NexantThinking™

Special Reports

Green Solvents: An Ideal Solution?

Brochure
September 2015

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Contents

1.1 BACKGROUND

In recent years, solvents have been scrutinized for their potential to cause harmful side effects and the chemicals industry is seeking greener alternatives in the face of tightening regulations and user concern.

Some 29 million tons of solvents are consumed annually, in a wide variety of applications, from coatings and inks to industrial cleaning. They are key ingredients in a number of processes and products; however, solvent selection is becoming increasingly complex. In addition to considering what physical properties are required from a solvent, industry players are adapting to growing environmental concern and regulatory pressure to minimize the use of unacceptable solvents. As a result, a multitude of products and processes in the solvent industry are being reformulated. Solvents with lower toxicity, sustainable origins, biodegradability, safer handling, and importantly, lower and less harmful emissions continue to increase in popularity and replace incumbent conventional solvent demand. Solvent substitution is trending “greener”, but (typically) not at the cost of product performance or process efficiency.

Most organic solvents are considered to be volatile organic compounds (VOCs). The EPA defines VOCs as, “any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates and ammonium carbonate, which participates in atmospheric photochemical reactions”, leading to ozone formation. Solvents that are not included in the EPA’s exempt list are subject to mass based VOC regulation, which treats all non-exempt chemicals as equals in their ability to generate ozone. This method of restriction limits innovation by unnecessarily limiting solvent VOC *content* instead of VOC *impact*. In California, the California Air Resources Board (CARB) regulates VOC emissions from aerosol spray paints (and other coatings) by focusing on the reactivity and volatility of solvents rather than just their mass. Therefore a paint formulator is able to use a greater amount of a solvent in their products if its reactivity value is below the specified limit. This report includes a discussion of solvent photoreactivity as a measure of potential to contribute to ozone formation.

Green solvent demand is approaching ten percent of demand at a global level and will continue to increase as manufacturers look to improve process efficiencies and reduce environmental footprint. Major solvent applications exist in the paints and coatings, printing inks, cleaners, pharmaceuticals, personal care, adhesives, and agriculture industries.

This report aims to give subscribers an understanding of the developments and potential for green solvents for use across a range of industrial applications, processes, and products.

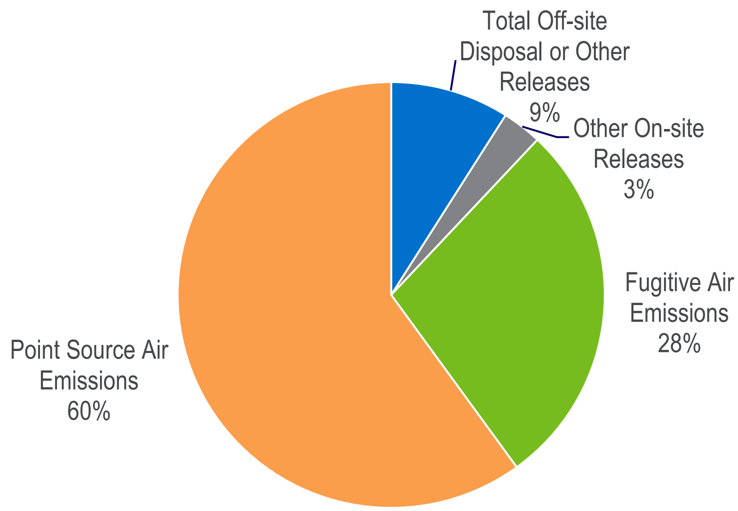
1.2 DRIVERS FOR GREEN SOLVENTS

Solvent technology innovators are actively investing in the advancement of green solvent technologies under the broad themes of minimizing solvent waste, solvent emissions, and solvent toxicity. The following describes some of these advancements and the drivers for change that are leading to new green solvent technologies and processes.

Solvents and Environmental Toxicity

One of the greatest contributors to the chemical industry’s environmental footprint is the use of solvents, due to the vast quantities in which they are used, their volatility, and their wide range of environmental impacts. There are some sixty commonly used industrial solvents, of which the vast majority are volatile and toxic compounds. As shown in Figure 1.1, emissions of hazardous air pollutants (HAPs) are primarily due to solvent evaporation, where molecules escape from the solvent into the atmosphere, either from point sources or as fugitive emissions. The hazardous handling properties and risks of atmospheric and soil contamination, particularly by chlorinated hydrocarbons, have led to significant efforts to reduce the consumption of hazardous solvents. This has led to a continuous shift towards more environmentally friendly processes and solvents, which have a smaller impact on the planet.

Figure 1.1 2013 U.S. Releases of Hazardous Air Pollutants (HAPs)
(Total = 189.5 thousand tons, USEPA)



VOCs and Ozone

The global desire to reduce low-level atmospheric ozone and smog has led to worldwide efforts to decrease the emissions of volatile organic compounds ("VOCs"). VOCs react with nitrogen oxides to form ozone, which combine with particle emission to form smog. Smog pollutes the atmosphere, reducing visibility and creating numerous health concerns. Reducing the formation of ground level ozone is a public policy issue around the globe. VOC regulation is traditionally monitored with a mass-based approach, but with the photochemical reactivity-based approach, the potential of a chemical to contribute to ozone levels could provide another mechanism for performance based solvent selection. The emission of reactive VOCs must be minimized and the processes employed by various industries be made less wasteful if the requirements of new legislation are to be met.

MIR and the Environment

The Maximum Incremental Reactivity (MIR) value measures the tendency of a chemical to form ground-level ozone and smog. The idea is that all VOCs were not created equal – depending on their reactivity, some VOCs are worse than others. The MIR value measures the reactivity of a VOC in the atmosphere. MIR aims to simplify VOC regulations by focusing on the molecules with the greatest potential to create smog. MIR values rank VOCs by their incremental reactivities, so that regulators can focus on the solvents with a MIR above a threshold value. To protect workers and the environment, and to comply with ever-tightening regulations, many solvent users are moving to low MIR solvents.

The California Air Resources Board was an early adopter of the MIR scale and its use is now being investigated by the EPA. In the United States, California first applied MIR for aerosols in 2000, and has continued to be at the frontier for environmental regulations concerning solvents. California is seen by some in the industry as an indicator for future countrywide and regional regulations.

