Demand** k bpd	**Bitumen Demand** k bpd	**Steel Production** M t	**Asphaltene Demand** k bpd	**Bitumen Demand** k bpd
2015	1.62	3,400	19,200	13.00	27	154
2020	1.97	4,100	23,400	15.82	33	187
2025	2.40	5,000	28,500	19.24	40	228
2030	2.92	6,100	34,600	23.41	49	277

The global bitumen demand would grow to approximately 35 M bpd whereas the Canadian demand would increase to just under 300 k bpd.

Carbon Fibres in Cars and Commercial Vehicles – Existing Products with Growth Potential

The growth rate in vehicle production between now and 2030 is difficult to estimate. It is likely that production in the USA and Canada will stay at current levels of 12 million and 2.3 million vehicles per year, respectively. Global annual vehicle production is approximately 91 million vehicles and will likely increase.

In order to estimate the carbon fibre demand associated with the production of new vehicles, it is assumed that the production figures remain unchanged and vehicles could each contain 100 kg of carbon fibres. It is reasonable to assume that this level of content will be reach by 2030 or shortly thereafter. At present, the carbon fibre content of cars and commercial vehicles is very small. The results of the estimates are shown in Table 8.

Table 8: Asphaltene and bitumen requirements resulting from new car and commercial vehicle production[30], each containing 100 kg of carbon fibres, by 2030.

	World	USA	Canada
Production rate, M units/y	91	12	2.3
Carbon fibre content, M t	9.1	1.2	0.23
Asphaltene requirement, k bpd	190	25	5
Bitumen requirement, k bpd	1,100	140	30

The demand that cars and commercial vehicle production creates for bitumen therefore exceeds the BBC objective of 100 k bpd for North America and the world.

Carbon Fibres for Wood Products - Existing Products with Growth Potential

The mechanical properties of wood (i.e., tensile strength and Young's modulus) can be significantly improved by the incorporation of carbon fibres. The fibres may be incorporated in the form of randomly distributed small fibres, meshes, or strands. In the latter case, the composite is analogous to 'reinforced concrete', with the fibre strands taking the role of steel rebars and the wood taking the role of concrete. The wood may also be a composite, such as plywood, oriented strand board (OSB), or particle board. Examples of carbon fibre – wood composites are shown in Figure 9.

Interior reinforcement[31] Exterior reinforcement Demonstration of strength

Figure 9: Examples of carbon fibre – wood composites

At present, the market for carbon fibre – wood composite products is confined to specialty and high-value products, manufactured on a small scale. The potential large-scale market by 2030 can be estimated using current production figures for wood[32] and assuming a certain fraction of the production (e.g., 10%) is enhanced by carbon fibres. The carbon fibre content of the enhanced products is estimated to be 10 v%. The resulting bitumen demand is shown in Table 9.

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[30] https://en.wikipedia.org/wiki/List_of_countries_by_motor_vehicle_production
[31] http://www.teijin.com/news/2015/ebd150204_30.html
[32] http://www.fao.org/forestry/statistics/80938/en/

Table 9: Asphaltene and bitumen requirements resulting from the incorporation of carbon fibres into 10% of particle board, oriented stand board, and sawlog production, with the resulting wood composites containing 10v% of carbon fibres, by 2030.

	World	USA	Canada
Particle Board and OSB			
Production volume, M m^3	110.9	16.0	8.8
Carbon fibre content, M t	1.9	0.3	0.2
Asphaltene requirement, k bpd	40.3	5.8	3.2
Bitumen requirement, k bpd	230	33	18
Saw logs and veneer logs			
Production volume, M m^3	677.8	130.7	118.1
Carbon fibre content, M t	11.9	2.3	2.1
Asphaltene requirement, k bpd	246	47	43
Bitumen requirement, k bpd	1,410	270	240
Total			
Production volume, M m^3	788.7	146.6	126.9
Carbon fibre content, M t	13.8	2.6	2.2
Asphaltene requirement, k bpd	286.3	53.2	46.0
Bitumen requirement, k bpd	1,640	300	260

The bitumen demand is significant in relationship to the 100 k bpd objective of the BBC Project. However, the results are sensitive to the assumptions regarding percentages of total wood production enhanced with carbon fibres and the carbon fibre content of the composite products.

Technologies

Carbon fibres are produced on an industrial scale principally from acrylic precursors (especially polyacrylonitrile (PAN)) and pitch. These feed-stocks result in good quality fibers and have high carbon efficiencies, i.e., over 85% of the carbon in the feed-stock is preserved in the fibres. Both production processes are complex and expensive.

Insights into the complexity of the PAN-based process is conveyed by the BMW video at https://www.youtube.com/watch?v=kaoq8Mc4xxw and the flowsheet shown in Figure 10.

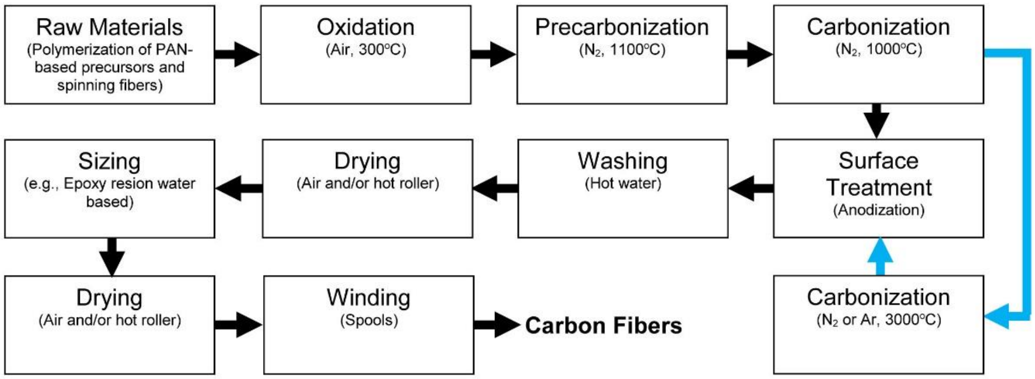

Figure 10: High-level flowsheet for carbon fibre production from PAN[33]

The alternative to PAN as a feed-stock is pitch, a generic term that includes bitumen, coal distillates, and carbonaceous pyrolysis products. Asphaltenes are potentially good feed-stocks for carbon fibres because they have a high carbon content and are rich in aromatics. Inherent disadvantages are their impurities, including metals, that reduce the strength characteristics of the fibre product. The principal processing steps are:

- production of precursor fibre by melt-spinning pitch, thereby creating the basic meso-phase structure for the final carbon fibres
- stabilization of precursor fibres
- carbonization of the stabilized precursor fibres
- graphitization of carbonized precursor fibres

Other processing steps such as surface treatment and winding are similar to those used in the PAN-based process.

Suitability of Bitumen as a Carbon Fibre Feed-stock

Relatively little is known about the suitability of bitumen as a feed-stock for carbon fibres, but research is currently underway[34]. Apart from identifying appropriate processing conditions and understanding the role of impurities, efforts are needed to reduce the processing time.

Given the composition of bitumen and the molecular structure of its constituents, there are good reasons to believe that high-quality carbon fibres can be produced from bitumen.

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33 Soo-Jin Park, Carbon Fibers, Springer Series in Material Science, **210** p 37 (2015)
34 Personal information exchange with Prof. Weixing Chen, University of Alberta (2017)

Reuse and Recyclability of Carbon Fibres

Long carbon fibres can be recycled into the form of shorter fibres that have lower performance characteristics. The final disposition of carbon fibres is gasification or incineration. Landfilling is also possible but undesirable due to their persistence.

GRAPHENE AS A REPLACEMENT FOR COPPER IN ELECTRICAL APPLICATIONS – NEW PRODUCT WITH HIGH MARKET POTENTIAL

Graphene is receiving wide attention and an excellent overview of graphene's potential and challenges is provided by Andrea Ferrari et al[35]. The current focus is the enhancement of scientific understanding and specialty applications, such as protective surfaces (i.e., coatings), sensors, and opto-electronics. However, large-scale uses, including composites and energy storage and conversions have also been recognized. Based on its outstanding electrical properties and low density, graphene also has the potential for large scale uses, notably the replacement of copper in electrical applications, including transmission lines, electrical motors, and electronics.

Copper usage information is provided by the US Geological survey[36]. At present, approximately 75% of copper is used for electrical purposes. If transportation becomes electrified and electrical transmissions systems are expanded to accommodate more renewable and intermittent energy sources (such as solar and wind energy), the demand for copper would increase sharply, providing a market opportunity for graphene.

It is difficult to project the transition to a greater reliance on electricity between now and 2030. The projections shown in Table 10 are based on annual growth rates in electrical copper use of 5% per year. This is likely a conservative estimate. Only global and US data are presented since similar information was unavailable for Canada. Canadian data will be included as it becomes available.

Table 10 indicates that, under the given assumptions, the bitumen demand from graphene by 2030 totals approximately 760 k bpd and 100 k bpd for the world and USA, respectively. However, this could change rapidly if high-quality graphene electrical conductors become available at prices that are competitive with copper.

