Biorenewable Chemicals

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Background

Bio-based feedstocks, since the 1980s, have presented themselves as possible alternatives to crude oil. In Europe, vegetable oil as a feedstock to produce glycerine through trans-esterification is an established process. Corn starch has also been used to produce a range of biodegradable polyesters. However, the use of bio-based feedstock for the production of chemicals has not taken off, since there is still a multitude of problems to be addressed in all parts of the value chain. To use a bio-based feedstock, one would have to address challenges arising in the collection, transportation and storage of the biomass, in addition to considering the yield and economics of production, in comparison to the incumbent feedstock crude oil.

With the chemicals and energy industry in Singapore accounting for around S$80 Billion and 30% of our total manufacturing output in 2010, it is important for Singapore to explore bio-based alternatives to maintain the competitiveness of our chemicals industry. The fast-growing biorenewable chemicals industry not only represents an inevitable shift as the traditional petrochemical industry re-invents itself in the light of a carbon-constrained future, but it offers a valuable economic opportunity for Singapore to renew its chemical industry and maintain its advantage as a leading chemical hub in the region.

The challenge for industrial corporations and government entities alike is to develop an appropriate strategy which takes into account not only the relevant scientific and technological solutions surrounding bio-based feedstocks, but also the industrial value chains and products that will address the needs of tomorrow. The strategy will need to be tailored to Singapore's need, given Singapore's resource-constrained status and unique geo-socio-political situation.

In this paper, through looking at the various technology options, global drivers and restraints, and assessing the role biorenewable chemicals could play in the renewal of Singapore's chemical industry, we would like to propose a research framework to position Singapore for an inevitable shift towards renewable feedstocks like biomass given the likely carbon and resource constrained future.

1. Table of Contents

2. The Biorefinery and Biorenewable Chemical Concept

2.1 Biorenewable Chemicals

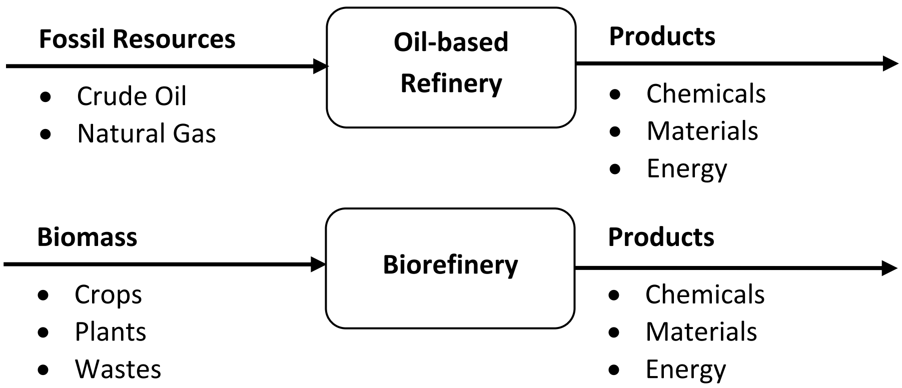
Biorenewable chemicals are chemicals derived from bio-based feedstocks, which are by virtue renewable since they can be seasonally cultivated and exploited. Examples are such feedstocks include corn, wheat, sugar cane and cellulose. The value of biorenewable chemicals is their potential to not only tap on cultivated sources for feedstock, but also offers the possibility of deriving value from bio-based agricultural, horticultural and municipal wastes by converting them into useful chemicals.

In most cases, prior to conversion to chemicals, the original biomass raw material will be converted into forms which can be more easily converted into chemicals - sugars, starch, lignocellulose and plant oil. In the subsequent sections, we will elaborate more on the feedstock options and their associating technological challenges.

2.2 Concept of a Biorefinery

Similar to an oil-based refinery which produces chemicals from fossil fuels, a biorefinery is a facility that looks at integrating biomass conversion process and equipment to produce fuels and chemicals from biomass.

Fig. 1 – Oil-based Refinery versus Bio-refinery



Biorefineries can be broadly classified into 3 major areas:

2.2.1 1st Gen Biorefinery (Single Feedstock, Single process, Single major product)

The first generation biorefineries are already producing substantial amounts of biorenewable chemicals and fuels. Most of these biorefineries are targeted at using one feedstock and producing a single major product. Many of these biorefineries also makes use of raw materials which are rich in easily convertible plant oils or simple sugar. An example of a first generation biorefinery is an ethanol-producing chemical plant with sugar cane as its feedstock.

2.2.2 2nd Gen Biorefinery (Single Feedstock, Multiple processes, Multiple major products)

A 2nd generation biorefinery is a natural extension of the 1st generation biorefinery which looks at maximising its returns through fully exploiting the feedstock to produce multiple products. An example would be Novamont's refinery in Italy which uses corn starch to produce a variety of chemicals, ranging from biodegradable polyesters to starch-derived thermoplastics[1].

2.2.3 3rd Gen Biorefinery (Multiple Feedstocks, Multiple process, Multiple major products)

A 3rd generation biorefinery corresponds to the most advanced type of biorefinery which looks at producing a variety of products from a diverse array of basic biomass raw materials. Diversity of product gives the high flexibility of changing to market demands, and diversity of products allows the refinery to secure feedstock from multiple sources. There are no large-scale commercial 3rd generation biorefineries at present, but a possible example of a biorefinery would be a lignocellulosic feedstock biorefinery which looks at converting lignocellulose from various sources like empty fruit branches, agricultural wastes and municipal lignocellulose-based wastes (i.e. paper), into useful chemicals.

[1] Novamont Mater-Bi (www.materbi.com)

3. Technology Overview

3.1 Feedstock Options

3.1.1 Sugars

Simple sugars in the form of mainly mono or disaccharides, can be easily extracted from sugar crops like sugar cane, sugar beets and sweet sorghum, and then converted into ethanol (established process) and other platform molecules like lactic acid and succinic acid (in development). Chemical conversion from sugar also forms the basis for the development of chemicals from starch and lignocellulose, since the first step is to convert the former 2 feedstocks in sugars.

75% of the world's sugar comes from sugar cane grown mainly in the tropical zones in the southern hemisphere, with Brazil, India and China forming the bulk of the production. The remainder of the sugar comes from mostly sugar beets from the temperate nations in the northern hemisphere, namely the EU and the US.

The sugar to ethanol process is very established, with Brazil blending their fuels with sugar-derived ethanol since the 1970s. Brazil's sugar to ethanol process is one of the most developed in the world, with the fermentation of sugars with yeast into ethanol, and using residential cane waste for heat/power generation. [2]

3.1.2 Starch

Starch mainly comes from food crops like maize, corn, potatoes, wheat and cassava. Most process involves the chemical hydrolysis of starch into glucose solutions, and subsequently into higher-value chemicals. In the production of the sugar solutions, side products like proteins also add to the value of the conversion process. Since the hydrolysis of starch into sugars is also well understood, the conversion of starch into chemicals is in a similar technological stage as sugars.

