The feasibility of a wood to ethanol plant using a thermo-chemical process

Report for EECA (public release version) - August 2008

Executive summary

A financial model of a thermo-chemical biomass to ethanol plant has been developed for LanzaTech. In a base case modelling scenario the plant produces 150m litres of ethanol and consumes 770,000 tonnes of wood per year. The total investment required to build the plant would be NZ$170m. The breakeven selling price is NZ$0.72 per litre.

Process

The financial model is based on a conceptual engineering model of the plant. Process steps are:

- Feedstock supply
- Feedstock handling
- Gasification
- Gas cooling and clean-up
- Fermentation
- Ethanol separation

The biomass is gasified using a steam gasification process. The required gas clean-up is assumed to consist only of a wet scrubbing step in the base case. Ethanol is produced using LanzaTech's fermentation process. Ethanol is distilled using conventional distillation and molecular sieves. An energy balance for the process has been developed.

Wood use and pricing in New Zealand

If the proposed plant is built in New Zealand it would become the single largest user of wood residues by some way. It could be expected that the plant would have an impact on the pricing of residues in the New Zealand market and this would create a dynamic that would be difficult to model. Rather than attempting to do so, wood pricing is based on a static analysis with a margin added to account for the expected market dynamic. Models developed by Scion are available that provide relate cost to supply residues in large volumes at different locations. A cost curve developed for supply of residues to Reporoa provides a good model for supply to the proposed plant. Above a certain volume it becomes cheaper to purchase pulp logs rather than transport residues large distances. Consequently, the feedstock is expected to be a mixture of wood residues and pulp logs. The average price is NZ$48 per tonne of wet wood.

Gasifier selection

Air blown gasifiers are unlikely to be suitable for LanzaTech's proposed plants. The nitrogen content of air imposes a number of costs throughout the process – heating during gasification, cooling after gasification, compression and a reduction in efficiency in fermentation. Two alternatives were considered - oxygen blown and steam blown gasification. Of these, steam blown gasification was favoured for modelling purposes. However, neither oxygen nor steam blown biomass gasifiers are used commercially at large scale meaning that LanzaTech will have to work with gasifier developers in the future rather than purchasing gasification solutions 'off-the-shelf'.

Financial results

The breakeven selling price of NZ$0.72 is made up of variable costs (mainly wood feedstock), fixed costs and capital costs. The price is sensitive to the input assumptions and a range of sensitivity analyses have been developed to characterise these. Key input assumptions relate to the required rate of return, capital costs of key components, the thermodynamic efficiency of the overall process and the gas clean-up steps required.

For plant sizes smaller than the base case, the loss of economies of scale forces the breakeven cost very high. For plant sizes bigger than the base case the economies of scale are largely cancelled by the extra costs to transport the amount of feedstock required.

The economics of LanzaTech's process compares well to Coskata, LanzaTech nearest direct competitor. The breakeven selling price also compares well to the cost to import ethanol into New Zealand.

Viability in New Zealand

Although the work indicates that LanzaTech's process is cost competitive with other sources of ethanol, the viability of any New Zealand biofuels producer is uncertain until greater certainty emerges about demand for biofuels in New Zealand. This is a direct consequence of government policy on biofuels and further clarity is not expected until 2010 at the earliest.

Please note that some details have been removed from this public version of this report to maintain commercial confidentiality.

For further information please contact

Dr Sean Simpson
LanzaTech Limited
+64 9 373 4929
sean@lanzatech.co.nz

Dr Adam Barker
Scarlatti Limited
+64 9 815 8485
adam.barker@scarlatti.co.nz

1. Introduction

This report describes a study carried out for LanzaTech by Scarlatti Limited between April and June 2008 to investigate the feasibility of a New Zealand-based syngas-to-ethanol plant using waste wood as a feedstock.