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35 Andrea Ferrari et al., Nanoscale 7(11), p. 4587-5062 (21 Mar 2015)

36 http://minerals.usgs.gov/minerals/pubs/historical-statistics/#copper

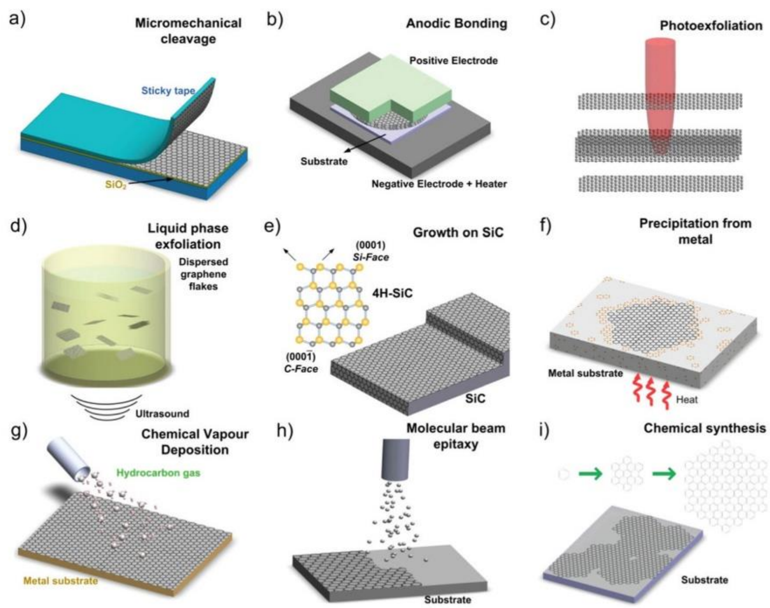
Table 10: Asphaltene and bitumen requirements resulting from graphene replacing 30 % of electricity-related copper use globally and in the United States, assuming copper demand grows annually by 5%

Year	World			USA		
	Copper Use M t	Asphaltene Replacement Demand for Graphene k bpd	Bitumen Replacement Demand for Graphene k bpd	Copper Use M t	Asphaltene Replacement Demand for Graphene k bpd	Bitumen Replacement Demand for Graphene k bpd
2015	13.8	64	365	1.3	6	35
2020	17.6	82	466	1.7	11	61
2025	22.5	104	595	2.2	14	77
2030	28.7	133	760	2.8	17	99

Technologies

Graphene is presently only available in small quantities, largely used for research purposes. The primary experimental production technologies are shown schematically in Figure 11. Method (i), chemical synthesis using benzene building blocks is of greatest interest to oil sands since bitumen is rich in aromatic compounds. However, this approach requires ultrapure and specific feed-stocks, as well as a gold substrate to order the feed-stock molecules. Further information of a scientific nature is given by Cai et al.[37]. Their work resulted in short and narrow graphene nano-ribbons.

[37] J. Cai et al., Nature, 466, p. 470-473 (22 Jul 2010)



(a) Micromechanical cleavage (b) Anodic bonding (c) Photoexfoliation. (d) Liquid phase exfoliation. (e) Growth from SiC. Schematic structure of 4H-SiC and the growth of graphene on SiC substrate. Gold and grey spheres represent Si and C atoms, respectively. At elevated temperatures, Si atoms evaporate (arrows), leaving a C-rich surface that forms graphene. (f) Precipitation from carbon containing metal substrate. (g) CVD process. (h) Molecular beam epitaxy. Different carbon sources and substrates (*i.e.* SiC, Si, *etc.*) can be exploited. (i) Chemical synthesis using benzene as building blocks.

Figure 11: Schematic illustration of the main experimental setups for graphene production[38].

Suitability of Bitumen as a Graphene Feed-stock

Bitumen is rich in aromatic compounds with hexagonal structures that are good starting points for graphene, which also has a hexagonal geometry. Bitumen should therefore be a good feed-stock for graphene. The main factors challenging bitumen as a feed-stock are the wide variety of organic (including aliphatic) compounds and inorganic constituents. Conventional distillation and extraction techniques are unlikely to achieve the purity of feed-stocks needed for graphene production.

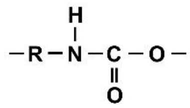
Reuse and Recyclability of Graphenes

Little is presently known about the reuse and recyclability of graphene, but they should be amenable to chemical and thermochemical (pyrolysis and gasification) conversion methods. Like other stable nano-materials, about which little is know, care needs to be taken not to introduce graphene into the environment (including landfills) without the necessary research that ensures safety.

38 Andrea Ferrari et al., Nanoscale 7(11), p. 4587-5062 (21 Mar 2015); p 4646

POLYURETHANES

Polyurethanes are typically thermosetting plastics, although thermoplastic forms are also available. Urethane plastics incorporate the urethane group



where R denotes one or more aliphatic or aromatic groups.

The properties of polyurethanes differ widely, largely dependent on their organic groups, chain length and manufacturing process. They range from soft, including foam-like structures, to hard plastics. The range of mechanical properties is shown in Table 11.

Table 11: Mechanical properties of select polyurethanes[39]

	Polyurethane Type			
	L42	L100	L167	L315
Hardness, Durometer Value	80A	90A	95A	75D
Specific Gravity	1.07	1.1	1.13	1.21
Tensile Strength, MPa	20.7	31	34.5	62
Young's Modulus, MPa	2.8	7.6	12.4	32
Solenoid Brittle Temp., ^{o}C	<-80	<-70	<-70	<-64

Polyurethanes have become ubiquitous, with their low density, good strength, low thermal conductivity, and inertness to common chemicals having led to extensive market success, as shown in Table 12.

[39] http://www.americanurethane.com/polyurethane-properties.html

Table 12: Uses of polyurethanes produced in the United States of America in 2015[40]

	M t	%
Building and Construction	863	35.9
Transportation and Marine	485	20.2
Furniture and Bedding	490	20.4
Machinery and Foundry	148	6.2
Appliances	124	5.2
Packaging	90	3.7
Textiles, Fibers and Apparel	20	0.8
Electronics	15	0.6
Footwear	7	0.3
Other	162	6.7
Total	**2,403**	**100.0**

Accurate information on global polyurethane use was not found in the open literature, but 15 M t is a reasonable estimate for 2015. The compound annual growth rate is expected to be somewhat in excess of 5%[41]. The resulting global market projections are shown in Table 13, together with corresponding bitumen demands based on carbon equivalent. The latter is a theoretical value based on the assumption that the carbon in polyurethanes originates entirely from bitumen. The theoretical value makes no allowance for conversion inefficiencies, losses, and carbon from sources other than bitumen. Furthermore, it is recognized that polyurethanes can be produced from feed-stocks other than bitumen. The carbon content of polyurethanes was taken as 75.6 wt%.

Table 13: Global projected polyurethane production (assuming compounded growth of 5% per year) and corresponding bitumen demand for 2015 to 2030

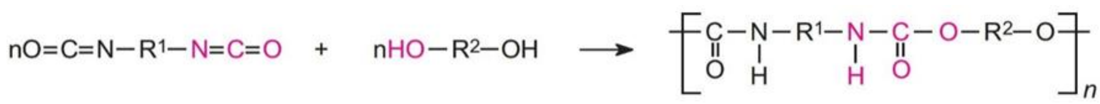
Year	**Global Production** M t/y	**Bitumen Demand** k bpd
2015	15.0	235
2020	19.1	300
2025	24.4	383
2030	31.2	490

40 The Economic Benefits of the, U.S. Polyurethanes Industry 2015, Economics & Statistics Department American Chemistry Council, September 2016

41 Polyurethane Market by Raw Material, Product, End User - Global Forecast to 2021, Newswire Association LLC. NEW YORK (Feb. 1, 2017)

Technologies

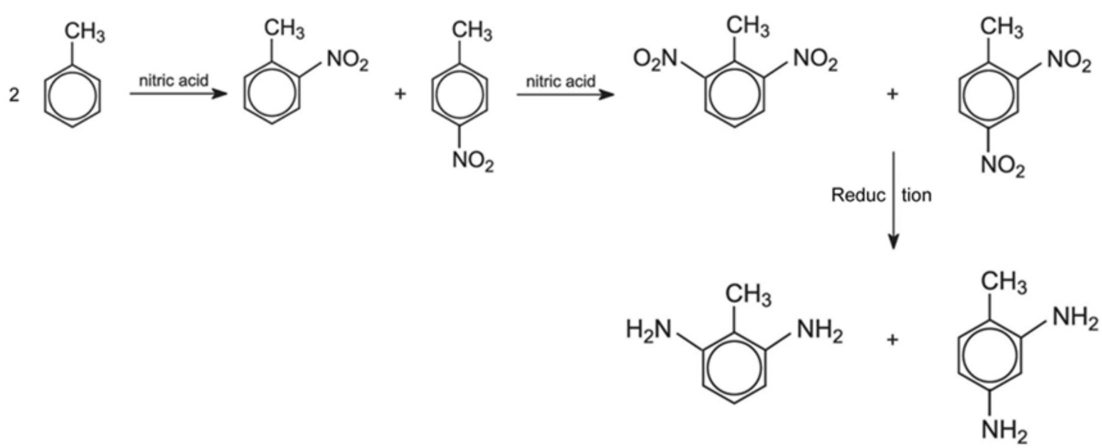
Polyurethanes are produced by the exothermic reaction of two feed-stocks: polyols (i.e., aromatic and aliphatic compounds with two or more -OH groups) and isocyanates (with one or more -NCO groups). An example is given by Eq. [1][42].