The use of starch crops for chemical production has raised deep concerns worldwide as it has purportedly brought about a damaging impact on food markets. This is particularly so for the less developed nations, especially when the demand of food crops for production of chemicals or fuels lead to a reduced supply for consumption.

3.1.3 Lignocellulose

Lignocellulose, with its abundance in nature and non-food property, poses great prospects as a potential feedstock for biorenewable chemicals. Lignocellulose biomass generally refers to inedible plant material in the form of cellulose, lignin and

[2] "Brazil's Ethanol Program – An Insider's View". Energy Tribune, 2008

hemicellulose. Lignocellulose's key advantage lies in its complementary nature with agricultural and human processes, in the form of forestry (sawdust, wood chips etc.), municipal (paper,cardboard etc.) and agricultural (rice husks, empty fruit branches) wastes.

There are however numerous challenges in the conversion of lignocellulose into chemicals, since many issues like kinetics of cellulose hydrolysis, removal and utilisation of lignin and pre-treatment of the vast array of lignocellulosic biomass remain as big challenges to the commercialisation[3].

3.1.4 Plant Oil

Unlike the 3 feedstocks mentioned in previous sections which produce sugar molecules, plant oil feedstock involves the extraction of oil, usually triglycerides, from the seeds of dedicated oil producing crops. Notable sources include palm, soy, rapeseed and sunflower seed. The recycling of waste oil derived from our daily wastes could possibly pose as potential sources, as exhibited by start-ups like US-based Blackgold Biofuels (biodiesel from sewage streams) and our local Alpha Biofuels (biodiesel from waste cooking oil).

It should be noted that since plant oils generally have higher energy contents than other bioenergy sources derived from sugar, much of the activity surrounding plant oil has been concentrated in the production of biodiesel as fuel replacement. In the production of biodiesel from plant oil, glycerol, a basic platform chemical for higher value chemicals is also produced, adding value to the process.

Production of chemicals from plant oil however still remains a challenge, mainly due the significant land-use change required and sustainability issues as a result of plant oil production. The carbon footprint of plant oil production is especially high in rural areas where deforestation of rainforests makes way for these new plantations, as exhibited by the regional palm oil industry[4] However, there is a recent trend in reinvestigating the production on novel molecules from triglycerides. Natural Oil Polyols (NOP) which are produced from soy bean and castor oil, for example, are investigated to substitute propylene oxide based polyols.[5]

3.1.5 Others

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[3] Axes of Development in Chemical and Process Engineering, Alain A. Vertes, 2010

[4]" Once a Dream Fuel, Palm Oil May Be an Eco-Nightmare", New York Times, 31 Jan 2007

[5] "New technology developed by Bayer MaterialScience enables production of natural-oil polyols via innovative, one-step process", Bayer MaterialScience, 2008

Chemical molecules can also be derived in other sustainable and novel ways, like micro-algae. Advances in synthetic biology and metabolic pathway engineering have encouraged the development of interests in the production of chemicals through novel platforms like microalgae and cyanobacteria. However, the scalability of such platforms remains a major technical challenge as large land areas are likely to be needed. Coupled with environmental safety concerns surrounding introducing genetically modified strains to the natural environment, uncertainty in the carbon price and threats from substitutes, commercial viability of such feedstocks are uncertain and not feasible in the near term. Land requirements for some of these sunlight hungry technologies will also be less attractive for areas like Singapore which faces land scarcity.

3.2 Manufacturing Process Options

3.2.1 *Biotechnological Process*

The use of biological approaches in processing of biomass and its related downstream chemicals is a paradigm shift for the industry. Many traditional synthetic processes can potentially be replaced by biological processes which offer better yield and reaction rates. Genetic modification of crops to increase yield, fermentation of sugars using biological enzymes, production of novel chemicals using genetically engineered organisms are all examples of what biotechnology can offer. Biotechnology also offers the possibility of the synthesis of complex molecules using techniques like one-pot catalytic processes, creating more direct and cost-effective routes for previously hard-to-synthesise molecules.

3.2.2 *Synthetic Process*

Like the current petrochemical industry, the biorenewable chemical industry also relies on traditional synthetic methodologies in its production. The greatest hurdle to large-scale deployment of such technologies however, is the tailoring of current methodologies to bio-based feedstocks. Currently, traditional catalysts used for synthetic production are usually not optimised for production from bio-based feedstocks, with some instances where bio-based derived byproduct actually render a catalyst ineffective. Examples of important synthetic routes used currently in the industry include the Fischer-Tropsch production of chemicals from syngas, and also transesterifcation of vegetable oils with methanol with an alkaline catalyst.

3.2.3 *Thermochemical Process*

Gasification and pyrolysis are two of the most common thermochemical processes. In both techniques, biomass is combusted at a high temperature in a controlled environment to produce syngas (gasification) or a liquid fraction (pyrolysis). Gasification is a technique which is already widely used in some systems (i.e. syngas from coal), but the gasification of biomass is however still a developing technology[6]. Pyrolysis of biomass is also a technology in development, with the product needing catalytic upgrading or reforming in order to be used as fuels or chemical feedstock[7]. For both processes, the energy required for the process could outweigh the environmental benefits.

3.2.4 *Hybrid Process*

It is important to note that most industrial chemical processes are a combination of various technological breakthroughs pieced together into a production chain. As we move into the era of novel biotechnological process-centric production of chemicals, it should be expected that the better understood synthetic and thermochemical processes would form a huge part of the production chain. A hybrid approach to work on a particular biomass or chemical product represents a powerful convergent innovation approach to manufacture chemical compounds that would otherwise be difficult to generate by just purely using either a biological or synthetic approach.[8]

3.3 Output Options

Biomass and crude oil are synonymous in the way that both are primarily made of carbon chains. Theoretically, any organic molecule which can be derived from petrochemicals, could also be derived from biomass. However, just like the petrochemical industry which has a list of more easily produced molecules, the biorenewable chemical industry will also have preferred routes which are expected to dominate the market in the next few decades.

Despite the concern on oil price and crude oil availability, we can be sure that crude oil will remain the primary feedstock for most commodity and cheap platform chemicals. The biorenewable chemical industry, in the short to medium term, is expected to offer alternative higher-value chemicals which are not readily or economically accessible through petrochemical-based synthetic processes. In the longer term, the biorenewable chemical industry could also offer a new range of chemicals and materials with similar or superior properties to the ones derived from petrochemicals.