1.1. About LanzaTech

LanzaTech New Zealand Ltd. was founded in early 2005 to develop, and commercialise proprietary technologies for the production of low cost fuel ethanol from the carbon monoxide in low-hydrogen waste gases produced by the steel industry. During 2007, following a successful funding round, the company expanded the focus of its process development program to include biomass-derived syngas which contain elevated levels of hydrogen gas. Consequently, LanzaTech's gas fermentation technology could be applied to enable the production of ethanol from either industrial waste gas or biomass syngas. A key component of LanzaTech's business strategy is to build and operate a wood syngas-to-ethanol plant to prove its technology at a commercial scale.

1.2. Purpose of the study

At the point that it becomes economic to do so, LanzaTech expects that it will build and operate at least one syngas to ethanol plant in New Zealand. A model to establish the business case of such a plant is critical both in its own right (to ensure that it makes economic sense to proceed with this plant specifically) and because LanzaTech's overall financial model depends on such plants paying licence fees and royalties to the company in the future.

1.3. Overview of the proposed plant

1.3.1. Process overview

The proposed plant would use a thermo-chemical process to convert woody biomass to ethanol. A thermo-chemical pathway involves gasification of wood into a 'syngas' consisting largely of carbon monoxide, hydrogen and carbon dioxide. Syngas is then converted to ethanol using either a catalytic or a biological process. In LanzaTech's case the process uses fermentation, that is, a biological process. Separation of ethanol from the fermentation mixture would use well-established distillation and ethanol drying technologies.

Thermo-chemical conversion is an alternative to enzymatic conversion of lignocellulosic biomass into ethanol ('cellulosic ethanol'). Like enzymatic conversion processes, thermo-chemical conversion technology is still technically immature and, as yet, commercially unproven.

1.3.2. Scale

The optimum scale of a plant is one of the questions addressed by this study. A 'base case' was developed for a plant sized to produce 150m litres of ethanol per year. This size was chosen simply because it matches the size of a maize ethanol plant evaluated by LanzaTech in 2006-07 which meant that some data were already available for some costs (such as distillation equipment). To put this size in context:

- A 150m litre plant was typical of the size of maize ethanol plants built in the USA until a few years ago. Modern plants are US maize ethanol typically at least twice this size.

- If New Zealand's biofuels sale obligation was met solely by ethanol (c.f. the more likely scenario of a mix of ethanol and biodiesel) demand for ethanol would be approximately 250m litres per year. Hence a plant this size would produce approximately 60% of New Zealand's biofuels demand.[1]
- A plant of this size would require wood feedstock in volumes comparable to those used by Carter Holt Harvey's Kinleith mill.

1.4. Scope and modelling approach

The primary objective of the study was to develop a comprehensive financial model that captured all of the key financial and engineering inputs for the proposed plant. Unlike, say, a maize ethanol plant however, there was no standard engineering design that could be evaluated in a base case. Indeed, it quickly became apparent that there are a number of major engineering decisions that LanzaTech still needs to evaluate, both for its own core technology (the fermentation process) and for other processes that contribute to the overall plant. These choices are discussed later in the report. In most cases it was well beyond the scope of this study to undertake the engineering analysis required to make these financially significant, but finely balanced, technology decisions. Even if a comprehensive engineering analysis had already been undertaken there would still be inherent uncertainty caused by the immaturity of the technology being modelled. For example, LanzaTech is not yet certain what the tolerance of its fermentation will be to gas impurities (LanzaTech suspects it will be pretty good but does not know for certain) and therefore is not certain what gas clean-up steps will be required after biomass gasification.

Notwithstanding the above, a lot of study time was spent on understanding the range of technology choices and attaching dollar value to the key parameters associated with each. This work sought to narrow options where possible, and to establish ranges for key variables associated with remaining design options.

The financial modelling process was designed to reflect the high degree of engineering uncertainty. The value of the financial model to LanzaTech is largely in its ability to undertake sensitivity analyses and explore 'what-if' scenarios.