New California Regulations

In 2015 to 2016, California passed new restrictions on solvents for a variety of common applications that are to come into full effect between 2016 and 2020. These more stringent regulations restrict the amount of VOCs per liter of product (25 g/liter, or less, depending on the application), prohibit the use of solvents that have an MIR value greater than toluene, and prohibit the use of volatile organic hazardous air pollutants (VOHAPs). In addition, the VOC composite partial pressure (CPP) must be less than 5 mm Hg at 20 °C. The vapor pressure, MIR and VOHAP restrictions will limit the range of solvents that industries can use in paints, inks, and adhesives formulations, etc., but provides flexibility for using low MIR solvents.

Bio-renewable Feedstocks

There is increasing interest in reducing reliance on the petroleum based feedstocks. Currently, the vast majority of organic solvents used are derived from crude oil. Fossil fuels and petrochemicals form some of the key building-blocks of modern society. However, concerns are mounting about the economic costs and environmental sustainability of the world's reliance on non-renewable fossil fuels. Consequently, some of the world's biggest players in the chemical industry seek to develop new feedstocks and products derived from bio-based materials. To date, the most successful bio-based product is ethanol derived from corn and sugarcane, but developers of bio-refineries are looking to expand product portfolios and reduce wasted inputs, modelling themselves after traditional refineries.

1.3 SUMMARY

This study addresses the commercial and environmental issues concerning solvent selection. It profiles the current regulatory environment surrounding issues such as ozone formation due to VOC emissions, solvent safety issues and toxicity. The study also includes: an overview of the solvent market, a selection guide for available green solvents, the key companies producing green solvents, emerging green solvents and their markets, and a discussion of the commercial implications of using alternative solvents. Green solvents included in this report have one of the following criteria:

The report will be a valuable resource for investors, marketers, solvents producers, and solvents consumers by clearly describing the landscape of existing and emerging "green" solvents. The key questions addressed by the study include:

- What makes a solvent green, and which solvents can be considered the greenest?
- What are some potential green solvent replacements given certain solubility requirements?
- What are the market implications associated with different green solvents? What environmental rewards or sacrifices might these solvents involve?
- What are the relevant government regulations affecting solvent use, emissions, and disposal? In what direction will future regulations trend? How will this drive solvent consumption and selection?
- What industries are key solvent consumers? What are the notable market trends in each industry?
- What are the most commonly used solvents, and which green solvents have already seen industry success?
- Who are the key industry players in green solvents production?
- What steps should a company take to become a more sustainable consumer or seller of solvents?

Solvent manufacturing companies and research institutions are actively investing in the advancements of green solvent technologies under the broad themes of minimizing solvent waste, solvent emissions and solvent toxicity. This study provides a practical, commercial approach to addressing these targets.

2.1 OBJECTIVE

The study objective is to analyze the technical, commercial and environmental status of the solvent industry by its major markets and determine the impacts of using green solvents. In many applications, green solvents have the potential to replace toxic, corrosive, volatile classical solvents and therefore greatly reduce the environmental footprint. In certain scenarios, green solvents may even provide cost savings through process efficiency improvements. The study considers critical elements of the green solvent supply chain to identify the components of this potential.

2.2 SCOPE

This study addresses the technical potential and commercial attractiveness of green solvent alternatives for industrial applications.

This report assesses and provides:

- Solvent industry segmentation of applications, solvent types and application technologies
- Global green solvents market size in 2014 based on current market information and forecast trends from 2014 to 2020 with historic consumption and high level analysis of regional trends
- The drivers, restraints and opportunities of the green solvents market
- Review of regulatory drivers impacting solvents and effectively promoting reduced solvent consumption or use of green solvents
- Chemical profile and commercial overview, including indicative pricing and applications, of more than 30 green solvents established in the market and emerging products reported as having green credentials
- Description of the Nexant Solvent Sustainability Index (NSSI) methodology used in this report to determine the relative greenness of so-called green solvents and ranking of the solvents studied (see Methodology Section 4.1)
- A comparison of the effectiveness of green solvents vs. traditional solvents based on Hansen Solubility Parameter (HSP) and other differentiators of solvent performance (see Methodology Section 4.1)
- A summary analysis of key companies providing green solvent solutions including a summary of the market position and key products of leading green solvent providers. Section 7 of the Table of Contents provides the list of companies that will be covered

Section	Page

4.1 INFORMATION SOURCES

The evaluations of green solvents and their applications were based on Nexant's in-house information enhanced by contacts with producers, end-users and other industry experts. Analyses of emerging solvent technologies were built up from a review of patents, public domain information and discussions with the companies developing the solvents.

Commercial information and forecasts were developed from Nexant's extensive in-house databases, augmented with selected regional fieldwork. Market projections were developed based on Nexant's in-house modeling systems and experience.

Nexant utilized its extensive network of primary and secondary resources to produce unique industry insights. This includes the use of public resources, including vendor and service company websites, government, national research laboratories public and NGO resources, academic papers and study reports, conference presentations, textbooks and manuals, and information from professional entities like the American Chemical Council (ACS), and regulatory agencies like the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB). Beyond these sources, Nexant contacted and interviewed experts in the industry to obtain a fact-based view and insight on green solvent applications and the regulatory and competitive landscape.

In order to obtain a comprehensive view and provide insights on green solvent applications feasibility from a regulatory perspective, Nexant leveraged its previous knowledge base in this area and utilized vast resources and databases provided by the EPA, United Nations, the European Commission and other regulatory agencies.

4.2 NEXANT SOLVENT SUSTAINABILITY INDEX METHODOLOGY

The term "green" is often used to express the goal of minimizing the environmental impact resulting from the use of a particular substance. However, the definition of "green" is rather fluid, and the term is used loosely and extensively in marketing materials.

There are many criteria that form the basis upon which a solvent may be labelled "green", including, but not limited to: a renewable feedstock, status as non-VOC (or functionally non-VOC), a high flash point, non-toxic, biodegradable, and recyclable.

Given that a solvent may possess many or only one of these attributes, how can the industry measure the greenness of a solvent in order that it can be compared with another? To answer this question, Nexant developed a method to quantitatively assess the relative "greenness" of solvents; the Nexant Solvent Sustainability Index, or NSSI.

The NSSI evaluates solvents on eight parameters in order to determine its relative greenness: feedstock, toxicity, biodegradability, VOC status, odor, fire hazard, vapor pressure, and reactivity. A solvent with perfect greenness in all categories will receive an NSSI of 100 percent, e.g. water. Less green alternatives are rated on a sliding scale down to zero.