[1]

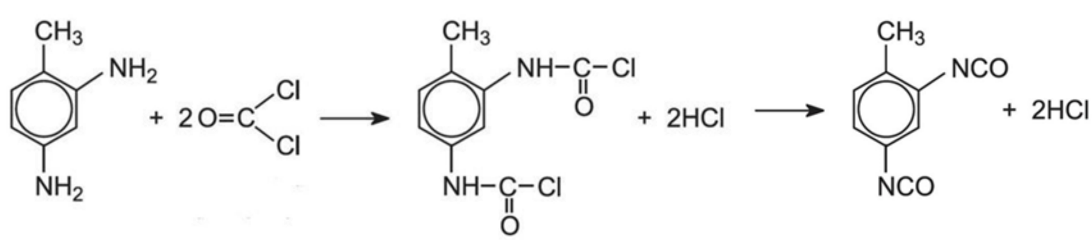
Isocyanate Diol Polyurethane

Toluene diisocyante (TDI) and methylene diphenyl diisocyanate (MDI) are the primary isocyanate feeds tocks in current use. TDI is produced from toluene by reaction with nitric and sulphuric acid, followed by reduction to toluene diamines:



[2]

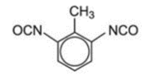
The diamines are then reacted with phosgene to yield toluene diisocyante (TDI):



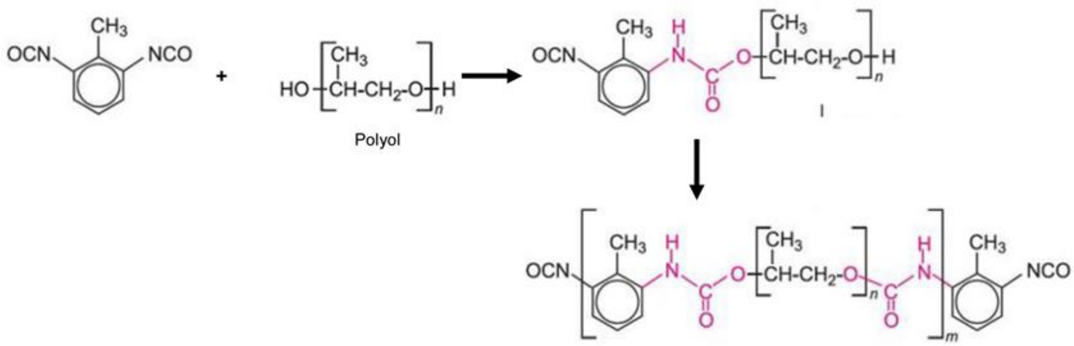
[3]

Phosgene TDI

[42] http://www.essentialchemicalindustry.org/polymers/polyurethane.html

The other TDI isomer,  , is formed simultaneously and by a similar route.

Polymerization occurs in accordance with reactions [4]:



[4]

The polyol determines the degree of cross linkage and hence polymer properties.

Suitability of Bitumen as a Polyurethane Feed-stock

Bitumen is rich in aliphatic and aromatic compounds that can, in principle, be reacted to yield diamines by treatment with nitric acid and sulphuric acid, followed by reduction. In view of the complexity of bitumen, more complex diamines would be formed than shown in Eq. [2]. This, in turn, would result in more complex polyurethanes having likely higher densities and rigidities. Their uses are presently unknown but could probably be valuable as construction materials for which there is a growing need.

The formation of select amines and isocyanates may also provide a means of separating bitumen constituents. Research is needed to address this opportunity.

The use of phosgene is complex and hazardous. It would be desirable to find alternate routes, like Asaki Kasei did for polycarbonates.

Reuse and Recyclability of Polyurethanes

Polyurethanes can be reused and recycled by mechanical, chemical and thermochemical (pyrolysis and gasification) methods. Given their stability, it is important not to direct them to landfills.

POLYURETHANE COMPOSITES

Given their good adhesion and chemical inertness, polyurethanes can also be used in composites. An example is SPS (Sandwich Plate System) developed and marketed by Intelligent Engineering[43]. SPS consists of polyurethane sandwiched between steel plates. SPS competes with reinforced concrete and, on a strength equivalent basis, is much lighter and smaller. Significant space savings are therefore possible. In addition, the SPS are factory produced and pre-sized, enabling quick installation. This is important for rapid construction and re-construction, such as bridge decks, where traffic delays need to be minimized.

SPS and similar composites deserve further consideration, especially if they can be competitively made in and marketed globally from Alberta.

POLYCARBONATES

Polycarbonates are thermoplastics based on the carbonate group[*], with bisphenol A (BPA) being the most common monomer feed-stock. BPA belongs to the diol family. The functional advantages of polycarbonates are based on the properties listed in Table 14.

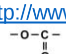
Table 14: Polycarbonate characteristics

Density	1,200	kg/m^3
Tensile strength	55 – 75	MPa
Young's modulus	2.0 – 2.4	GPa
Abbe number (indicating transparency)	34	
Glass transition temperature	147	^{o}C
Upper working temperature	115 to 130	^{o}C
Electrical conductivity	10^{-14} - 10^{12}	S/m

Polycarbonates are widely used as substitutes for glass in bottles, containers, domes, and windows, especially where weight is important, as in aviation. Polycarbonates are also making major inroads into the automotive sector (for windshields and sun roofs, head- and tail-lamp covers). Optical discs and CDs used to be a significant market for polycarbonates, but demand has declined. Small, but high-value applications include optical lenses and eye protection gear.

The current global market projections are shown in Table 15, together with corresponding bitumen demands based on carbon equivalent. The latter was calculated using the same approach as for polyurethanes. The current polycarbonate production is approximately 4.3 M t per year and the growth rate is estimated at 4% per annum[44].

[43] http://www.ie-sps.com/

[*] 

[44] http://news.ihsmarkit.com/press-release/commodities-pricing-cost/after-major-downturn-global-demand-polycarbonate-growing-agai

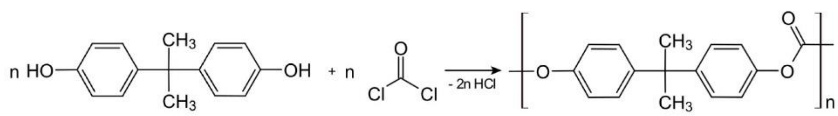
Table 15: Global projected polycarbonate production and corresponding bitumen demand for 2015 to 2030

Year	Global Production M t/y	Bitumen Demand k bpd
2015	4.3	68
2020	5.3	83
2025	6.4	100
2030	7.8	122

Technologies

Polycarbonates are produced by two primary processes, the basic chemistry of which is shown below:

Phosgene Process[45]

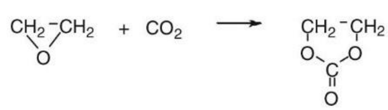


[5]

Bisphenol A Phosgene Polycarbonate

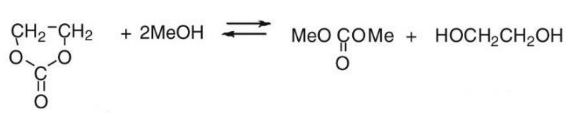
Asaki Kasei Process[46]

This is a multi-step process that has two major advantages: the use of toxic phosgene is avoided and the CO_2 generated in the formation of ethylene oxide is fully utilized.



[6]

Ethylene Oxide Ethylene carbonate



[7]

Ethylene Carbonate Methanol Dimethyl carbonate Monoethylene glycol

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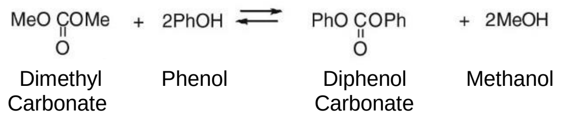
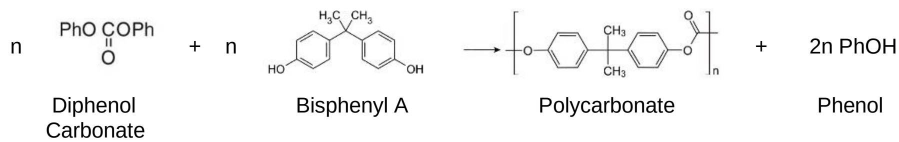
45 M. Rui P.F.N. Costa and R. Bachmann, Polycondensation, in Handbook of Polymer Reaction Engineering, T. Meyer ed., 57-151, J. Wiley & Sons (2005)

46 S. Fukuoka et al., Catl Sur Asia, 14, 146-163 (2010)



[8]



[9]

Both processes are inherently complex and depend on high-purity feed-stocks, including Bisphenyl A, which is made by reacting acetone with phenol.

Suitability of Bitumen as a Feed-stock

Bitumen contains few compounds with -OH groups and therefore is not directly suitable for producing polycarbonates, based on bisphenyl A or other diols. However, bitumen is rich is aliphatic and aromatic compounds that can, in principle, be reacted to yield diols or polyols. One approach is to use nitrous oxide as the reagent.

Little appears to be known about this subject but further research would provide additional insights.

Reuse and Recyclability of Polycarbonates

Polycarbonates can be reused and recycled using mechanical, chemical and thermochemical (pyrolysis and gasification) methods. Given their stability, it is important to collect end-of-life polycarbonates and avoid introducing them into the environment.

CONTROLLED-RELEASE FERTILIZERS – EXISTING WITH GROWTH POTENTIAL

Sustainable, efficient, and cost-effective agriculture is critical to the well being of the growing world population and to the economies of Alberta and Canada. Fertilizers play an essential role in modern agriculture, with nitrogen (N), phosphorous (P), and potassium (K) being the primary nutrients required by plants. In addition, soils must have a significant carbon content to support the micro-organisms and processes that enable plants to grow.

Replenishing N, P, K, and carbon are essential to sustained agricultural productivity and producers have become increasingly reliant on the application of fertilizers, such as urea (rich in N), ammonium phosphate (rich in N and P), and potash (rich in K). Plant nutrient requirements are not constant during the growing season, as shown by Figure 12 for wheat. Significant amounts of applied fertilizers are therefore lost due to leaching and decomposition. The losses are often in the range of 50%[47].

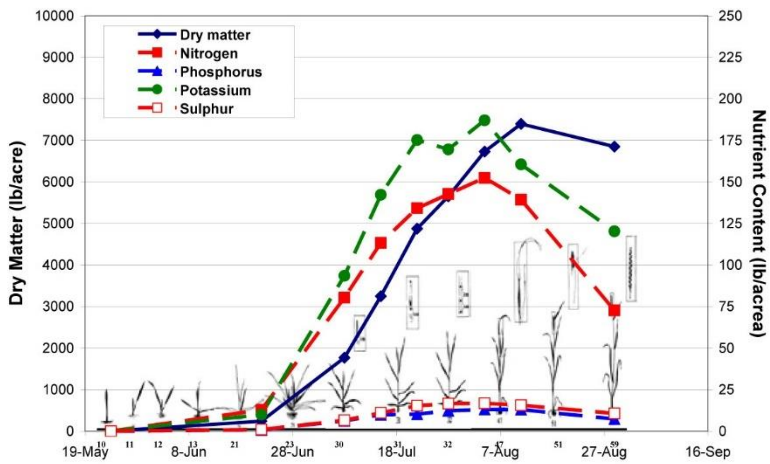


Figure 12: Biomass accumulation and nutrient uptake for wheat[48]

One way to address these problems is to use 'controlled-release fertilizers'*, i.e., fertilizers that release nutrients gradually and in accordance with plant needs. A comprehensive account of such fertilizers is given by Trenkel[49]. Figure 13 is a schematic depiction of a controlled-release, multi-nutrient fertilizer, in which moisture penetrates the resin coating and the nutrients are released over time. Instead of resins, other barrier materials have been used, including sulphur and organic polymers. The coating material is typically 10 wt% of the fertilizer.