[6] The Future of Industrial Biorefineries, World Economic Forum, 2010

[7] Pyrolysis of biomass to produce fuels and chemical feedstocks, Energy Conversion and Management Seder Yaman, 2004

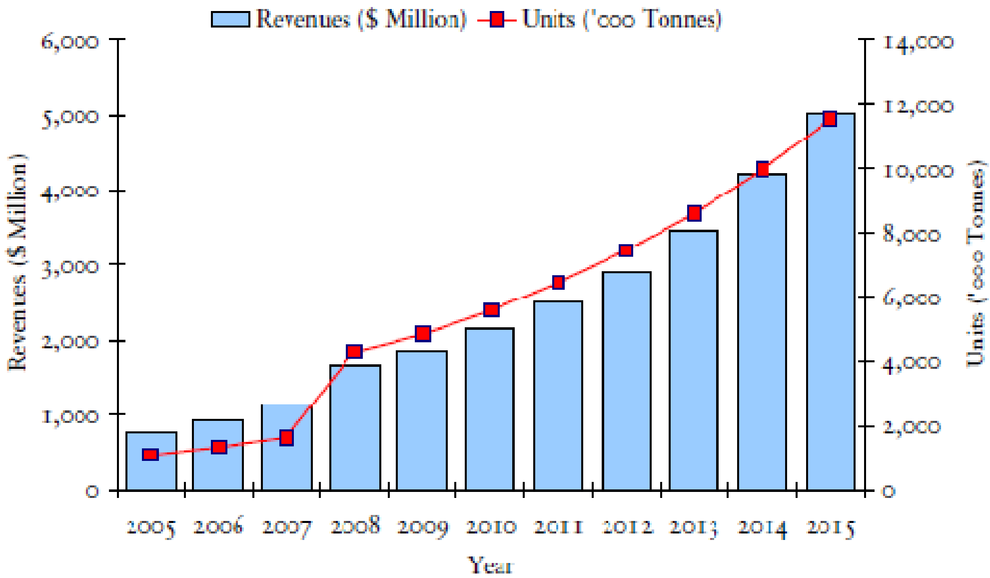
[8] Axes of Development in Chemical and Process Engineering, Alain A. Vertes, 2010

4. Global Outlook

4.1 Global Trend

The global biorenewable chemicals market stands at total revenue of US$2.4 billion. This steadily growing market has experienced a compound annual growth rate (CAGR) of around 15%, a growth trend that is going to increase as the world resumes a more normal production page and new bio-based chemicals such as bioethylene come to market. By 2015 the BRC market is expected to be worth US$5 to 7 billion, with a CAGR of around 20% between 2010 and 2015. The largest region for biorenewable chemical sales continues to be the U.S., which captured 21.6% of the BRC market in 2009.[9]

Fig. 2 – Global Biorenewable Chemicals Market: Unit Shipment and Revenue Forecasts[10]



Although this is a small amount as compared to the trillion-dollar global chemical industry, the evolution of the chemical industry a bio-based one seems to be inevitable due to underlying irreversible global drivers for the chemical industry.

4.2 Global Market Drivers

4.2.1 Desire for Stability and Predictability of Feedstock Availability and Price

Crude oil in the past 3 years has experienced price fluctuations from as low as US$50/barrel to values as high as US$125/barrel. This has added business uncertainty to

[9] Biorenewable Chemicals World Market Report, Innovaro 2010

[10] Strategic Analysis of the Worldwide Market for Biorenewable Chemicals, Frost & Sullivan, 2008

the chemical industry and related businesses, and has spurred the industry to look actively into alternatives like deriving chemicals from biomass.

In comparison, biorenewable feedstocks offer the advantage of ready availability, particularly in the case of lignocellulose, and also a renewable cultivation and harvesting cycle. This would allow for more price predictability since biomass can be harvested from most parts of the planet and are unlikely to be highly commoditised. The demand for biorenewable feedstocks could also have a positive impact on rural economics where crop cultivation is the main industry.

4.2.2 Environment Pressures and Carbon Constrained Future

The petrochemical industry is known to be a carbon-intensive and energy hungry industry. This is a concern as various companies are faced with regulatory frameworks which govern carbon emissions, which excess emissions and energy efficiency will translate into additional costs.

Therefore, in the recent years, some companies are exploring the possibility of replacing fossil-derived chemicals with green alternatives in their existing chemical product lines. e.g. lactic acid from C5/C6 sugars. There are also new players focused in the specialised production of chemicals and products derived from biomass sources. e.g. polylactic acid from Corn by NatureWorks LLC.

Although the decrease in carbon emissions in the production of various biorenewable is debatable, it is generally envisioned that biorenewable feedstocks have the potential to generate a lower carbon footprint given the cultivation of biomass is carbon-consuming.This could potentially translate into costs as we are likely into a future with carbon costs. At present, it is also estimated that some 30% of consumers are willing to pay a 10% premium for bio-based products[11].

4.2.3 Potential of Novel Products and Processes with Enhanced Performance

Currently, most of the world's current chemicals and polymer-based products are derived from the petrochemical value chain. The biorenewable route could offer possibilities of the development of new process and products which could not have been possible with the petrochemical route. The possibility of creating an entirely value-chain with novel techniques and know-how is definitely an exciting prospect.

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[11] Quoted from articles citing Jorge Fergie, Partner, McKinsey & Co., 2010

Example: FDCA as PET Replacement

FDCA is a potential biorenewable chemical that could find use as a replacement monomer for making PET-type plastics. It can be produced from carbohydrates such as glucose and fructose that can undergo dehydration in the presence of acidic catalysts to form 5 hydroxymethylfurfural (HMF),which under mild conditions can be oxidized to FDCA.

At the moment, there are several obstacles to overcome for FDCA to become a viable alternative monomer in the production of PET-type plastics, namely that it remains to be demonstrated that polymers with the desired properties can indeed be made from FDCA on a large scale. Another limiting factor to the use of FDCA is the current high cost of dehydrating carbohydrates and purifying HMF.

Source: The Renewable Chemicals Industry, ChemSusChem, 2008, 1

4.3 Global Market Restraints

4.3.1 Competition with Petroleum Based Chemicals

Currently, biorenewable chemicals have not proven itself to be widely economically competitive with the products derived from highly-streamlined petrochemical processes. Significant technological advancements in many areas including catalysis, bio-catalysis, separation and process integration are still needed to bring the manufacturing processes to commercial scale. Unlike petrochemicals, biorenewable chemicals can come from a variety of feedstocks from different geographical regions and the economic viability will be heavily dependent on the regional feedstock prices.