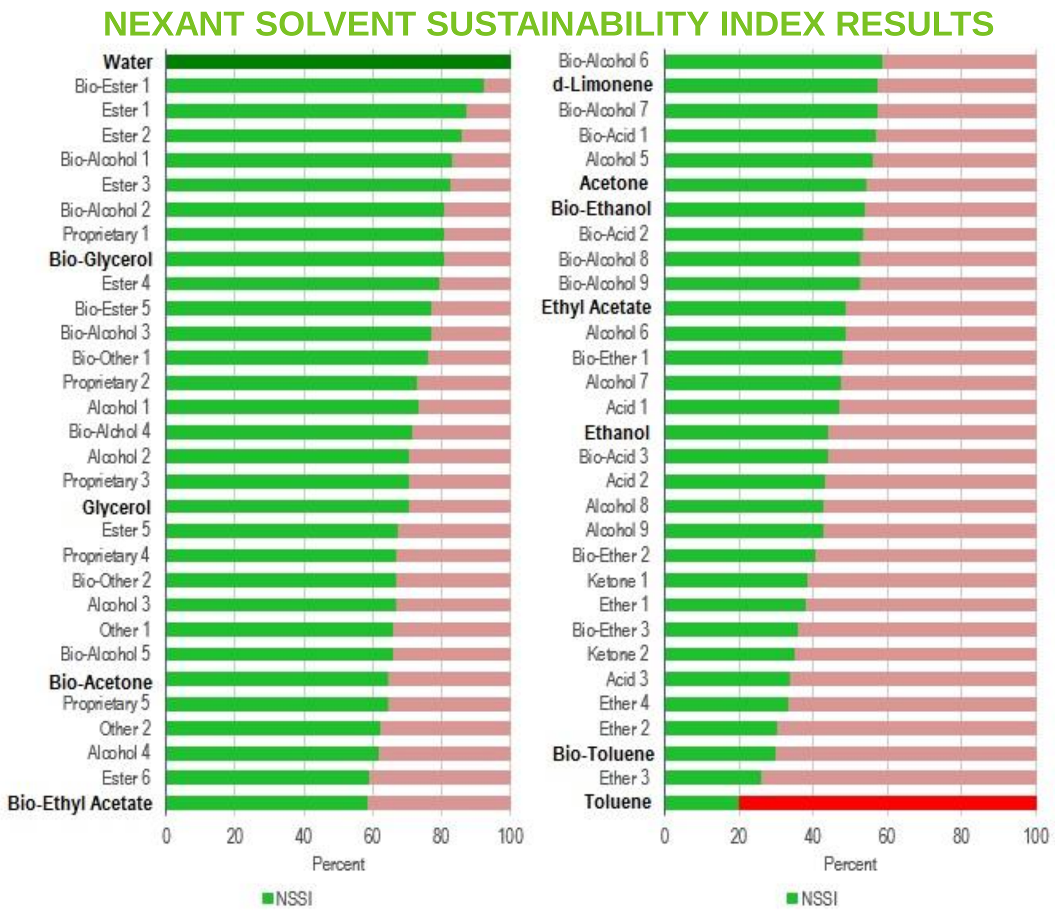
Figure 4.1 NSSI Methodology

NEXANT SOLVENT SUSTAINABILITY INDEX

PARAMETER	KEY OBJECTIVES
Feedstock	Provide bonus for renewable feedstocks
Toxicity	Measure hazard potential for humans and the environment
Biodegradability	Assess ease with which product biodegrades and its potential to bio-accumulate
VOC	Consider VOC regulatory status
Odor	Assess whether odor is unpleasant
Fire Hazard	Measure flashpoint and fire safety regulations for process and consumer safety
Vapor Pressure	Determine the ease with which the solvent enters the atmosphere
Reactivity	Measure chemical reactivity considering risk of ozone formation and explosion

Figure 4.2 provides a sample of the 62 solvent assessments that Nexant completed in the special report: “Green Solvents: An Ideal Solution?”

Figure 4.2 Selected NSSI Rankings



* Toluene has been included as a reference conventional solvent

Ethanol is the oldest and most successful biorenewable chemical product in commercial production. Aside from its more pervasive end-uses in fuels and beverages, ethanol is an important solvent in detergents, cosmetics, lotions, soaps, shampoos, and other consumer products. Solvent applications for ethanol account for a very small percentage of total demand. The majority of future demand growth will likely continue to come from fuel applications, while demand for solvent applications will be more stable. Petrochemical ethanol has an NSSI rating of 44 percent; bioethanol is rated at 54 percent.

Acetone is a conventionally sourced petrochemical product with broad solvent demand in paints, coatings, adhesives, inks, manufacturing, pharmaceutical, and food applications. Bio-acetone is commercially available at significant scale at a very small premium and is naturally present in many fruits and vegetables. The acetone market is dominated by solvent, methyl methacrylate (MMA) and BPA demand, and is centered in China, the US, and Western Europe. Acetone's NSSI is 55 percent, or 65 percent for bio-acetone.

Glycerol can be used as a solvent in a variety of applications, including anti-freeze, botanical extracts, and in the food industry. Glycerol has the potential to be a suitable replacement for a number of solvent applications. Though its use as a solvent has been limited in the past, demand has increased recently. Importantly, glycerol is produced as a byproduct to biodiesel, and abundant biorenewable supply is available at a relatively low cost. Nexant finds that glycerol stands up quite well as a green solvent, with petro-derived glycerol scoring an NSSI of 71 percent and biorenewable glycerol an NSSI of 81 percent.

Ethyl Acetate is regarded as one of the least toxic of industrial organic solvents. As a solvent, ethyl acetate finds use in a wide range of applications, including printing inks, varnishes, and car care chemicals and in the production of enamels, plastics, and rubber. Ethyl acetate has seen above average growth in the solvents sector, as it has substituted for hazardous air pollutants (HAPs) such as MEK and toluene, particularly in the developed world. However, the outlook is for lower growth, as a result of the ongoing reductions in volatile organics that has led manufacturers to formulate away from solvent based coatings. Ethyl Acetate received an NSSI rating of 49 percent, with its biorenewable counterpart 10 points higher.

d-Limonene has been widely touted as a green solvent as it is a major component of the oil extracted from citrus rinds. The past decade has seen the use of d-limonene expand enormously, and a great deal of d limonene goes into making paint solids. By far the largest growth sector has been the use of d-limonene in cleaning products for both industrial and household applications. However, supply is unstable and entirely dependent upon citrus fruit production, and is thus susceptible to supply chain challenges. Though d-limonene is advertised widely as being a green solvent, there is evidence to suggest that it is not actually as green as perceived, having quite notable aquatic toxicity ratings, and a high tendency to form ground-level ozone. d-Limonene has an NSSI of 58 percent.