At present, controlled-release fertilizers are not widely used in large-scale agriculture, mainly due to their high cost. They are extensively used in horticulture and turf maintenance, especially golf courses.

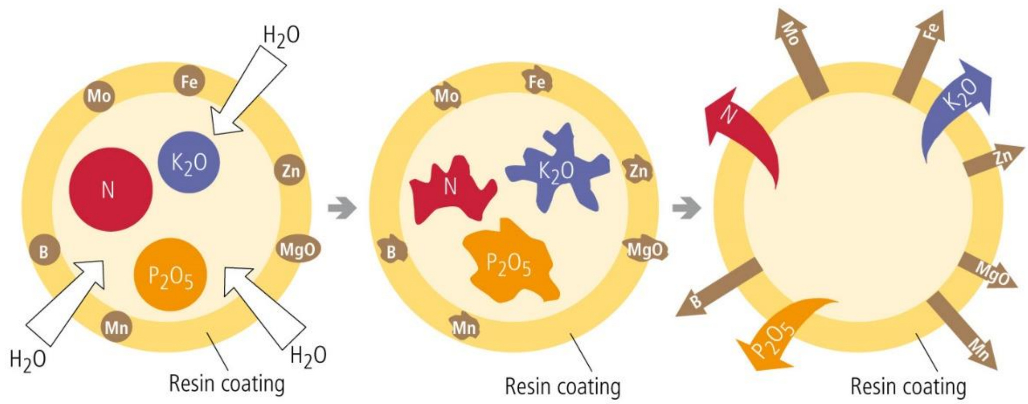
Coating materials could be made from bitumen. They could be asphaltenes, polymers or waxes derived from bitumen. In the case of asphaltenes, the heavy metals would have to be removed to ensure that no metal contamination of the soil occurs upon repeated application of the fertilizer. The coating would also be biodegradable, thereby adding organic carbon to the soil.

The 2014 requirements and 2030 projected bitumen requirements for controlled-release fertilizers are estimated using data from the International Fertilizer Association[50], subject to the assumptions stated in Table 16. Unfortunately, data are only publicly available on

[47] M.M. Hashim et al., Rice Science, **22**(5), 250−254 (2015)
[48] S.S Malhi et al., J. Plant Nutr. **30**: 641-658 (2007)
* In this report, 'slow release fertilizers' are included in 'controlled-release fertilizers'
[49] M.E. Trenkel, Slow and Controlled-Release and Stabilized Fertilizers, Int. Fertilizer Industry Assoc., Paris, France (2010)
[50] International Fertilizer Association, http://www.fertilizer.org/statistics

a global and regional basis. It was therefore not possible to provide estimates for Canada and the USA.

As shown by Table 16 the bitumen requirements for the world exceed the BBC Project target of 100 k bpd of bitumen.



Moisture penetration | Fertilizer dissolution | Fertilizer release

Figure 13: Nutrient release from a multi-component controlled-release fertilizer using a resin coat

Table 16: Estimates of bitumen requirements for controlled-release fertilizers containing 10 wt% of bitumen-derived shells, assuming a market penetration of 20%, and a growth in fertilizer demand of 3% per year.

Fertilizer	**2014**		**2030**	
	World	**North America**	**World**	**North America**
Urea				
Production, M t	175.4	1.1	281.5	1.7
Bitumen content, M t	3.5	0.02	5.63	0.03
Bitumen requirement, k bpd	61.0	0.4	97.9	0.6
Potash				
Production, M t	64.5	19.5	103.6	31.4
Bitumen content, M t	1.3	0.4	2.1	0.6
Bitumen requirement, k bpd	22.4	6.8	36.0	10.9
Ammonium phosphates				
Production, M t	63.3	9.9	101.5	15.8
Bitumen content, M t	1.3	0.2	2.0	0.3
Bitumen requirement, bpd	22.0	3.4	35.3	5.5
Total				
Production, M t	303.2	30.5	486.6	48.9
Bitumen content, M t	6.1	0.6	9.7	1.0
Bitumen requirement, bpd	105.5	10.6	169.3	17.0

ADDITIVE MANUFACTURING MATERIALS

Additive manufacturing (or '3D printing') is a comparatively new way of producing solid objects of complex shapes. It has the inherent advantage over other manufacturing techniques of building up shapes by successive deposition of very small particles, rather than removing materials from larger blocks or forcing materials into molds or through dies. As a result, complex shapes and objects with internal cavities can be readily manufactured.

A comprehensive overview of additive manufacturing is provided by Bandyopadhyay[51], including a summary of its advantages and challenges. Additive manufacturing is not very efficient for the production of large numbers of identical items (as needed, for example, in the automobile sector). It is better suited for producing personalized items for large numbers of customers and meeting a wide variety of needs, like medical implants and prostheses. The basic advantages and challenges of additive manufacturing are summarized in Figure 14.

[51] A. Bandyopadhyay, Chapter 1: Global Engineering and Additive Manufacturing, Additive Manufacturing, CRC Press (2016)

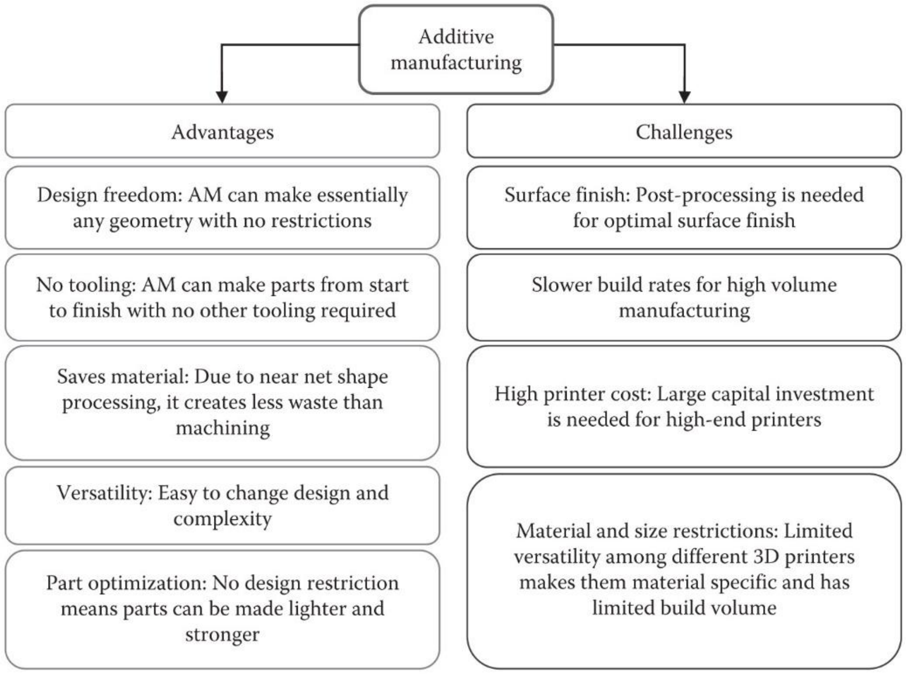


Figure 14: Advantages and challenges of additive manufacturing as presented by Bandyopadhyay

Materials used in additive manufacturing were initially limited to basic polymers, but the range has widened considerably and now includes advanced polymers, metals[52], and ceramics[53].

Growth in the additive manufacturing market is expected to be very rapid with, Siemens forecasting 300% growth between 2013 and 2023.

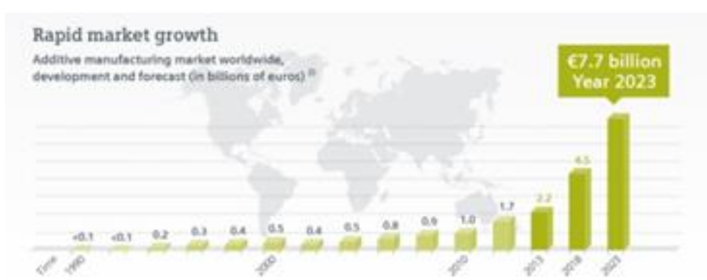


Figure 15: Siemens' estimates of Additive Manufacturing market (2013 – 2023)[54]

[52] M.J. Galba and T. Reischle, Chapter 4. Additive Manufacturing of Metals Using Powder-Based Technology, in Additive Manufacturing, CRC Press (2016)

[53] S. Bose et al. Chapter 5. Additive Manufacturing of Ceramics, in Additive Manufacturing, CRC Press (2016)

[54] https://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/Additive-manufacturing-facts-and-forecasts.html

It should be noted that the projections shown in Figure 15 represent the total value of the additive manufacturing market, not just the value of the market for materials.

Unfortunately, detailed information on the materials market for additive manufacturing is only available from commercial publications. It was therefore not possible to characterize and evaluate the market in this report. This should be done in Phase 2 of the BBC Project.

It is important to note that additive manufacturing may not only present opportunities for hydrocarbon constituents in bitumen, but also inorganic constituents, such as clays.