More importantly, even if the feedstock prices are currently low, the future is also uncertain and there is no guarantee that they will stay at these levels. As with any other commodity, as the demand of bio-based feedstocks increases, the cost of feedstock will also likely increase, making biorenewable chemicals increasingly less attractive compared to petrochemical counterparts. The prospect of oversupply of certain biorenewable chemicals driving down the price is also a concern to companies.

4.3.2 Business Integration in Nascent Unconventional Field

Similarly, in the area of business integration, the nascent biorenewable chemical industry will also have to evolve significantly for the industry to grow. The raw material will likely be provided by the agricultural companies, with biotechnology companies developing novel bio-catalysts for the processes, and chemical manufacturers being both the consumers and suppliers of biorenewable chemicals. With the uncertain public incentives for bio-based production (which depends on international climate change negotiations) and fluctuating prices of petroleum products and commodities, companies from different parts of the value chain hesitate to make a significant commitment to an investment especially if the next stage of manufacturers in the production value chain are unwilling to jointly mitigate their risks (i.e. production volume, price fluctuations).

4.3.3 Large Investment needed for Commercialisation

Based on a 2010 report from the World Economic Forum on future of biorefineries[12], with the recent financial crisis, venture capital and private equity funding have become tougher to access, making it difficult to finance pilot commercial plants. In addition, venture interest in the biorefinery/biotech business has been decreasing in the recent years, as funds are beginning to realise that large amounts of capital are needed to commercialise the technology. This is exacerbated by high uncertainty, since governments provide financial support and incentives on a relatively short-term basis (years), while the horizon for success for such technology is long term (decades).

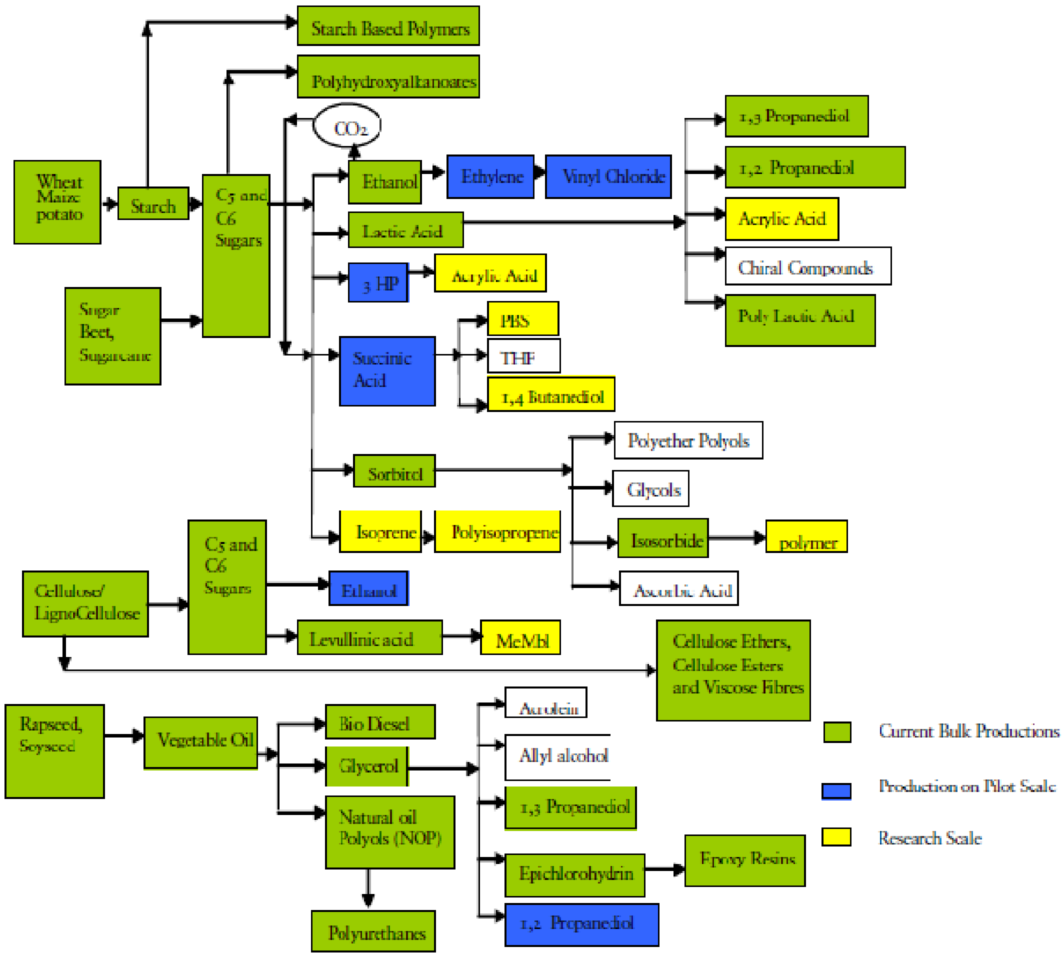
4.4 Current State of Industry Development

Much of the developments in biomass conversion have been concentrated on the production of biofuels, mainly due to the need for fossil transportation fuel replacements and associating policy and political mandates. The biorenewable chemical industry however has been nascent, with sporadic activities across the globe. The choice of feedstock also greatly differs from region to region, with temperate countries like US favouring feedstocks like corn and wheat, and tropical countries like Brazil favouring options like sugar cane and tropical plant oils.

Fig. 3 below shows some of the key routes of the biorenewable chemicals industry around the world. It should be noted that the figure is not intended to be comprehensive, and bulk production in the biorenewable chemical industry is not comparable in terms of scale and efficiency to bulk production in the petrochemicals industry.

[12] The Future of Industrial Biorefineries, World Economic Forum, 2010

Fig. 3 – Status of Biorenewable Chemicals Market, 2008[13]



4.5 Potential Impact of Biorenewables on Chemical Industry in the Next Decade

As the chemical industry start to look at alternative feedstocks due to the global market drivers as highlighted in section 4.2 the chemical industry in the next few decades will still likely be dominated by incumbents, due to the sheer size of their network and existing product trees. Nevertheless, the nascent field still offer many exciting opportunities to new players who could offer new product lines.

Traditional Chemical Companies (i.e. BASF, Dow Chemicals, Shell etc.)

The existing chemical industry has been looking at replacing fossil chemicals with bio-based alternatives to improve either the carbon footprint or to diversify the feedstock

[13] Strategic Analysis of the Worldwide Market for Biorenewable Chemicals, Frost & Sullivan, 2008

for feedstock security. It is likely that small incremental changes will be made to their existing product lines to accommodate for these new bio-based feedstock or chemical building blocks. A good example will be Dow Chemicals, which recently is looking at producing ethylene from sugarcane derived ethanol, instead of the traditional route of producing ethylene from steam-cracking petroleum fractions, and then using the ethylene produced to derive other chemicals[14].