4.3 HANSEN SOLUBILITY PARAMETERS

Empirical solvent polarity parameters such as the Hansen Solubility Parameters provide a way of analyzing solvent behavior and give a better description of the solvent effects than considering single physical constants such as the dielectric constant (ε_r). Empirical parameters, like single physical constants, can give an idea of the electrostatic properties of a solvent but they additionally include a more complete assay of the intermolecular forces acting in solution such as hydrogen bonding.

The Hansen Solubility Parameters (HSP) are an industry standard way of comparing and selecting solvents for various applications, based on the adage that *like dissolves like*. HSP theory is based on the assay of three solubility parameters: non-polar dispersion (δ_D), electrostatic (δ_P), and hydrogen bonding (δ_H) for each material of interest. Overall Hansen parameters (δ) have been determined for thousands of existing solvents and solutes according to the equation:

$$\delta^2 = \delta_D^2 + \delta_P^2 + \delta_H^2$$

Solvents with similar Hansen solubilities are miscible in most proportions; dissimilar values yield limited solubilities.[1]

In order to determine if a material is likely to be solubilized by a solvent, or solvent mixture, the three solubility parameters are determined or estimated for both solute and solvent and then used in the following equation to calculate the distance between the Hansen parameters (R_a) :

$$R_a^2 = 4(\delta_{D1} - \delta_{D2})^2 + (\delta_{P1} - \delta_{P2})^2 + (\delta_{H1} - \delta_{H2})^2$$

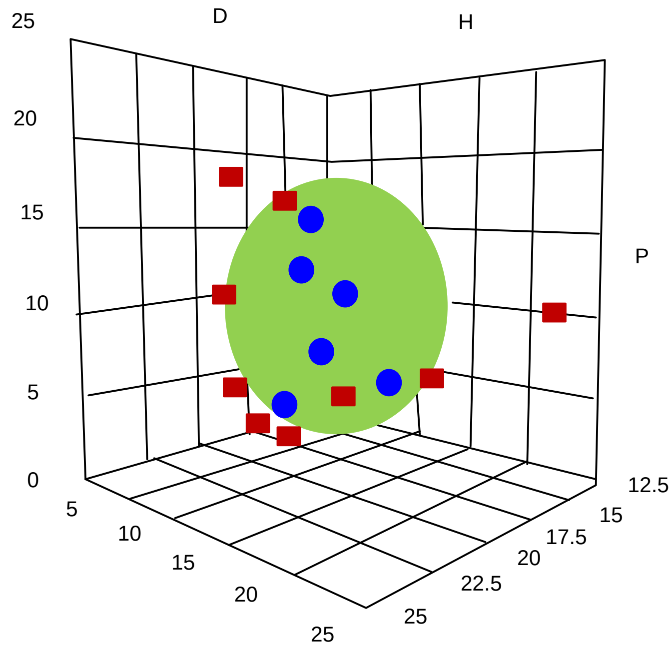
If the distance (R_a) is less than the radius of interaction for the solute (R_o), the solvent would be expected to dissolve the solute. A convenient means of determining the suitability of a solvent is to calculate the ratio R_a/R_o. If this ratio is less than one then solute-solvent interactions are favorable and the solute will dissolve; a ratio equal to one represents boundary conditions and the system will partially dissolve; a ratio above one indicates unfavorable conditions with progressively higher values representing progressively unfavorable interactions.

The three parameters can be visualized as the coordinates for a point in three dimensions called the *Hansen Space*. The figure below represents low hydrophilicity carbon black. The HSP values are approximately [16, 10, 7] for [D,P,H], respectively. These are real-world data and different types of carbon black behave

[1] Hansen, C. M. J Paint Technol 1967, 39, 511.

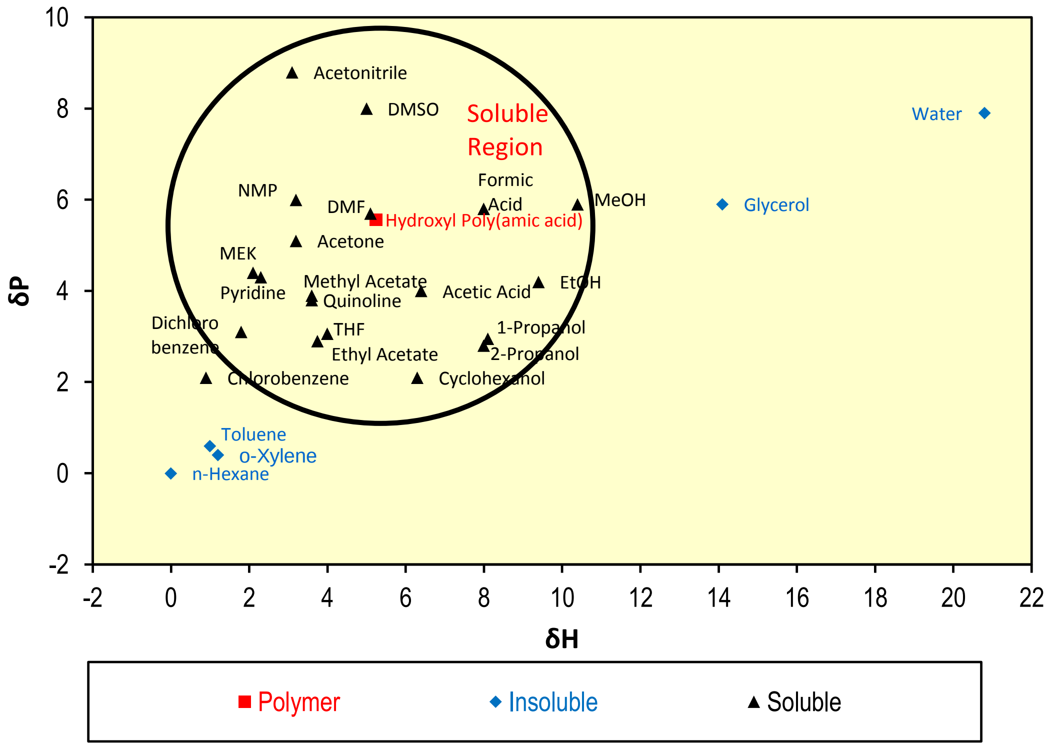
very differently in different solutions. Carbon blacks like this one with low δ_D values will dissolve more easily into low δ_D solvent formulations (e.g., simple aliphatics) whilst carbon blacks with higher δ_D are better suited to higher δ_D formulations (e.g., aromatics).