VANADIUM

Bitumen has long been known as a potential source of vanadium. The use of ionic liquids may enable efficient and cost-effective vanadium extraction directly from bitumen. Indirect vanadium recovery is also possible by processing petroleum coke (typically obtained in the production of synthetic crude), which has vanadium and nickel concentrations in the range of 5 wt% and 1.5 wt%, respectively.[55]

There are two major market impediments to vanadium recovery from oil sands:

- Prices have fluctuated significantly (see Figure 16), ranging from US$5,710 (in 1993) to US$64,100 (in 2005) per metric ton of vanadium[56]. In 2014, the price averaged US$22,100 per metric ton. The fluctuations are expected to continue since there are only three major supplier countries (i.e., China, South Africa, and Russia) and demand is strongly tied to the stainless-steel sector, which is largely dependent on the state of the global economy.

- If vanadium is removed from a large portion of Alberta's bitumen production (presently 2.5 M bpd with a vanadium content of 200 ppmw), 30,000 t of vanadium would be produced annually. As a result, the Alberta oil sands sector would contribute approximately 35% to the global production of vanadium and likely decrease vanadium prices. Global production values are shown in Figure 17.

[55] Alberta Energy, http://www.energy.alberta.ca/OilSands/792.asp
[56] US Geological Survey, http://minerals.usgs.gov/minerals/pubs/historical-statistics/#vanadium

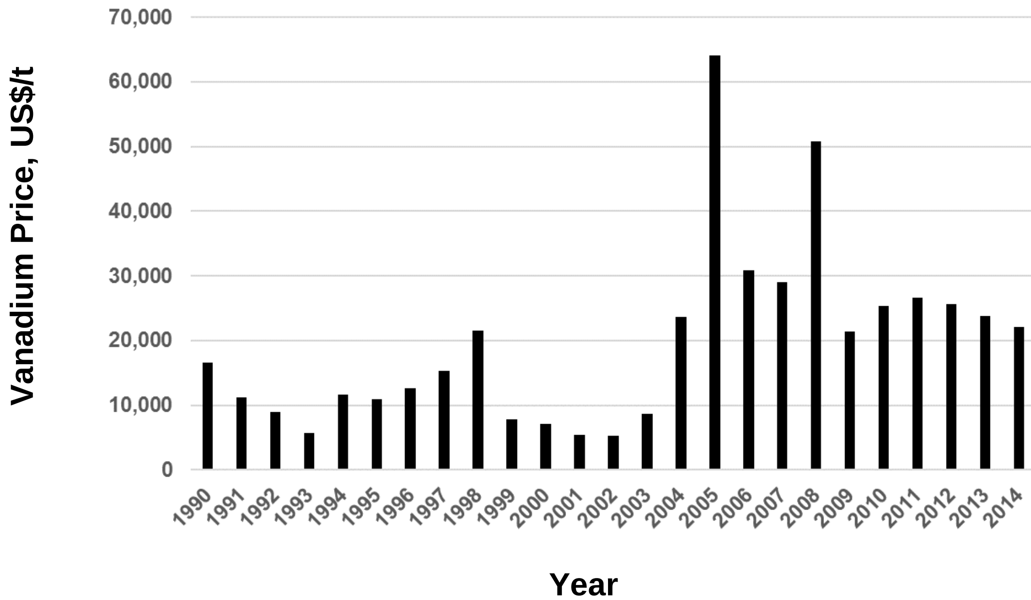


Figure 16: Vanadium prices for the period of 1990 to 2014

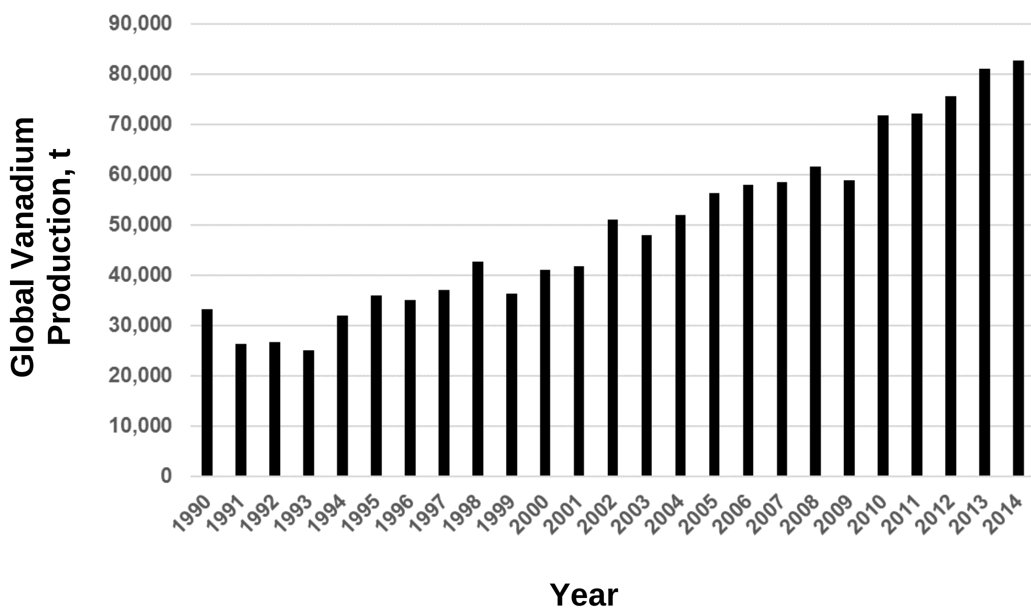


Figure 17: Global vanadium production for the period of 1990 to 2014[57]

Assuming a vanadium price of 22,100 US$/t, the total value of Alberta's annual vanadium production would be US$640 million.

It is therefore important to give consideration for novel uses of vanadium.

[57] US Geological Survey, http://minerals.usgs.gov/minerals/pubs/historical-statistics/#vanadium

One such use could be vanadium redox flow batteries. These batteries have been proposed and are being evaluated for the large-scale storage of electricity. The growth rate, size, and characteristics of this market are presently unknown.

The following estimate is presented as a guide:

			Reference
Bitumen			
Flow rate (stipulated)	500	k bpd	
Vanadium concentration	200	ppm w	Industry
Vanadium yield (@100% recovery)	5,802	t/y	
Redox Flow Cell			
V concentration in electrolyte	0.5	gmol/L	Blanc and Rufer[58]
Energy storage density	20	W h/kg electrolyte	L. Li et al.[59]
Energy storage	4,556	M Wh/y	

Alberta's target for renewable electricity is 5,000 M W by the year 2030, which is equivalent to 43,800,000 M Wh/y.

The vanadium production from 500 k bpd is therefore capable of storing approximately 0.01% of the annual targeted electricity production from renewable sources. Even if only 10% of the renewable electricity has to be stored in redox cells, vanadium redox cells represent a potentially very large market for vanadium recovered from bitumen.

It should be noted that the above estimates are approximate. In particular, energy densities in excess of 40 W h/kg electrolyte have been reported by Liyu Li and others. This would change the market demand for vanadium significantly.

One limiting factor of vanadium redox flow cells is the solubility of the vanadium in the electrolyte. This can be enhanced by using various additives, but long term trials and related experience are outstanding.

Electrolytes other than vanadium solutions have been suggested for redox flow cells. They include alkaline quinone solutions[60]. Such flow cells are still in early stages of development but they would potentially be of interest to the BBC Project because bitumen is a source of quinones and the quinone cells use carbon electrodes. The latter could potentially also be made from bitumen.

58 http://cdn.intechopen.com/pdfs/12523.pdf
59 Liyu Li et al., Adv. Energy Materials, 1, 394-400 (2011)
60 Kaixiang Lin et al., Science, 349 (6255), p. 1529-1532 (Sep. 2015)

NICKEL

The nickel content of bitumen is typically in the 80 ppm w range, i.e., significantly less than 200 ppm w for vanadium. Nickel can also be removed directly from bitumen by means of ionic liquids but neither their scientific fundamentals, technology, nor economics have been established. Nickel can also be recovered from petroleum coke by standard metallurgical processes.

Nickel is extensively used in stainless steels, with the market being very large. Except for 2006 and 2007, prices have been fairly steady and increasing. Global production is continuing to increase. Figure 18 and Figure 19 provide price and global production information for nickel.