New Players

It is likely that in the next few years we will see an increase in the number of companies which will look at producing novel chemicals and products from biomass, but have similar or improved properties compared to chemicals derived from current petrochemicals. These companies are not held back by current infrastructure and tend to focus on shorter processes that convert bio-based feedstocks or intermediates directly into a few targeted polymers or chemicals. Many of these new players operate based on proprietary technology which they have developed or in partnership with biotechnology players. Some of these companies are also spinoffs from agricultural or plastic makers looking for business opportunities in adjacencies (e.g. Natureworks LLC which is a joint venture between Cargill and Teijin).

[14] ICIS Chemical Business, “Dow studies bio-based propylene routes”, Feb 2011.

5. Key Technological Challenges to Commercialisation

There are multiple key challenges in the entire biomass-to-chemical process, including collection, transportation, storage, economics, perishability, separation, variability, standardisation and yield.. Many of these challenges could be solved through technology improvements, but many also require solutions which would require commercial, societal and political will.

For the purpose of this paper, we will briefly cover some of the key technological challenges surrounding the production of chemicals from biomass. The challenges are aptly summarised in the World Economic Forum's Future of Industrial Biorefineries 2010 paper:

5.1 Feedstock Yield and Composition of Biomass

Feedstock yield and composition are still critical concerns in the primary conversion of biomass. Improvements in these areas would require expertise in plant genomics and breeding programmes to cultivate crops of desired traits in desired quantities. Desired traits include improved resistance to degradation, ability to grow in harsh conditions, increased sugar concentration and reduced lignin content. Modest improvements to present crops could potentially bring large economic benefits to the production process.

5.2 Efficient Catalysts and Enzymes

A key challenge is the need to develop more efficient catalysts and enzymes which are versatile and robust. A catalyst or enzyme which could work in a laboratory process could easily be deactivated by impurities in a real conversion process. Catalysts which could work on a diverse array of basic biomass raw materials comprising of the base material (i.e. lignocellulose in wood, rice husks etc.) would be ideal.

5.3 Microbial Cell Factories

Another challenge is the need to develop microbial cell factories or "black boxes" which can produce a desired product with high productivity. The concept of microbial cell factory is one in which when a particular feedstock molecule is fed to cell factory, a desired target chemical molecule would be the output of the cell factory, after going through complex metabolic pathways in the cell factory. This concept is central to the theme of synthetic biology and would require many significant technical advances.

5.4 Efficient Separation Technologies

Once a compound can be produced via catalytic processes or microbial cell factories, it is likely that it would have to be recovered in an efficient manner. That would require developments in separation technologies. At the moment, the separation phase is by far the most wasteful and expensive stage of biomass conversion, accounting for 60% to 80% of the process costs for many mature chemical processes. For example, the production of succinic acid through fermentation processes generates very dilute and complex aqueous solutions which are hard to separate[15].

5.5 Processing and Logistics

The need to optimize processing and logistics (i.e. transportation and storage of biomass and their derived products) present a different group of technical challenges. To solve these challenges, it would require expertise in a vast array of areas ranging from establishing preservation techniques to control physical and chemical modification of initial biomass feedstocks, to the formulation of end-product polymers or molecules which can come in all forms and phases. To devise a commercially viable process from biomass to chemicals will be a highly multidisciplinary endeavour and would require cross-sector collaborations or individuals with a breadth of experience.

[15] The Biorefinery Concept – An Integrated Approach, James Clarke, 2008.

6. Biomass-to-Chemicals Research Landscape

6.1 Relevant Research Capabilities

Understanding the technological challenges facing the industry, the following (non-exhaustive) list of research capabilities would be relevant in the development of a nascent biorenewable chemicals industry:

a) Plant Biology & Genomics
b) Mechanical Processing
c) Bioinformatics and Molecular Genetics
d) Metabolic Pathway Engineering
e) Catalysis and Bio-catalysis
f) Synthetic Biology and Systems Biology
g) Industrial Biotechnology
h) Formulation Science
i) Separation Technologies
j) Process Engineering

6.2 Biomass-to-Chemicals Research Landscape in General

In the global arena, most of the efforts in biomass conversions are more tailored towards fuel development, although there are still significant efforts in R&D aimed at the derivation of high-value chemicals from biomass feedstock. Apart from work resulting from the many pockets of excellence in various well-known institutes of higher learning in various countries, a significant part of development in the area is achieved through private biocatalyst providers, biotechnology companies and chemical providers. There are few consolidated efforts initiated by the government funding bodies. The NSF CBiRC presented below is probably an exception rather than a norm.

NSF Engineering Research Center for Biorenewable Chemicals (CBiRC)
[Iowa State University [5 years, US$18.5M, 25 researchers, 75 grad students, since 2008]
The aim of CBiRC is to enable the transformation of the chemical industry through the optimized coupling of two catalyst types such that a biocatalyst will convert glucose to an intermediate chemical that can be readily converted by a chemical catalyst to the desired chemical product. The CBiRC offers close partnership with the industry and has worked with companies like GlycosBio, Danisco, Royal DSM N.V., Elevance Renewable Sciences Inc., Genomatica Inc., Novozymes, POET and Solazyme Inchas. The CBiRC currently has 3 major thrusts: New Biocatalysts for Pathway Engineering, Microbial

Metabolic Engineering and Chemical Catalyst Design. The state of Iowa has committed US$99M in the building of a larger Biorenwables complex which will house the CBiRC laboratories, in addition to other entities like the Biobased Industries Centre to work on business and policy issues in biorenewables; a harvest, storage and transportation consortium, and a biorenewables education program sponsored by the Cargill Foundation.

The lack of CBiRC-like research centers in the world could provide Singapore with a unique opportunity to establish a lead in the area of biorenewable chemicals research.

6.3 Key Research Performers in Singapore

*6.3.1 Science and Engineering Research Council (SERC) @ A*STAR*

Institute of Chemical and Engineering Sciences (ICES)

ICES is a research institute under the SERC which is located on Jurong Island. It has more than 200 researchers working on various aspects of chemistry, chemical engineering and process development. The institute covers capabilities ranging from organic synthesis, homogeneous and heterogeneous catalysis, industrial biotechnology, crystallization and particle sciences and process science. With its strong capabilities, advanced infrastructure as well as close proximity to the petrol-chemical industry, ICES offers an attractive value proposition to its industrial counterparts and is currently working with various companies like Mitsui Chemicals, Nippon-Shokubai and EADS in the development of biorenewable chemicals and related technology.