1.5. Variances to EECA reporting requirements

It will be apparent that this study doesn't closely fit the type of study implied in the EECA grant application - that is, evaluating biomass as an energy source to be retrofitted to an existing industrial process. Consequently some of the items that EECA have identified for reporting against have limited meaning in the current study and others were not dealt with in any depth. Individual comments are made below. Conversely other items not identified by EECA are critical to the findings of this study and they are covered in this report. Table 1 outlines EECA's expected reporting requirements and how they are treated in this report.

Reporting points	**Section in the report**
Existing energy balance (an energy audit)	Not applicable for this study

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[1] These numbers changed during the course of this work with the release of a revised biofuel sales obligation in the Biofuel Bill. See conclusions.

Energy conversion technology options and selection, including assumed conversion/efficiency factors	Section 3.
New energy balance showing where the energy from the woody biomass is used	Section 3.7
Uptake of woody biomass, annual volume and quality requirements	Section 3.1
Supply of woody biomass; sources, volumes, quality, security of supply through the year, and the cost	Section 3.1
Provisions for delivery, storage and feeding the woody biomass to the process	Sections 3.1 and 3.2
Operating levels; peak capacity, operating hours per day, days per week, weeks per year	Section 3.9.2
Capital costs and operating costs, including woody biomass transport and processing costs (compared to existing)	Section 3
Other potential barriers or risks, such as resource consents	Section 6.2
Economic analysis for the project including sensitivity to energy prices, capital costs and other key risks	Section 4

Table 1: EECA reporting requirements

1.6. Structure of this report

This report is structured in five sections following this introduction.

- Section 2 outlines the methodology followed and lists the groups and individuals contacted during the course of the work.
- Section 3 describes the process modelled and sets out the key assumptions used in the model.
- Section 4 sets out the results of the financial modelling.
- Section 5 compares the economics of LanzaTech's process to other ethanol production methods.
- Section 6 contains a discussion about the implications of the study findings for LanzaTech.

2. Methodology

2.1. Proposed approach (letter of proposal)

The approach followed in this study largely followed the outline proposed by Scarlatti in a letter of proposal to LanzaTech ahead of starting the project, that is:

- Prepare a New Zealand market summary. This would be based on the work previously undertaken for LanzaFuels. The purpose is to specify base case assumptions for
    i. Selling price
    ii. Volume demanded

- Quantify the costs and availability of wood waste feedstock:
    iii. Availability / requirement
    iv. Costs to acquire, harvest, store, dry
    v. Logistics requirements

  Some of this information is already available from the work undertaken for LanzaFuels to evaluate wood waste as a heating fuel. This information base will be built up through by accessing published information and through interviews with forestry industry participants and logistics firms.

- Create an engineering process model. This should cover:
    vi. Conceptual layout and design
    vii. Technology assumptions
    viii. Conversion factors
    ix. Energy balance
    x. Operating levels

- Prepare cost estimates for:
    xi. Capital costs
    xii. Running costs

- Build a financial model based on discounted cash flow in Excel. Outputs will include:
    xiii. NPV
    xiv. Projected P&L
    xv. Projected balance sheet
    xvi. Funding requirements

- Add a sensitivity analysis to the Excel model. Parameters to vary will include:
    xvii. Ethanol selling price (import parity)
    xviii. Feedstock (wood waste) costs
    xix. Conversion parameters
    xx. Size / scale (particularly investigate the dis-economies of scale that might arise through building a scaled down first plant)

- Analyse how key inputs will vary compared to New Zealand in other markets (e.g. US biomass cost / availability)

- Determine what license fees / royalties could / should be paid by an operating plant
    - xxi. From a financial standpoint
    - xxii. By benchmarking to comparable companies

2.2. Variation to the approach described in letter of proposal

There were some relatively minor deviations from the approach proposed. The main one of these was to omit the last bullet point above. Following further guidance from LanzaTech no work was undertaken to model the license fees that a plant might be able to earn.