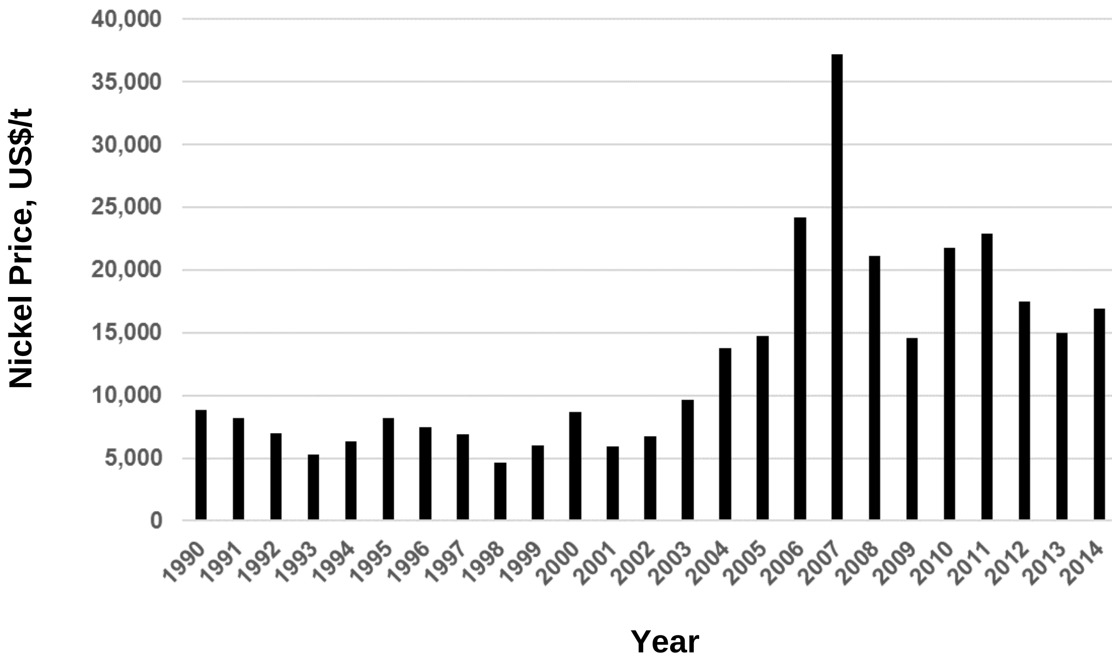


Figure 18: Nickel prices for the period of 1990 to 2014

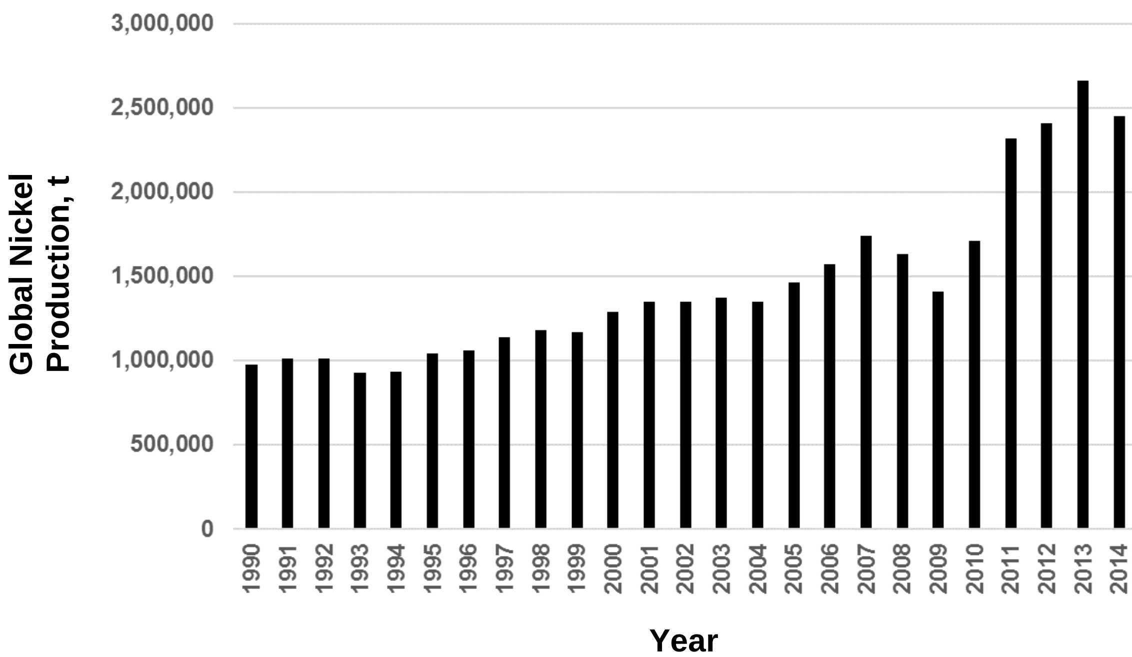


Figure 19: Global nickel production for the period of 1990 to 2014

The total potential nickel recovery from Alberta oil sands (at 2.5 million bpd) is approximately 12,500 t/y, representing just 0.5% of global nickel production. Alberta would therefore not influence global nickel prices significantly. The corresponding value of Alberta's annual nickel production would be US$210 million, assuming a price of 16,000 US$/t.

INORGANIC OIL **SANDS CONSTITUENTS AND THEIR POTENTIAL FOR NON-FUEL PRODUCTS**

The mineral composition of oil sands varies in accordance with its location and they are classified as estuarine clay (EC), marine clay (MC), estuarine sand (ES) or marine sand (MS). The following table provides a comprehensive summary of mineral types in the oil sands.

Table 17: Mineral composition (wt%) of oil sands[61]

Sample	Size fraction (μm)	Quartz	K-feldspar	Calcite	Dolomite	Siderite	TiO_2 minerals	Kaolinite	Total 2:1 clays	Chlorite	Pyrite
EC after DS	Bulk	52.3	2.7	0.0	0.3	3.0	0.7	14.4	25.3	1.3	0.0
EC after DS	>45	89.3	3.3	0.0	0.1	0.5	0.2	3.3	3.3	0.0	0.0
EC after DS	2–45	69.0	3.3	0.0	0.1	0.7	0.8	9.5	14.8	1.8	0.0
EC after DS	<2	4.2	1.0	0.8	0.3	1.0	0.3	28.9	58.9	4.6	0.0
EC after DS	0.2–2	6.9	0.6	0.0	0.2	0.1	0.3	37.0	52.6	2.3	0.0
EC after DS	<0.2	1.2	0.9	1.3	0.3	1.1	0.0	21.4	64.8	8.9	0.1
MC after DS	Bulk	72.1	3.9	5.5	1.4	0.1	0.3	8.9	7.5	0.2	0.1
MC after DS	>45	88.5	3.8	1.8	0.8	0.0	0.0	3.0	2.1	0.0	0.0
MC after DS	2–45	55.0	4.6	9.5	2.8	0.4	0.1	14.2	10.9	2.3	0.2
MC after DS	<2	8.2	0.0	13.8	1.2	0.4	0.0	30.4	40.6	5.2	0.2
MC after DS	0.2–2	16.4	1.3	7.7	1.0	0.3	0.0	38.4	33.7	1.2	0.0
MC after DS	<0.2	1.9	2.4	7.4	0.7	0.9	0.0	20.9	54.9	10.7	0.2
ES after DS	Bulk	94.5	3.6	0.0	0.1	0.1	0.0	0.8	0.7	0.2	0.0
ES after DS	>45	94.7	4.0	0.0	0.1	0.1	0.0	1.1	0.0	0.0	0.0
ES after DS	2–45	63.2	8.5	0.0	0.0	0.2	0.5	18.2	7.7	1.3	0.4
MS after DS	Bulk	86.8	3.7	1.4	0.8	0.3	0.2	4.1	2.5	0.0	0.2
MS after DS	>45	93.0	2.8	0.4	0.4	0.3	0.2	1.5	1.2	0.0	0.2
MS after DS	2–45	58.3	4.5	2.9	2.2	0.6	0.2	17.6	10.4	2.4	0.9
MS after DS	<2	18.7	4.1	7.1	1.8	1.6	0.0	30.9	31.8	3.4	0.6

Total 2:1 clays – the sum of illite and illite–smectite.
DS – Dean Stark extraction.

Table 18: Clay composition (wt%) of oil sands[62]

Component	Composition (wt%)
Quartz	55
Kaolinite	25
Illite	10
Sanidine	5
Anatase	5

Quartz and clays (including Kaolinite, Illite, and Smectite) are the predominant inorganic constituents of oil sands. They are the primary raw materials for ceramic tiles, stoneware, and porcelain[63,64]. Kaolinite is also widely used as an additive in paper manufacture to enhance gloss. It is presently unclear whether these mineral constituents would be competitive with raw materials from other sources, given their association with small amounts of salts, bitumen, and treating chemicals in the hot water bitumen extraction process. In most cases, high purity raw materials are needed.

Too little current information could be found to permit an evaluation of the market potential of quartzes and clays in the Phase 1 study. Consideration should be given to pursue this in future.

[61] M. Osacky et al., Fuel 113, 148-157 (2013)
[62] R. Chow, J. Zhou, D. Wallace, Oils Sands Conf., Edmonton, AB (2006)
[63] Ferrari and A.F. Gualtieri, Appl. Clay Sci, 32, 73-81 (2006)
[64] I.E. Odom, Phil. Trans. Roy. Soc (London), Series A, Math and Phys Sci, 311 (1517), 391-409 (1984)

In addition to the minerals shown in Table 17, the inorganic constituents of oils sands contain so-called 'heavy minerals'. These minerals are oleophilic and are recovered in the froth treatment stage of bitumen separation. They are listed in Table 19[65].

Table 19: Potentially valuable heavy mineral constituents of oil sands

Mineral	wt%	Mineral	wt%
Opaques:		*Non-Opaques:*	
Altered Ilmenite	23.0	Tourmaline	16.7
Leucoxene	16.6	Zircon	15.2
Pyrite	4.0	Garnet	6.0
Rutile	4.0	Staurolite	4.8
Ilmenite	2.8	Siderite	3.0
Goethite	1.6	Calcite	0.6
		Kyanite	0.6
		Apatite	0.6
Others			
Monazite, feldspars, micas	0.5		

The metal zirconium occurs in the form of zircon, $Zr\,Si\,O_4$ and technology development is underway for its separation from oil sands processing streams[66],[67].

The primary end uses for zircon are ceramics, zirconia, zirconium-based chemicals, refractories, and foundry and casting applications. Zircon sand is preferred in applications where high-quality finishes and tight tolerances are required owing to its lower expansion coefficient and greater stability at high temperatures compared with other materials. Zircon is also used as a natural gemstone and may be processed to produce cubic zirconia, a synthetic gemstone and diamond simulant[68]. The production data shown in Table 20 are based on the same reference.