At ICES, an Industrial Biotechnology group was started in 2007 to focus on the utilisation of renewable resources to produce fuels and chemicals using microorganisms and/or enzymes as catalysts and have achieved modest success in developing fermentation processes for the production of chemicals from various feedstock. A snapshot of some patents filed in the past year includes:

a) A Method for Producing Ethanol via In-Situ Xylose Isomerization and Yeast Fermentation [US Provisional Patent Jul 2010]

b) Process for Preparing Ethanol from Crude Glycerol Using Novel Bacteria [PCT Patent App Mar 2010]

c) A method of Random Introduction of Point Mutations to Small Size DNAs [US Provisional Patent Jan 2010]

d) A Method For Improving Complex Phenotypes of Microorganisms by Novel Gene Shuffling [US Provisional Patent 2009]

The key strength of ICES is the ability to address key challenges in the entire value chain of the biomass-to-chemicals industry, tapping on capabilities ranging from synthesis to formulation to scale-up. With ICES's capabilities in traditional catalysis and synthetic methodologies, hybrid system level solutions employing both biological and synthetic techniques can also be developed. The Industrial Biotechnology group is however small (15 researchers), hence finding a focus and the leveraging of resources from other institutes would be important.

Institute of Materials Research and Engineering (IMRE)

IMRE is a research institute with more than 250 researchers working on various aspects of the materials development paradigm, developing new materials and improving the structure-performance relation of various material systems. The institute has key capabilities in photovoltaic, nano-composites, solid state lighting and functional polymeric material systems.

At IMRE, the development of new polymeric composites and monomers enhances the value of the end product of a biomass-to-chemical process, through the development of lower cost processes and improvisation of material performance. The development of material properties allow for biomass produced chemicals to find applications in a variety of industries which are interested in utilizing performance materials which are "green". Snapshot of patents in related areas include:

a) Elastomers cross-linked by Poly(lactic acid) Stereocomplex [PCT Patent App Apr 2010]

b) Supported nickel catalyst made by nanoparticle transfer method for autothermal reforming of diesel fuels [US Provisional Patent Jul 2010]

Singapore Institute of Manufacturing Technology (SIMTech)

SIMTech develops high value manufacturing technology and human capital to enhance the competitiveness of Singapore's manufacturing industry. Although not directly related to the biomass-to-chemicals process, the institute's capabilities in manufacturing technology and precision engineering can play a role in the manufacture of end products resulting from the biomass-to-chemicals process, and also in the pre-treatment mechanical processing of biomass.

Institute of High Performance Computing (IHPC)

Home to A*STAR's modelling capabilities, the institute has capabilities in computational material science and fluid dynamics which can play a role in modelling systems which could eventually be developed into actual biorefineries.

*6.3.2 Biomedical Research Council (BMRC) @ A*STAR*

The BMRC oversees the development of core research capabilities within A*STAR research units specialising in bioprocessing; chemical synthesis; genomics and proteomics; molecular and cell biology; bioengineering and nanotechnology; and computational biology. The BMRC research institutes have traditionally focused very much on promoting translational medicine and cross-disciplinary research, as part of its efforts to advance human healthcare. Although there has been little focus on biomass-to-chemicals R&D in the council, the various basic capabilities are highly relevant to the needs of the upcoming bio-process intensive chemical industry

<u>Institute of Bioengineering and Nanotechnology (IBN)</u>

IBN has a research thrust which looks at catalysis systems for various applications for the pharmaceutical and chemical industry. Within, there is a small group of 10 researchers who conduct research in the area of novel catalysts systems used for the dehydration of biomass into useful chemicals and fuels. IBN's capabilities in nanoengineering of catalysis could play a role in the development of the biomass-to-chemicals R&D efforts.

<u>Bioinformatics Institute (BII)</u>

BII uses bioinformatics means to understand biomolecular mechanisms that underlie biological phenomena, develop computational methods to support discovery process and also undertake experimental verification of predicted molecular and cellular functions of genes and proteins with biochemical methods. The institute has strong capabilities in Biomolecular Function Discovery, Biomolecular Modelling and Design, Genome and Gene Expression Data Analysis, and Imaging Infomatics. Similar to other BMRC RIs, most the capabilities in BII has been dedicated to the advancement of human health and related applications, but could potentially play a role in biorenewable chemicals related technologies.

<u>Genomic Institute of Singapore (GIS)</u>

GIS pursues the integration of technology, genetics, and biology towards the goal of individualised medicine. The scientific focus of GIS is to investigate diverse biological and biomedical problems, including cancer, infectious diseases, stem cells and development, with an emphasis on insights gleaned from genomic sequences and from technologies that probe gene regulation and its control.

The genetic engineering capabilities at GIS would definitely be useful to the biomass-to-chemicals effort. For example, a toolkit of genes that encode enzymes to catalyse the necessary chemistry within a host organism could be developed. At GIS, there is a small effort by Dr. Neil Clarke working on algae, primarily with the model organism

Chlamydomonas. The group is engaged in gene knockdown experiments, gene expression analysis, and lipid composition characterization, all aimed at elucidating the metabolic and regulatory networks relevant to the manipulation of lipid production in algae.

Bioprocessing Technology Institute (BTI)

BTI was established in 1990 with the mission to pursue innovative and cutting-edge research in bioprocess science and engineering leading to technologies which will impact biomedical science and bio-manufacturing. The institute has strong capabilities in Immunology , Expression Engineering , Stem Cell Research , Animal Cell Technology , Microbial Cell , Downstream Processing and Analytics , Analytics and "-OMICS" Technologies.

The understanding of metabolic pathway and engineering could possibly be applied to biomass-to-chemicals R&D, but the difference in application does require a radically different approach to the overall problem in the context of developing a route to a chemical, rather than protein based active ingredient which BTI is familiar with.

6.3.3 National Universities – NUS and NTU

Singapore's 2 national universities – National University of Singapore (NUS) and Nanyang Technolological University (NTU) have deep capabilities residing in various groups in the academic departments, and it would not be feasible to list all of them for the purpose of this report. The university groups can be seen as critical research performers which would provide relevant expertise or plug capability gaps in bigger initiatives. At A*STAR, our ability to fund research projects in the local national universities have resulted in our symbiotic relationship with them, where we leverage on the universities' strengths to achieve our research objectives. NUS and NTU, being the premier educational institutes in Singapore, are also vested with the task to train our local scientific manpower, which would be essential in creating a pool of biorenewable chemicals industry related scientists/engineers.