2.3. Groups and individuals contacted in the course of this study

Over the course of the study LanzaTech and Scarlatti made contact with a number of external organisations and individuals to discuss aspects of the work. These included:

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2.4. Other references

In addition to personal contact, data was gathered from:

- Purchased references (mainly on biomass gasification)
- Scientific papers and technical reports
- Internet searches
- References sourced though Khosla Ventures

3. Plant and process design

The plant was modelled by breaking the process into the seven parts shown in Figure 1. Six of these components model the linear process from wood supply through to ethanol separation. Overheads and the capital cost of utilities were applied across the plant.

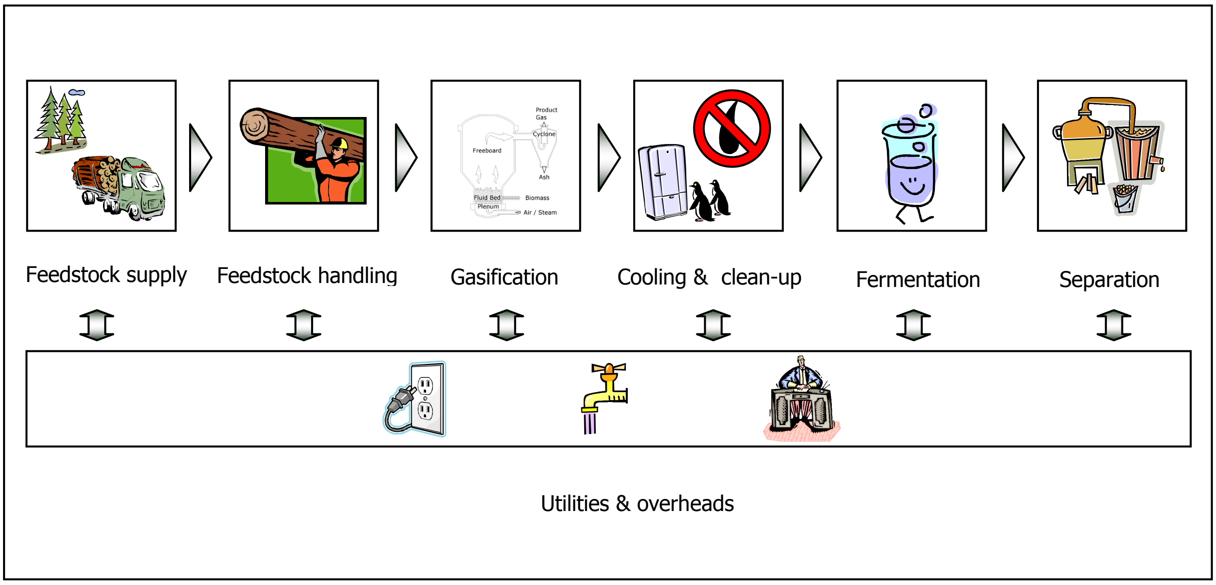

Figure 1: Elements of the plant design

For each component the main items that the study sought to establish were:

- The basic design
- Conversion efficiency variables
- Capital costs
- Operating costs

3.1. Feedstock supply

The base feedstock for the plant was initially assumed to be forestry residues. However, back-of-the-envelope calculations at the start of the study quickly established that demand from a plant of the proposed size (in the base case) would match or even exceed all available forestry waste from North Island forests[2]. To overcome this shortfall pulp logs were considered as a ‘top-up’ feedstock.

3.1.1. Cost and supply - residues

The availability, cost to transport and energy value of New Zealand forestry residues have been modelled in considerable detail by Scion. Models are available that illustrate how the cost of sourcing forestry residues alters for different locations and how this will vary over time. At the start of the modelling work it was expected that Scion’s help would be needed to prepare cost–volume curves for a range of potential location scenarios. However, after an initial meeting with Scion, and having considered the curves shown in Figure 2, it became apparent that further work was unwarranted at this stage.