Figure 4.3 Example of HSP Space for Carbon Black



It is often simpler to visualize the impact of Hansen parameters in two dimensions. The figure below (which ignores the dispersive term for now) depicts the solubility of the polymer hydroxyl poly (amic acid) in various solvents. As can be seen, only the solvents that are located within, or close to the polymer's sphere of interaction are successful in solubilizing the polymer. Other solvents such as toluene and glycerol are unworkable.

Figure 4.4 Example of 2 Dimensional HSP Space
(for hydroxyl poly (amic acid))



HSP Theory is an empirical polarity method which has shown particular success in predicting the solubilities of polymers and petrochemicals in conventional solvents. Several other empirical solvent parameter theories have been derived via equilibrium and kinetic measurements including the work of Hildebrand and Kamlet and Taft. The most applicable theory will depend very much upon the solute and solvent under consideration.

4.3.1 Solvent Performance and Substitution Potential

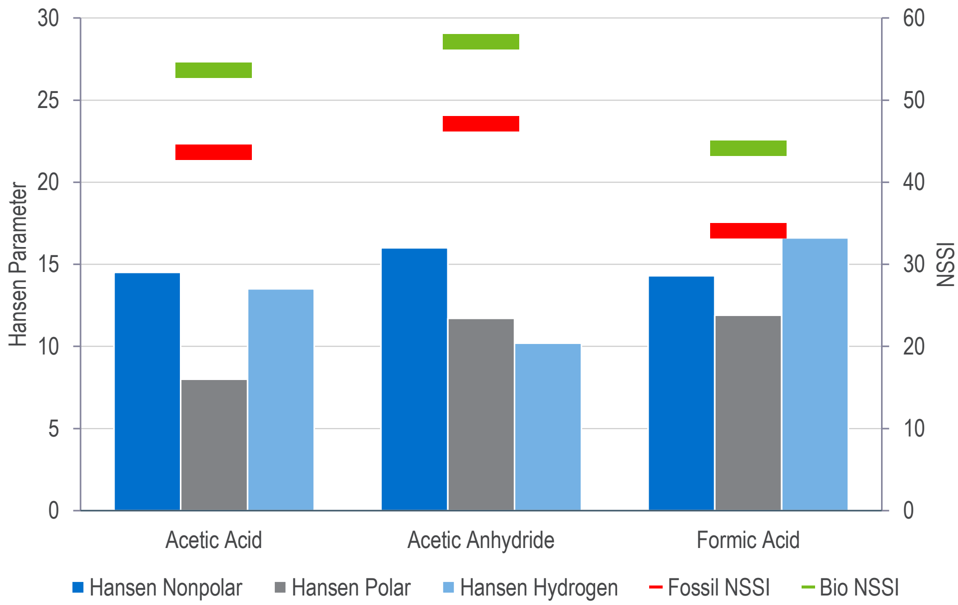
For each solvent product considered in this report, Nexant discusses the availability of bio-routes, rates the green credentials according the NSSI methodology, provides the HSP data and provides a SWOT analysis of the strengths, weaknesses, opportunities and threats of each solvent.

As a result of this analysis, the reader can compare the sustainability credentials of various solvents – and assess the opportunity of shifting to higher NSSI rated (or "greener") solvents. While the goal of shifting to green solvents is often driven by company sustainability targets; as researchers, process chemists, and formulators already understand, it can be technically difficult to substitute new solvents into existing processes and formulations – and even more difficult to do it with a truly "green" solvent.

Nexant believes that the intermediate goal should be to build *more* sustainable value chains by improving the safety of processes, reducing the environmental impact, and using more biorenewable feedstocks. Therefore, while certain solvents reviewed here received low ratings according to the NSSI, in truth, they may be more sustainable and an improvement compared to incumbent solvents.

The following figure indicates the substitution potential analysis contained in the report using three acids as an example.

Figure 4.5 Indicative Acid Substitution Potential



The acids analyzed in Figure 4.4 show similar HSP characteristics; however, acetic acid and acetic anhydride are markedly more green solvents compared to formic acid according to the NSSI. Therefore, Nexant recommends that those who require acidic solvents avoid the use of formic acid if possible. The HSP parameters and NSSI rankings for both the conventional production route and biorenewable production route have been plotted in the figure above.

While Nexant makes no attempt to identify the best solvent for every application, the report provides the subscriber with a toolset to compare efficacy (HSP and other properties) and sustainability (NSSI and other factors) among alternatives.

5.1 GENERAL

Nexant uses multidisciplinary project teams drawn from the ranks of our international staff of engineers, chemists, economists and financial professionals, and from other Nexant groups to respond to the requirements of each assignment. Most of the consulting staff possesses credentials in both scientific and commercial disciplines plus substantial industrial experience. The collective talents of our staff are strategically located and closely linked throughout the world, resulting in valuable insights gained through a variety of perspectives.

Nexant is an international consultancy and is dedicated to assisting businesses within the global energy, chemical, plastics, and process industries by providing incisive, objective, results-oriented management consulting. Over four decades of significant activity translates into an effective base of knowledge and resources for addressing the complex dynamics of specialized marketplaces. By assisting companies in developing and reviewing their business strategies, in planning and implementing new projects and products, diversification and divestiture endeavors and other management initiatives, Nexant helps clients increase the value of their businesses. Additionally, we advise financial firms, vendors, utilities, government agencies and others interested in issues and trends affecting industry segments and individual companies.

Nexant was formed as an independent global consulting company in 2000, combining a number of companies that had a long history of providing consultancy services to the chemical and refining-related industries. Nexant's experience covers all aspects of project development relating to major refinery, petrochemical, and polymer investments, ranging from grassroots plants to revamps of existing process units. Nexant's key offices serving the petrochemical and downstream oil sectors are located in New York, London, Bangkok and Bahrain, and locations for other offices are shown in Figure 5.1.

Figure 5.1 Nexant Office Locations

From major multinationals to locally based firms and governmental entities, our clients look to us for expert judgment in solving compelling business and technical problems and in making critical decisions.