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65 J. Oxenford et al., Heavy Minerals from Alberta's Oil Sands, SGS Mineral Services, Tech Paper 2001-12 http://www.sgs.ca/~/media/Global/Documents/Technical%20Documents/SGS%20Technical%20Papers/SGS%20MIN%20TP2001%2012%20Solutions%20for%20Oil%20Sands%20Metallurgy.pdf

66 G.M. Marshall et al., Minerals Eng. 65, p. 70-87 (2014)

67 http://www.titaniumcorporation.com/s/OilSands.asp?ReportID=137458&_Type=Oil-Sands-Project&_Title=Processing-Operation

68 https://minerals.usgs.gov/minerals/pubs/commodity/zirconium/index.html#myb

Table 20: Zirconium production (metric tons) expressed as Zr Si O_4.
(Information on US production is excluded for proprietary reasons)

Country	Year				
	2010	**2011**	**2012**	**2013**	**2014**
Australia	549,000	762,000	605,000	388,000	551,200
South Africa	383,000	427,000	400,000	210,000	386,547
China	140,000	150,000	140,000	150,000	150,000
Indonesia	50,000	130,000	120,000	120,000	110,000
Mozambique	37,100	43,600	46,900	31,400	50,800
India	27,800	39,000	40,000	40,000	40,000
Ukraine	30,000	26,000	20,000	41,000	40,000
Sri Lanka	9,200	30,000	35,000	30,000	30,000
Madagascar	7,490	13,075	15,000	16,000	23,800
Brazil	23,236	23,283	20,425	22,000	22,000
Kenya	--	--	--	--	15,004
Senegal	--	--	--	--	9,040
Vietnam	6,852	13,862	15,558	7,587	8,514
Russia	9,308	8,914	7,969	9,000	8,000
Sierra Leone	7,092	8,496	1,120	2,951	2,357
Malaysia	1,267	1,685	442	379	400
Total	**1,280,000**	**1,680,000**	**1,470,000**	**1,070,000**	**1,450,000**

Oxenford et al.[65]65 estimate that the Suncor and Syncrude plants processed approximately 330,000 bpd of bitumen, creating tailings containing 80,000 tons per year of zircon. This represents about 5.5% of global production in 2014. With significantly expanded open pit mining operations and full zircon recovery from their tailings, the oil sands sector would make a significant, but not dominant, contribution to global zircon supply.

COMBINED SWOT MATRIX

The Combined SWOT matrix is shown in Figure 20 and provides a high-level, pictorial summary of the insights obtained on the various product categories.

Asphalts have the greatest near-term strengths, including market size, proven quality, and exceptional suitability of oil sands bitumen as feedstocks. Their main weaknesses relate to product value and transportability. Graphenes, by contrast, are the least proven products. While having exceptional potential for large-scale electrical applications, graphenes are largely unexplored for these applications. In terms of SWOT characteristics, other products fall between asphalts and graphenes.

	STRENGTHS	WEAKNESSES
Asphalts	Excellent properties, market size	Low value, transportation logistics and costs
Carbon fibres	Excellent properties, market size, high value	Production technologies and costs
Graphene	Excellent properties, market size, high value	Production technologies and costs; feedstock suitability
Polyurethanes and Polycarbonates	Good properties, market size	Production technologies and costs
Controlled-release Fertilizers	Efficacy for select crops Canadian strengths in fertilizer manufacture	Cost effectiveness for major crops
Additive Manufacturing Materials	Potential use of organic and inorganic components	Unproven production technologies; market uncertainties
Vanadium	Bitumen value and upgrading economics	Unproven process technologies and costs
Nickel	Bitumen value and upgrading economics, stable market	Unproven process technologies and costs
Clays	Very large supply from open pit oil sands operations	Complex mixtures; unproven separation processes; unproven products
Zircon	High value	Unproven recovery processes and costs

	OPPORTUNITIES	THREATS
Asphalts:	Large and growing market	Competition from other feedstocks
Carbon fibres:	Rapid growth of large market; wood composites	Other materials and feedstocks
Graphene:	Potentially very large market	Competition from other materials
Polyurethanes and Polycarbonates	Large regional and global markets	Competition from other feedstocks; price pressures
Controlled-release Fertilizers	Growing regional and global markets	Competition from other feedstocks
Additive Manufacturing Materials	Rapidly growing regional and global markets	Competition from other feedstocks
Vanadium	Potential new markets for vanadium redox cells	Alternative vanadium sources; price volatility
Nickel	Enhancement of bitumen processing efficiencies	Price volatility
Clays	Potential new markets, including additive manufacturing	Competition from other sources
Zircon	Value added to tailings	Competition from other sources; price volatility

Figure 20: Combined SWOT matrix for non-combustion products

CONCLUSIONS

The following conclusions result from Phase 1 of the BBC Project.

1. The organic constituents of oil sands have considerable market potential to produce non-combustion products. Table 21 is a summary of the 2030 global market estimates for asphaltenes and associated bitumen. The potential, from a volume perspective, is especially good for asphalts and carbon fibres as replacement for steel. Unfortunately, no estimates could be provided for materials produced from bitumen for additive manufacturing.

Table 21: Summary of estimated asphaltene and bitumen demand for 2030. Notes important assumption associated with the text of the source tables.

	Asphaltenes k bpd	**Bitumen** k bpd	**Source Table**
Asphalts	3,600	20,400	Table 4
Carbon Fibres			
Current uses	5.1	29.2	Table 6
Steel replacement	6,100	34,600	Table 7
Vehicle use	190	1,100	Table 8
Wood composites	287	1,640	Table 9
Graphene	133	760	Table 10
Polyurethanes		489	Table 13
Polycarbonates		122	Table 15
Controlled-release Fertilizers		105	Table 16

Some products like carbon fibre-wood composites and controlled-release fertilizers are particularly well suited for Alberta since the Province is a bitumen, wood and fertilizer producer.

2. Asphalts and new asphalt transportation technologies could have potential for major near-term market success, especially as bitumen-derived asphalts are known to have very high quality.

3. Carbon fibres produced from the asphaltene fraction of bitumen have major mid- to long-term market potential. Competitive, large-scale production technologies remain to be demonstrated and collaborative partnerships with fibre users are essential.

4. Controlled-release fertilizers have mid-term market potential, requiring both new manufacturing technologies and demonstration of crop value under Canadian and international conditions.

5. Graphenes have major long-term potential as replacements for copper in electric machinery and power distribution. Early collaboration with a wide range of researchers (including researchers at the Canadian National Institute for Nanotechnology in Edmonton) would be fruitful.

6. Large potential markets are only one important criterion for bitumen demand and success. Another critical criterion is price competitiveness which, in turn, depends on the inherent properties of bitumen and the process technologies required to convert bitumen into saleable products. The products shown in Table 21 must compete with products made from other feed-stocks, notably conventional crude oil, natural gas, and, increasingly, bio-products.

7. The present technologies for making the products shown in Table 21 are complex, even for conventional feed-stocks that have narrower composition ranges than bitumens. Except for asphalts, bitumens may therefore be disadvantaged, a problem that can only be overcome by better technologies. Critical technologies are more advanced separation and chemical conversion processes.

8. There appear to be no basic problems with the re-usability, recyclability, and end-of-life conversions of products listed in Table 21, although data are missing in some cases. For example, little is presently known about these issues for graphenes.

9. The recovery of vanadium from bitumen (for bitumen production rates of 500 k bpd or more) would significantly impact the present global supply of vanadium and therefore its price, unless new markets can be found. Vanadium redox batteries would provide such a market if they can be successfully deployed for storing electricity from intermittent sources, such as solar and wind.

10. The recovery of nickel from bitumen (for bitumen production rates of 500 k bpd or more) would not significantly impact the global nickel market or price.

11. Zircon recovery from froth processing of bitumen would modestly impact the global zircon market.

12. Market opportunities for quartz and clay minerals, produced from open pit mining operations, should be revisited since current information was not found. It might be possible to use fine clays as materials for additive manufacturing.

13. All oil sands extraction and conversion processes are energy intensive. Sources of clean energy are integral to the successful conversion of oil sands constituents into non-combustion products.

The specific conclusions regarding non-combustion products from oil sands, their production technologies, and markets should be viewed as preliminary, with all estimates being approximate. Other products may also be added. These issues will be addressed in Phase 2 of the BBC project, with the assistance of a contractor identified through an open Request for Proposal.

The primary conclusion is that the market potential for growth of existing and new non-combustion products from oil sands is sound, reaching the target potential of 100 k bpd per product category and 500 k bpd in aggregate. Due to the scale of oil sands production, the markets are primarily global in extent. Reaching the market potential is complex, posing important technical, transportation, and marketing challenges.

ATTACHMENT 1 COMPREHENSIVE WANT STATEMENT FOR BBC PROJECT

Project Name:	**Bitumen Beyond Combustion (BBC) Project**	
Project Team:	John Zhou	Project Leader, Alberta Innovates
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	Prit Kotecha	Suncor
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	Nathan F. Maycher	Conoco Phillips
	Axel Meisen	Alberta Innovates
	Gary Millard	Shell
	Meera Nathwani-Crowe	Shell
	Joy Romero	CNRL
	Cecile Siewe	Canmet Energy
	Clementina Sosa	Cenovus
	Craig Stenhouse	Cenovus
	Donald Wood	Bowman Centre for Sustainable Energy

The members of the Project Team are energy-sector experts with a focus on oil sands and closely related subjects, whose companies and organizations have shared interests in BBC, including the development of an RFP for a detailed study of its market potential and challenges

GENERAL PROJECT OBJECTIVE: Identification and assessment of the techno-economic potential of oil sands constituents for producing non-combustion products

Specific Project Objectives - Phase 1: *Completion date: March 31, 2017*

a. Identify, characterize, and evaluate the major *organic* oil sands constituents (bitumen, heavy oils, asphaltenes, etc.) and their potential for uses other than fuels
b. Identify and create a list of actual and potential non-fuel products that can be made from the *organic* oil sands constituents and their mixtures (including diluted bitumen)
c. Identify, characterize, and evaluate the major *inorganic* constituents and their potential uses
d. Identify and create a list of actual and potential products that can be made from *inorganic* oil sands constituents
e. Provide high-level information on the technologies (including their costs, energy requirements, and environmental impacts) for making the products
f. Outline the long-term disposal issues and requirements of the products, including their recyclability
g. Summarize the above results (based only on information available in the public domain) so that they serve as a basis for an RFP to undertake detailed market and technical analyses

For objectives a to d, restrict the identification, characterization, and evaluation to major uses of oil sands with potential aggregate markets exceeding approximately 0.5 million bpd oil equivalent for each product. The market potential is expected to arise from the expansion of existing markets and/or the creation of new markets. In most cases, the market potential is not expected to be reached in less than 5 to 15 years. Individual companies may achieve market penetration sooner and at levels significantly less than 0.5 million bpd oil equivalent.