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[2] In the final model the overall feedstock demand is 770,000 tonnes per year in the base-cost.

Figure 2, shows a set of curves developed by Scion for a study to show the cost of supply wood residues to selected dairy plants around New Zealand. The dominant feature illustrated by the chart is that the marginal cost per tonne of wood[3] increases as the volume requirement increases. The cost of the wood is primarily a function of the average distance that it is required to be transported and this increases as the area needed for sourcing the wood increases. This creates a 'diseconomy' of scale as the plant size increases.

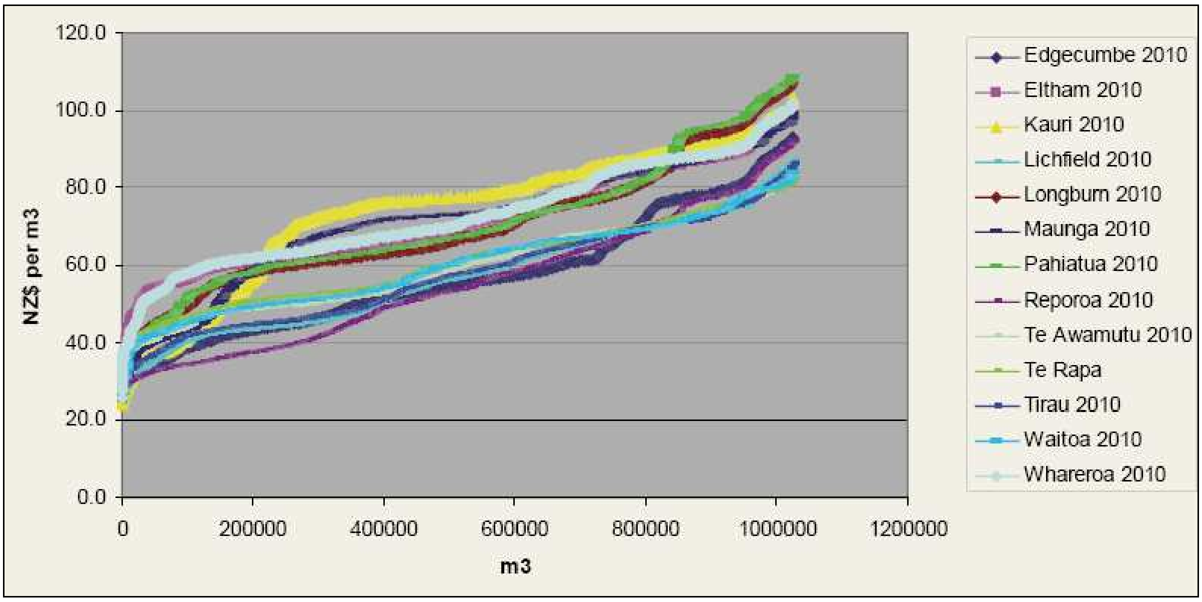

Figure 2: Cost to supply forestry residues for a given volume and location

(Source: Scion - Bioenergy Options for New Zealand – 2008)

As the cost to transport wood will dominate all other transport costs to or from the plant (including finished goods) it can be expected that the plant would be located as close to large sources of forestry residues as possible. In practice in New Zealand this means the plant would be expected to be located in or near the central North Island forest. Of the curves shown in Figure 2, the one for Reporoa fits best with this location model and so this was used as the basis for modelling work. For modelling purposes the curve was idealised as a straight line starting at NZ$30 per tonne.

3.1.2. Cost and supply – pulp logs

Although the curves in Figure 2 indicate that there is sufficient volume for the plant to be fed solely by forestry residuals this is not an economically attractive option at a large scale. Beyond a certain volume of feedstock, pulp logs are a cheaper source of wood than residues. In addition, security of supply is likely to be far greater if the plant can use logs as well as residues. One of the recommendations of a survey of North American biomass energy facilities[4] was to design for fuel flexibility:

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[3] In Figure 2, m^3 and tonnes can be used virtually interchangeably as volume refers to the solid wood component (c.f. the volume of a pile of chips) and the density of wood is very close to 1 tonne per m^3.