Nexant's clients include most of the world's leading oil and chemical companies, financial institutions, and many national and regional governments. Nexant, Inc. is active in most of the industrialized countries of the world, as well as in most of the developing areas including the Middle East, Africa, and East and Southeast Asia.

Major annual subscription programs are:

- Process Evaluation/Research Planning (PERP)
- Petroleum & Petrochemical Economics (PPE) – United States, Western Europe, and Asia
- Polyolefin Planning Service (POPS)
- Biorenewable Insights (BI)
- World Gas Model (WGM)

The PERP program covers technology, commercial trends, and economics applicable to the chemical industry. The program has more than 40 subscribers, including most of the major international chemical companies. Many of the processes to be analyzed in this multi-client study have been assessed in the PERP program.

The PPE program provides historic and forecast analysis of the profitability, competitive position and supply/demand trends of the global petroleum and petrochemical industry. The program includes capacity listings and analysis, global supply, demand and trade balances, profitability, competitiveness, and price analysis and projections for all the major petrochemical value chains. The PPE program is supported by an internet-based planning and forecasting tool that provides online access to the database behind the reports of the PPE program.

The POPS program provides reports on the global polyethylene and polypropylene industry. It is recognized globally as the benchmark source for detailed information and analysis on current commercial, technical and economic developments in the polyolefins industry. Coverage includes: capacity listing and analysis, detailed consumption, supply/demand, trade, operating rates, price forecasts, technological developments, new products, inter-material substitution and regional competitiveness.

The BI program provides in-depth evaluations and reliable data on the technology, cost competitiveness and business developments of biorenewable chemicals and fuels. BI was created in response to the increasing activity in this industry segment in recent years, including entrances and exits of players, emergence and commercialization of new technologies, feedstocks, product types, as well as growing interest from companies in the oil, chemical, financial and other sectors.

WGM projects global, regional and national gas supply and demand balances, international gas trade by pipeline and LNG and both contracted and spot gas prices. Contract prices are estimated based on projected prices for a basket of escalators – up to five per contract – including gas hub prices as well as more traditional oil and coal prices. The model considers every country in the world which either consumes or produces natural gas. WGM is supplied with a comprehensive database on gas production, LNG and pipeline infrastructure, as well as long term contracts, storage facilities and demand projections.

5.2 ASSIGNMENTS UNDERTAKEN COVERING SOLVENTS AND RENEWABLES

5.2.1 Multiclient Work

During the past ten years, Nexant has completed a number of major multi-subscriber studies. Selected multi-subscriber studies which included coverage of biochemicals and biofeedstocks include:

5.2.1.1 Select PERP Reports

- **PERP Report 2013 S3 Bio-Jet** – A study of the technology, and economics of producing bio-based Jet fuel
- **PERP Report 2013 S5 Bio-Butadiene** – A study of the technology, and economics of producing bio-based on purpose butadiene
- **PERP Report 2011 S3 Algae Technology** – A study of the technology, and economics of producing algae based fuels and chemicals
- **PERP Report 09/10S4 Biobased Commodity Feedstocks** – A study of the technology, and economics of producing commodity biofeedstocks
- **PERP Report 06/07S11 "Green" Polyethylene** – A study of the emerging biotechnology, processing technologies and economics of producing and recovering polyethylene, and a comparison to conventional routes
- **PERP Report 07/08S11 "Green" Polypropylene** – A study of the emerging biotechnology, processing technologies and economics of producing and recovering polypropylene, and a comparison to conventional routes
- **PERP Report 06/07S4 Glycerin Conversion to Propylene Glycol** – A study of the emerging biotechnology, processing technologies and economics of producing and recovering propylene glycol from glycerine, and a comparison to conventional routes
- **PERP Report 08/09S11 Plants as Plants** (PHAs) – A study of the emerging biotechnology, processing technologies and economics of producing and recovering polyhydroxyalkanoates (PHAs), as an alternative to conventional polyesters
- **PERP Report 00/01S3 Biotech Route to Lactic Acid/Polylactic Acid –** A study of emerging biotech routes to lactic acid and polylactic acid. Processing technologies, and economics of producing and recovering lactic acid and polylactic acid are investigated
- **PERP Report 08/09S7 "Green" Acetyls** – A study of emerging biotech routes to acetic chemistry. Processing technologies, and economics of producing and recovering acetates are investigated
- **PERP Report 09/10S8 "Green" Glycols and Polyols** – A study of emerging biotech routes to glycols and polyols (e.g., propylene glycol and sorbitol). Processing technologies, and economics of producing and recovering glycols and polyols are investigated

5.2.1.2 Other Multi Client Reports

- **1,4 butanediol/tetrahydrofuran** — A study of commercial petrochemical and emerging bio-based process technologies. Includes process economics for five petrochemical-based and two emerging bio-routes on a same scale, same location basis. Also included are selected regional economic analyses, and regional market supply/demand
- **Biorenewable Insights Report Jun 2014 Bio-Based Acrylic Acid** – A study of the technical, commercial, and economic aspects of producing acrylic acid via bio-based sources, and to investigate future capacities
- **Biorenewable Insights Report Jul 2014 Biomass Gasification –** A study of the technical, commercial, and economic aspects of producing power, syngas, and/or chemicals via biomass gasification are examined. Planned capacities are also investigated

- **Biorenewable Insights Report Jul 2014 Cellulosic Feedstocks –** A study of the technical, commercial, and economic aspects of producing cellulosic biofeedstocks. An analysis of the availability of agricultural residues in different regions is also included
- **Biorenewable Insights Report Jul 2014 Bio-Based BTX and PX –** A study of the technical, commercial, and economic aspects of producing aromatics, including *para*-xylene, via bio-based sources. Announced as well as risk-adjusted capacities are presented based upon analysis of individual projects
- **Biorenewable Insights Report Jul 2014 Next Generation Bioethanol –** A study of the technical, commercial, and economic aspects of producing ethanol from cellulosic feedstocks, including risk-adjusted future project capacities. Implications for the existing industry are examined with respect to margins and returns

Nexant's has also completed a number of definitive studies on specific regions. These studies have analyzed the business structure and opportunities for many of the chemicals covered in this proposed study within the context of a changing economic environment. In addition to these studies, Nexant maintains a global commercial and technoeconomic database covering the principal petrochemicals, intermediates, and polymers.