Specific Project Objectives - Phase 2: *Completion date: May 30, 2017*

a. Prepare and issue an RFP to undertake detailed market and technical analyses on oil sands constituents for producing non-combustion products, covering the subject matter identified in Phase 1 a to f and
   - include both current and emerging/potential products and processes with major commercial potential
   - identify experts and centres of expertise in Alberta and elsewhere on the techno-economic potential of oil sands constituents for producing non-combustion products
b. Evaluate RFP responses
c. Identify and recommend the top respondent(s) to permit selection of the Contractor

Specific Project Objectives - Phase 3: *Completion date: December 1, 2017*

a. The Contractor undertaking the detailed market and technical analyses on oil sands constituents for producing non-combustion products, covering the subject matter identified in Phase 1 a to f and in Phase 2 a
b. The Contractor summarizing the results so that they serve as the basis for a White Paper on the production of non-combustion products from oil sands constituents

DUPLICATION

Significant previous work has been performed by organizations and companies inside and outside Alberta on the Project objectives. Maximum use is to be made of this work.

TECHNOLOGY READINESS LEVEL

The TRLs of processes should be reported or, if unknown, estimated.

BENEFITS FOR ALBERTA

Finding commercially competitive additional or alternate uses of oil sands constituents is of considerable importance to Alberta because they will help to

- diversify Alberta's economy
- create new high-level employment opportunities, both in the oil sands industry and its supply sectors
- absorb some or all of the additional capacity (>1 million bpd) of expanded and new oil sands operations over the next 5 to 10 years
- protect Alberta's oil sands industry from potential declines in demand of fossil fuels
- lessen Alberta's dependency on inter provincial and international pipeline capacity
- mitigate Alberta's greenhouse gas emissions
- stimulate investment in Alberta

PROJECT SUPERVISION AND EXECUTION

All phases of the project will be supervised by the Project Team.

Phase	Execution
1	Axel Meisen
2a	Alberta Innovates staff and Axel Meisen
2 b and c	Project Team
3	Contractor (to be selected and appointed)

ATTACHMENT 2 THE CHALLENGE OF SCALE: NON-COMBUSTION PRODUCTS FROM PETROLEUM AND PER CAPITA CONSUMPTION OF BITUMEN

Non-combustion products from petroleum

Data from the US petroleum refinery sector enables insight into the general relationship between total petroleum use and the amounts dedicated to combustion and non-combustion products.

As shown in Figure 21, US refinery inputs are primarily used to create combustion products, rising from 12.8 (92.3%) to 15.6 (94.7%) million bpd in 1993 to 2015, respectively. The corresponding numbers for non-combustion products are 1.1 (7.7%) to 0.9 (5.3%) million bpd in 1993 to 2015. This means that US refineries reduced both the actual and percentage of refinery feeds destined for non-combustion products. The change also reflects the impact of higher margins for combustion products than non-combustion products (such as petrochemical feed-stocks) and occurred even though US refineries increased the use of heavier crudes.

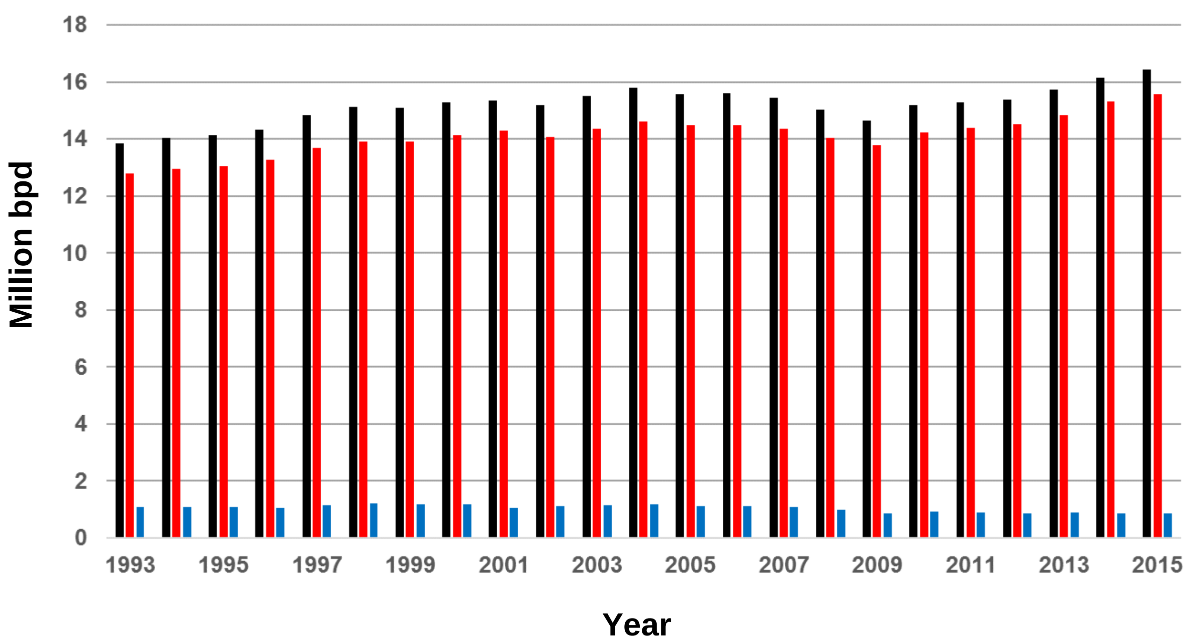

Figure 21: Gross input to US refineries (——), input dedicated to combustion products (——), and input dedicated to non-combustion products (——). The data are yearly averages, based on information provided by the US Energy Information Agency[69],[70]

[69] U.S. Gross input to refineries (2016), https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MGIRIUS2&f=M
[70] U.S. Refinery yield (2016), https://www.eia.gov/dnav/pet/PET_PNP_PCT_DC_NUS_PCT_A.htm

More detailed information on the breakdown of US refinery inputs dedicated to combustion and non-combustion products is shown in Table 22. Finished motor gasoline, distillate fuel oil, Kerosene-type Jet Fuel, and Residual Fuel Oil are produced from approximately 80% of the refinery inputs. By contrast, non-combustion products were produced from less that 8% of refinery inputs in 1993 and declined to just over 5% in 2015. Asphalts and Road Oil commanded the largest fraction destined for non-combustion uses.

Table 22: Gross input to US refineries and products dedicated to combustion and non-combustion uses in 1993 and 2015

	1993		**2015**	
	k bpd	**%***	**k bpd**	**%***
Gross Inputs to Refineries	13,850		16,430	
Combustion Products				
Finished Motor Gasoline	6,100	44	7,100	43
Distillate Fuel Oil	2,900	21	4,550	28
Kerosene-Type Jet Fuel	1,220	9	1,480	9
Residual Fuel Oil	770	6	390	2
Petroleum Coke	570	4	800	5
Still Gas	610	4	630	4
Liquefied Petroleum Gases	540	4	570	3
Kerosene	40	0.3	020	0.1
Aviation Gasoline	30	0.2	020	0.1
Sub-total	*12,770*	*92*	*15,560*	*95*
Non-combustion products				
Asphalt and Road Oil	420	3	310	2
Naphtha for Petrochemical Feed-stock Use	130	1	170	1
Other Oils for Petrochemical Feed-stock Use	260	2	90	0.6
Lubricants	150	1	170	1
Special Naphthas	50	0.4	30	0.2
Miscellaneous Petroleum Products	40	0.3	90	0.6
Waxes	10	0.1	10	0
Sub-total	*1,070*	*7.7*	*860*	*5.3*

* percentages are rounded and do not sum exactly

The BBC Project objectives (100 k bpd per product category and 500 k bpd for the sum of categories) therefore represent substantial fractions of the US refinery runs.

The US data and related insights should only be taken as a guide because:

- oil sands bitumens have technical and cost characteristics different from most other crudes processed by US refineries
- US refineries may not be representative of global and Canadian conditions

More detailed work is required and will be undertaken in the next phase of the BBC Project.

Per Capita Consumption of Bitumen

Another way of viewing the challenge of scale is to estimate the required per capita use of bitumen corresponding to specified bitumen production rates. **Table 23**Table 23 provides such estimates for Canada, the USA, and the world, based on United Nations population projections[71].

Table 23: Required daily per capita use of bitumen at specified bitumen production rates for the years 2015, 2030, and 2050

Year	Country/ Region	Population (M)	Per capita bitumen use (L/d) at bitumen production of:		
			500 k bpd	2,500 k bpd	3,500 k bpd
2015	Canada	36	2.2	11.1	
	USA	325	0.2	1.2	
	World	7,325	0.01	0.05	
2030	Canada	41	2.0	9.8	13.7
	USA	363	0.2	1.1	1.5
	World	8,425	0.01	0.05	0.07
2050	Canada	45	1.8	8.8	12.3
	USA	401	0.2	1.0	1.4
	World	9,551	0.01	0.04	0.06

The table includes not only the Project target of 500 k bpd, but also the current and projected bitumen production rates for Alberta.

As shown by Table 23, the required per capita uses of bitumen are substantial. 500 k bpd of bitumen requires a per capita use of approximately 2.2 L/d for Canada. When averaged over the US population, the corresponding use is about 0.2 L/d at present. On a world-wide basis, the required uses are significantly smaller, but would necessitate global market reach and penetration from Alberta, which are difficult to achieve. These estimates confirm the need for pursuing potential markets in Canada and abroad.

71 United Nations population projections for urban and rural populations: https://esa.un.org/unpd/wup/CD-ROM/