6.3.4 Temasek Life Science Laboratory (TLL)

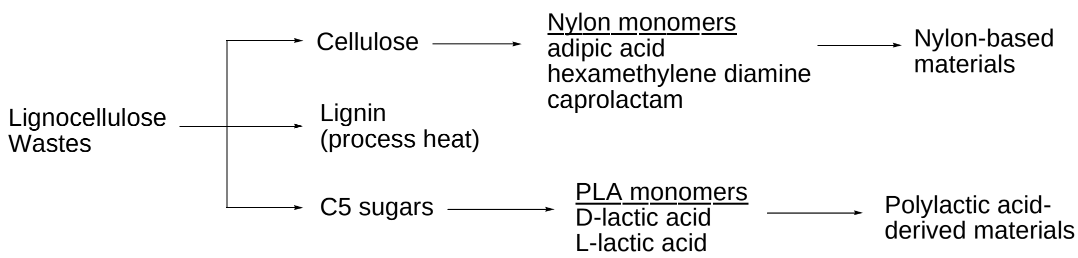
TLL is a non-profit organization affliated to the national universities which undertakes cutting edge research in molecular biology and genetics utilizing a broad range of model organisms. TLL's main capabilities include cell biology, developmental biology, neuroscience, pathogenesis and bioinformatics. Utilizing a range of molecular and cell biology approaches and computational data mining, TLL focuses primarily on understanding the cellular mechanisms that underlie the development and physiology of plants, fungi and animals.

TLL has achieved success in applications in Jatropha and rice cultivation. A local company which looked at oil production from Jatropha (JOil Pte. Ltd.) was spun off resulting from their work. TLL could potentially play a role in development of feedstock which could be optimized for chemical production.

6.4 SERC Value-added Chemicals in Lignocellulose (VACL) Programme

It would also be timely to introduce the SERC VACL programme which is the largest and most targeted effort in Singapore to address the biomass-to-chemicals challenge. The 3-year programme was started in Mar 2010, with a funding of S$9M and 21 FTEs.

Fig. 4 – VACL Programme Value Chain



Singapore generates some 1.8M tonnes of lignocelluloses wastes per year – 0.27M tonnes for wood and timber, 1.26M tones of waste paper and cardboard, and 0.23M tones of horticultural wastes. About half the lignocelluloses wastes are incinerated while the remaining recycled as lower value products. In addition, the region's food and oil producers generate tonnes of lignocellulose wastes in the form of empty fruit brunches and agricultural wastes.

Recognizing the demand of various chemical producers like NatureWorks, Mitsui Chemicals, BASF, Purac and Invista for lactic acid and nylon monomers, SERC devised the VACL programme which looks at developing technologies for production of PLA and Nylons from lignocellulosic sources. In the proposed process, lignocellulose will be deconstructed to cellulose, C5 sugars, and lignin. Cellulose will be converted to Nylon monomers via levulinic acid derived from acid-catalyzed conversion of cellulose. C5 sugars will be transformed to either D-lactic acid or L-lactic acid by fermentation. Lignin can be used to provide heat for running of a bio-refinery. New applications and novel materials will then be developed for the bio-based Nylon and PLA.

At SERC, we recognize that our key advantage is the ability to pull together capabilities from our research institutes and the universities to create solutions which would address all parts of the value chain. The VACL Programme being an interdisciplinary effort, draws on existing capabilities from three SERC RIs (ICES, IMRE and SIMTech) and 2 local universities (NUS and NTU). The biological and synthetic conversion of lignocellulose wastes to monomers is studied by ICES and NUS, with SIMTech looking at challenges in the mechanical processing of the lignocellulose wastes. The formulation and development of PLA and Nylon based materials in the form of nano-composites or thermoplastic elastomers are then studied by IMRE together with research groups from NTU and SIMTech. Finally, a group in NUS looks at the integration of the entire process in a systematic and quantitative manner, using modeling and optimization approaches.

7. Strategic Relevance of Biorenewable Chemicals to Singapore

As illustrated in the previous sections, as the world is faced with new challenges like climate change and resource constraints, it is expected that the non-renewable fossil fuel based chemical industry will develop with a renewable focus. This shift in landscape will bring together with it new opportunities for Singapore to renew its chemical industry and maintain its lead as a top chemical hub in Asia.

7.1 A Greener, More Sustainable and More Competitive Jurong Island Ver 2.0

Today, Singapore's Jurong Island hosts over 95 global companies including heavyweights such as Shell, ExxonMobil, Chevron, DuPont, BASF, Sumitomo Chemicals and Mitsui Chemicals. Jurong Island has drawn cumulative fixed asset investments of over S$30 billion and employing about 8,000 as of date[16]. With the chemicals and energy industry in Singapore accounting for around S$80 Billion and 30% of our total manufacturing output in 2010, it is important for Singapore to explore bio-based alternatives to maintain the competitiveness of our chemicals industry.

Specifically for Singapore, biorenewable chemicals offer the development of the Singapore chemical industry with the following possibilities:

a) A more robust and cost-competitive chemical industry based on replacing current fossil fuel based chemical building blocks with biorenewable chemical building blocks;

b) A "cleaner" chemical industry based on bio-based feedstocks which could satisfy the increasingly environmentally conscious society looking for cleaner alternatives. (It is however arguable if bio-based feedstocks are actually cleaner, especially in the near term. In one case, it was found that GHG savings from corn ethanol would equalize and pay back carbon emissions in 167 years[17]);

c) A new biorenewable chemical industry in Singapore with new derivatives and novel end products derived from biomass that have no synthetic counterparts;

d) An integrated chemical hub which brings together investments from incumbent chemical giants, new specialty players, regional agricultural players,

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[16] Economic Survey of Singapore, MTI, 2010

[17] Searchinger, T. "Use of US Croplands for Biofuels Increases GHG through Emissions from Land-use Change", Science, 2008.

biotechnology companies and other players in the value chain to develop new business opportunities

In addition, in response to the needs to keep Jurong Island competitive, Singapore's Economic Development Board (EDB) developed the Jurong Island v2.0 initiative[18] to look at ways to enhance the sustainability of the island. Under the umbrella of the initiative, EDB has commissioned a consultancy study to understand the economics of utilizing regional biomass as feedstocks for the local chemical industry, and also the feedstocks' potential derivatives. Through the study, it is envisioned that Singapore can narrow down and develop strategies to establish niche areas which would allow Singapore to better compete in the global chemical manufacturing arena.