5.2.2 Single Client Studies

- **Glycerine Carbonate Market Study**- Nexant conducted a market analysis of ***glycerol*** carbonate markets in North America and Western Europe to assist the client in commercializing a novel bio-transformational route to glycerol carbonate from methyl carbonate and glycerine
- **C_1 value chain analysis-** Nexant conducted a study profiling 32 chemicals in the C_1 value chain: process technologies, feedstock consumptions, production economics, major producers, technology licensors, market size, market growth forecasts, and end-uses
- **Value chain analysis-** Nexant conducted an analysis of technologies and international regional markets for multiple integrated downstream petrochemical products, including DME and Ethylene Glycol. The study assesses potential profitability of each chain, identifies opportunities and threats, market dynamics and competitive strategy
- **Isobutanol: market segmentation & attractiveness-** Nexant conducted a study that involved Identification of addressable markets for bio-isobutanol, including investigation of sales cycles, substitution dynamics, price points for: feedstock for the production of glycol ethers; starting material for the production of wear inhibitors and anti-corrosion additives for lubricants; solvents for printing inks and coatings; additive for polishes and cleaners; solubilizer for textile industry applications; additives for aircraft de-icing fluids; feedstock for the production of floatation aids; dehydrating agents; humectant for cellulose nitrate; feedstock for the production of certain acrylates
- **Evaluation Of New Bio-Ethanol Technology** – The client had developed an improved process for the production of bioethanol but required independent verification that this was superior to other available technologies. The technology was assessed and benchmarked against other commercially available technologies this included auditing and evaluating the efficiency, yields, technology risks on scale-up and additionally assessing the competitive positioning and level of IP protection. The technology was found to deliver improved efficiency and the study outcome was used to support their business case and has now been installed at several commercial production plants
- **Multiple Technoeconomic Due Diligences** – In advance of IPOs, Nexant performed comprehensive technoeconomic analysis, including technology and markets. In such capacities, Nexant has investigated and evaluated multiple conversion technologies, including cellulose hydrolysis as well as thermochemical platforms for products from biomass

- **Biofeedstock Analysis** – For the energy division of a major Asian multinational, Nexant developed a matrix scoring bio-feedstocks, with a cost ranking analysis and projection of likely future improvements, all related to their use in conversion technologies. The matrix was on a wide geographic basis against criteria of which would be best for the company to pursue with respect to cultivation or production status and other technical and price-related issues. Technologies for biofuels production were also ranked, with a special emphasis on bioethanol versus biobutanol
- **Global Biofuels Strategy** – For a leading U.S.-headquartered multinational firm based in the agricultural sector, Nexant performed a global, comprehensive analysis comparing technological, supply chain, and geographic options for its potential involvement in the biofuels sector. Work included ethanol and biodiesel as well as next generation status of activities in plant biotechnology, process development, feedstocks, and commercial aspects
- **Hydrocarbon Fuels And Chemicals Via Sugar Fermentation: Process Development Assistance** – For a biotech developer of sugar fermentation routes to C_5 hydrocarbon-based vehicle fuels and specialty chemicals, Nexant provided assistance including process flowsheet and capex review, troubleshooting, and cost reduction strategies, product recovery studies, and process safety analyses
- **North American Biofuels From Waste Streams: Markets, Siting And Logistics** – For a venture capital firm developing projects to make bio-alcohols from waste cellulosic, Nexant performed a series of eight separate engagements looking at multiple site locations and performed several technical and market evaluations to assist in this development
- **Chemicals/Biofuels From Corn –** Nexant was engaged by the National Corn Growers Association (NCGA), under US DOE sponsorship, to study potentials for production of chemicals from corn in the near term, a study that quickly focused on fuel ethanol derivatives, the available and emerging technologies to implement these routes, and the economic feasibility of these industrial models. Some of the options explored were for more convenient forms of biofuels ("biogasoline", n-butanol, etc.) derived from bioethanol and a recommendation was to pursue ethanol to ethylene strategies that had been written off by previous DOE analysts
- **Amyris Due Diligence –** For a syndicate led by Morgan Stanley, Nexant performed the technical due diligence for the first industrial biotech IPO in mid-2010. The technology which Amyris uses includes synthetic biological molecule development, fermentation and subsequent separation, purification and finishing steps. Key markets are pharmaceuticals (anti-malarial therapeutics), biochemicals, and biofuels. We have conducted engagements for Amyris which have covered commercial and technical aspects, including commercial facilities in different geographical markets
- **Bio-butanol Due Diligence** – Nexant recently studied a confidential bio-butanol platform for a syndicate including Morgan Stanley and other multi-national banks. The process proposed involved conversion of lignocellulosic material to fermentable sugars and downstream fermentation. Nexant's role included review of technology package and mass balance (technical due diligence), plant site visit (audit), interviews with plant lead engineer and management, capex teardown and analysis, industry benchmarking on a technical and cost basis, as well as market sizing and verification