7.2 Key Value Propositions of Singapore

The development of the biorenewable chemical industry is a possible avenue in maintaining the competitiveness of our chemical industry, given the inevitable shift for the industry towards bio-base feedstocks. In the development of such an industry, Singapore offers the following value propositions:

a) Easy Integration into Jurong Island

As described in section 7.1, Jurong Island is a leading petrochemical in the region with more than $30B worth of fixed assets. The island, being an integrated petrochemical hub, allows for easy access to basic feedstock (i.e. steam and natural gas) and other resources which would be essential for chemical production. The presence of other chemical producers and specialty chemicals companies offer opportunities for business integration and a ready market of consumers for biorenewable chemicals.

b) Biodiversity and Varied Agricultural Industry in Region

The South-east Asian region plays host to an agricultural industry which is varied and substantial – Palm Oil industry in Malaysia, Rice production in Thailand etc. Agricultural and horticultural wastes could potentially play as feedstock to the biorenewable chemicals industry. Biodiversity in the tropical climate also offers unique opportunities in exploiting biomass which can generate high value-low quantity chemicals (i.e. essential oils, therapeutic molecules), and also R&D

[18] Jurong Island v2.0 is an initiative to enhance the long-term competitiveness and sustainability of Singapore's energy and chemicals industry, which mainly resides in Jurong Island of Singapore. Endorsed by the Economic Strategies Committee in February 2010 as one of the key recommendations to transform the Singapore economy in the long term, the focus of JIv2.0 is on feedstock options, system-level optimization and infrastructure developments that would create new competitive advantages for the industry.

opportunities like ICES's work with Mitsui Chemicals in the development of novel biocatalysts derived from the wealth of micro-organisms in tropical climate.

c) Excellence in Logistics

Singapore is an established port-of-call and one of the largest marine bunkering ports in the world. Excellent logistics coupled with close proximity to countries with significant agricultural output, Singapore will be poised to achieve success in the biorenewable chemical industry akin to the petrochemical industry.

d) Established R&D Infrastructure and Robust IP Protection

In the nascent biorenewable chemical industry, as exhibited in the previous section, there are still numerous technological challenges to be solved. An established R&D infrastructure in Singapore in the form of A*STAR and other IHLs can allow companies to quickly develop and deploy their solutions in partnership with the public research agencies. Robust IP protection in Singapore will ensure that technologies and processes developed in Singapore are also duly protected.

7.3 Key Restraint for Singapore: Lack of Resources

Although Singapore sits in an area of rich biodiversity, Singapore does not have direct access to biomass nor land to grow the biomass required. Lignocellulosic wastes in Singapore offer opportunities for conversion, but it is not sufficient to supply at a scale for commercial viability. Hence it is apparent that we will need to rely on our regional countries for feedstock and would imply that the feedstock supply for the chemical industry would have to be subjected to economic and political risks beyond Singapore's control.

It is also likely that similar to our petrochemical industry, we would need to rely on Singapore's excellence in logistical for our feedstock supply. EDB's JIv2.0 consultancy study will cover the calculation of the costs associated with the logistical process. Since transporting bulk biomass will never be as cost-efficient as transporting liquid feedstocks (i.e. sugars, plant oils etc.) due to the huge disparity in energy density, primary conversion of biomass to these liquid feedstocks would have to be carried out at source. The prospective biorenewable chemical industry in Singapore will hence likely be looking at these liquid feedstocks as the starting point.

8. Positioning Singapore through Technology Development

8.1 Motivation of Research in Biorenewable Chemicals

Understanding that there is strategic relevance for Singapore to develop its biorenewable chemical industry, and that there are numerous technological challenges to be resolved, we seek to **establish a technology development framework which will position the Singapore chemical industry for an inevitable shift towards renewable feedstocks like biomass given the likely carbon and resource constrained future.**

8.2 Key Value Propositions of A*STAR in Biorenewable Chemicals

A*STAR is well poised to lead the establishment of such a technology development framework together with the industry and other technology partners because of the following value propositions:

a) Ready Capabilities Developed in ICES and Other RIs

   ICES's capabilities in catalysis, bio-catalysis, industrial biotechnology, process engineering are all poised towards addressing the needs of the chemicals and future biorenewable chemical industry. Complementary expertise in materials engineering, modelling and mechanical engineering present in IMRE, IHPC and SIMTech offer opportunities to address the varied research challenges of the nascent biorenewable chemical industry. Expertise in genetic engineering, metabolic engineering, and bioinformatics in the BMRC could also be potentially realigned and tapped on for greater impact.

b) Ability to Provide Integrated Solutions in Partnership with IHLs as Exhibited through the VACL Programme

   The VACL programme, which was started around 1 year ago, is an established effort in converting lignocellulosic biomass to nylon and polylactic acid, bringing together researchers from ICES, IMRE, SIMTech, NUS and NTU. The programme exhibited A*STAR's ability to pull together capabilities from various research performers to provide an integrated and customised solution.

c) Ability to Connect Players through Leveraging R&D Resources

   In close partnership with EDB, the industry can leverage on A*STAR capabilities and resources to jointly develop solutions potentially through our Industry Alignment Fund. Through platforms like consortiums and centres, A*STAR and EDB could also play the matchmaking role of bringing together industry players from various parts of the value-chain, facilitating the development of the nascent industry.

8.3 Key Considerations in the Development of Technology Framework

8.3.1 Genericity Versus Specificity

The business of biorenewable chemicals production and utilisation faces as many economic hurdles as technological ones. Determining the viability of investment in the development of a certain conversion route requires deep technical foresight and sharp business acumen. With the field being relatively nascent, there is also very limited data on viable routes and business models. To complicate this, business viability is also severely affected by global and regional developments (i.e. carbon market, political circumstances). Incorporating genericity in the technology framework, by focusing on the development of fundamental science, toolkits and expertise would enable Singapore to quickly adapt and support the development of the industry.

However, it is also not feasible to have no particular chemical targets as research objectives, especially since the field of biomass conversion is particularly broad as the entire world seeks to define the industry. Breakthroughs in specific key processes would allow for Singapore to be the first to adopt such processes, allowing the companies in Singapore to maximise their returns.

Hence in the development of the technology framework, it is important to ensure that fundamental science is engaged and basic capabilities are built, while also at the same time constantly assessing and identifying potential routes which could be developed into technologies that would have a significant impact on the local chemical industry. The latter is akin to a drug development process, where there are substantial risks in developing technologies which would eventually be non-translatable into the chemical industry.

8.3.2 Rooting the Value in Singapore

In all parts of the value chain, there are key technological challenges to be addressed. The cultivation and primary processing of solid biomass remains major challenges which has to be addressed, together with challenges in secondary processing of sugars/oils and process development.

Since there is no significant agricultural industry in Singapore, it is likely that primary conversion will happen at source in other nations. Developments in primary processing of biomass would hence have limited impact on the Singapore industry, as the liquid product in form or sugars or oil would likely be the starting biorenewable feedstock for Singapore.

Hence, in the development of the research framework, more focus should be given to developing the process from the point of sugars/oil, rather than biomass. It is important that the investment in R&D should be targeted at developing technologies which would allow value to be rooted in Singapore.