- **Energy Utilization of Switchgrass Residue** – For a leading multinational energy company, Nexant studied and compared options for using this finely-divided biomass process residue (from PHAs production) at a typical mid-western U.S. location for fermentation/residue IGCC, co-firing in existing coal boilers, or biomass gasification integrated combined cycle power generation. Biomass supply and logistics costs were modeled along with the conversion processes and the energy pricing scenarios in the context of "green electricity" pricing and GHG emissions reductions trading
- **Biomass Gasification Process - Technical and Market Development Assistance** - For a developer of an indirectly heated steam-fluid bed gasification process already commercialized for the pulp and paper sector, Nexant assisted the client in achieving better process economics and other improvements in a project to apply the gasifier to a Fischer Tropsch paraffins synthesis, through a value engineering engagement with a team of the client's experts, their EPC, and other experts and stakeholders in the development; Nexant also assisted in a broad-based study of potential markets for the project's multi-faceted product slate
- **Fermentation Routes to Bio-Succinic Acid/BDO** – In a series of studies for a number of different stakeholders, Nexant evaluated technologies, markets, and competition for fermentation routes being developed for this potential raw material for polybutylsuccinate, 1,4-butanediol, and other chemicals derivatives, and compared to petrochemical routes
- **"Forest Refinery" Industry Evaluation** - A U.S. national laboratory retained Nexant to assess the technical and economic feasibility of a forest refinery designed to manufacture chemical products from trees. The analysis screened a variety of biomass conversion technologies and compared the production costs and energy consumption levels of each route to conventional routes. Processes evaluated included fermentation, lignocellulose separation, lignin conversion and gasification
- **Hunest Biorefinery Market Study** - A project to revitalize a former Nitrokemia site in Hungary to convert circa 200,000 tons per year of biomass into biopolymers, green solvents, and intermediates. Nexant was engaged to undertake a market study of the commercial opportunities for the project covering mainly pricing and the European market in order to guide the company in developing its marketing strategy for the project
- **Biochemical Opportunities in the United Kingdom** - The National Non Foods Crops Centre (NNFCC) engaged Nexant to provide a focused analysis of renewable chemical opportunities in the United Kingdom. The project was in part undertaken to gain a better understanding of the opportunities for the United Kingdom to integrate renewable feedstocks into its chemical manufacturing base. Nexant's analysis was used to support the development of research and development programs in both academia and industry organizations
- **Hydrocarbon Fuels and Chemicals via Sugar Fermentation: Process Development Assistance** – For a biotech developer of sugar fermentation routes to C_5 hydrocarbon-based (isoprene homologues) for vehicle fuels, chemical intermediates and specialty chemicals, this was a series of three projects to provide assistance, including process flowsheet and capex review, troubleshooting, and cost reduction strategies, product recovery studies, and process safety analyses
- **Advanced Biobutanol Process Technology, Economic, and Market Due Diligence** - For a prospective investor in this technology development, Nexant performed a broad-based feasibility study/due diligence. Butanol was examined for its proposed fuel potential as well as for its large existing market as a solvent and chemical feedstock. The economics of the incumbent petrochemical route was compared

- **Chemicals from Corn** - This was a broad-based study for the National Corn Growers Association (NCGA) funded by the U.S. DOE, to identify and screen chemicals that could be feasibly produced from corn. The study considered a wide range of potential sugars, and fermentation-derived acids, alcohols, and other building blocks, but emphasized fuel ethanol derivatives, including basic petrochemicals, solvents, intermediates and specialties, and application of the Reactive Distillation technology sponsored by the NCGA
- **Business Development Strategy** – For the world leader in the Soybean Industry, a business development strategy for entering the biodiesel business covering market opportunity by region, feedstock supply analysis, price and profitability analysis, market entry strategy, technology section, cost competitiveness and project financials
- **Global Biofuels Strategy** - For a leading U.S.-based multinational firm grounded in the agricultural sector, Nexant performed a comprehensive analysis comparing technological, supply chain, and geographic options for involvement in the biofuels sector
- **Food & Ag Waste Fermentation: Boubyan Petrochemical/Mom-Ecap/Coinc** – Initially engaged in a series of three assignments by Boubyan (Kuwait) for technical and market due diligence on the IBRC (Vancouver, BC) EATAD process to digest putrescible MSW fraction (food waste, etc.) to produce liquid and solid fertilizer/fungicide products for potential application in Kuwait. Later Nexant was referred by IBRC for similar feasibility analyses, market research, and project development assistance for MOM-ECAP to use the process in the NYC – Bronx Harlem Yards. Assisted MOM in approaches to NY City Council. The project was yet later moved to Woodbridge, NJ, and Nexant performed a bankable due diligence on the final design and location. The project was built and is operating. This was followed up with a 2008 global market study for a potential investor in Indonesia
- **Biodiesel Byproduct Glycerine Market Opportunities** – For a U.S.-based multinational agricultural products company, Nexant studied near term and long term prospects for market disposition of biodiesel byproduct glycerine and glycerol pricing dynamics, including current and developing or speculative applications, competition with propylene glycol, sorbitol, and other polyols. Chemical derivatives, fuel uses, freezing point depression, and agricultural applications were identified as longer term strategic solutions for the glut of glycerine. The project led to a number of conference papers and publications, and this is being followed up by that client and others
- **Biodiesel Glycerine Chemical Derivatives** – For a major multinational propylene glycol (PG) manufacturer, Nexant studied the future supply and demand for biodiesel and derivative glycerine and potentials for various uses including chemicals production. This included a detailed assessment of emerging commercial technologies to make PG from glycerine, as well as the competition between glycerine and PG for various applications
- **Glycerine Pricing Analysis** – As part of the commercial due diligence of a U.K. based oils and fats processor that co-produces refined glycerine, a focused assessment of glycerine pricing scenarios in alternative applications
- **PLA** – For this key renewable, biodegradable commodity polymer, polylactic acid, or polylactide (PLA) made from corn or sugar substrates, Nexant evaluated production technologies and markets for a number of different stakeholders
- **Chemicals by Depolymerization of PHAs: Petrochemical Competitive Benchmarking –** For a developer of fermentation and crop-based PHA (polyhydroxyalkanoates) production that exploring the feasibility of depolymerizing these natural polyesters to make commercial chemicals (monomers, intermediates, solvents, etc.), Nexant provided analysis of the same C_3 and C_4 chemicals production via petrochemical routes, and assisted in developing process and cost models of the speculative depolymerization routes

- **Fermentation Propanol to Green Propylene – Confidential** This report identifies discusses four routes to producing propylene from renewable feedstock (corn, sugarcane and glycerine). Bio-propylene, bio-based chemicals, biological route, biotechnology, genetically modified organism (GMO), and bacteria are included in the study
- **Biopolymers for Beverage and Food Packaging** – For a U.S.-based, leading, multinational beverage and food company, Nexant performed a study of the technical and economic feasibility of using, and issues around, selected bio-based polymers for packaging in the future, including PLAs, PHAs, green polyethylene, and others. For this, Nexant evaluated and compared three radically different emerging routes to green *p*-xylene production for feeding production of green PTA to react with green MEG to make 100 percent green PET bottle (and fiber) resin
- **Bioethylene for Beverage and Food Packaging** – For another U.S.-based, leading, multinational beverage and food company, Nexant performed a study of the technical and economic feasibility of using, and issues around, green polyethylene. For this, Nexant evaluated and compared green MEG production for PET bottle (and fiber) resin
- **Biopolymer Value Chain** – Investigate renewable feedstocks for biopolymers, biopolymer compounding and polylactide
- **Sustainability and Plastics** - Client was interested in understanding how increased awareness of environmental issues and of the related initiatives might affect the polyolefins business in the future and asked Nexant to provide a high level review of the following conventional polymer displacement threats to conventional polymers: biodegradable polymers, bio-based polymers, and recycling. The main focus was on polypropylene in North America; wider issues were considered

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