[4] Highlights of Biopower Technical Assessment: State of the Industry and the Technology (NREL/TP-510-33502)

> *Many biomass plants change fuels significantly over the years, as opportunities arise or old fuel sources dry up. These changes are often not predictable. The best strategy to deal with this problem is to have a plant design and permits that allow as much fuel flexibility as possible.-*

MAF statistics indicate that the total volume of wood available in New Zealand from pulp logs is at 3-5 times greater than for residues[5]. The average domestic price for pulp logs over the past five years has been NZ$43 per tonne at the mill[6]. A higher value (NZ$60 per tonne) was used in the base case to reflect:

- Recent prices are higher than the historic average.
- Informal feedback (from CHH) that the MAF statistics seem low.
- As forestry residues take on economic value forest owners will seek to charge for them.
- Demand from a new plant would alter the supply & demand balance for pulp logs in New Zealand.

3.1.3. Price model used

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3.1.4. Other considerations

The model presented above makes a number of known simplifications. Neglected factors include:

- Pulp logs pricing is unlike to remain flat as demand increases. Like residues logs prices will increase as they need to be transported further. However, the effect will be mush less pronounced than for residues.
- Much of New Zealand's wood is already contracted - the impact of this on pricing is not quantified.
- There may be an opportunity to locate the plant away from the Kinleith and Tasman mills (i.e. outside of the Central North Island forest). This could make residues more expensive but reduce competition for pulp logs. This was not explored.
- External long-term supply and demand factors for wood were not considered.

While these factors may be important for LanzaTech to consider in the future they are almost certainly less significant than other variables in determining the overall economics of the plant (see sensitivity analyses presented in section 4.3).

3.1.5. Energy content

Dry wood has energy content (heat of combustion [lower heating value]) of approximately 19 GJ per tonne. The energy content of wet wood drops linearly with moisture content because water (with no energy value) contributes to the overall mass of the wood and because energy is required to evaporate it. At 50% moisture the heating value drops to approximately 8 GJ per tonne[7].

3.1.6. Biomass required

In the base case the total wood requirement is 770,000 tonnes per year.

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[5] See http://www.maf.govt.nz/statistics/forestry/annual/aptr/index.htm

[6] See http://www.maf.govt.nz/forestry/statistics/logprices/

[7] EECA - Forest residue harvesting for bioenergy fuels

3.1.7. Biomass costs in other markets

Considerable work has been undertaken to quantify the costs and availability of biomass in other markets, particularly in North America[8]. Studies cover agricultural residues, dedicated bioenergy crops and mill residues, in addition to forestry residues. Median costs presented in these studies are similar to those modelled here although these values range somewhat. A conclusion that can be drawn from this is that the financial results determined in this study would apply pretty well to other markets. This contrasts, for example, to a maize ethanol plant as the maize cost in New Zealand is significantly different to those in other markets.

3.2. Feedstock handling

3.2.1. Handling steps

The feedstock handling process is illustrated in Figure 3. Residues are transported to the site and weighed on arrival at a weighbridge. They are unloaded and then moved by front end loader and conveyer to a storage pile. Pulp logs are chipped or hogged and then this wood is mixed with residues. The wood is stored for one month to ensure that the plant has a buffer stock in case of any interruption to supply and to start the drying process. Feedstock is drawn from the bottom of the wood pile (to ensure inventory turnover) using an underpile auger, screened for metal contaminants and finally reduced to 1-2cm particle size by a hammer mill prior to gasification.

Alternative handling configurations may also be possible. For example, Aden et al.[9] propose screening and milling prior to storage.

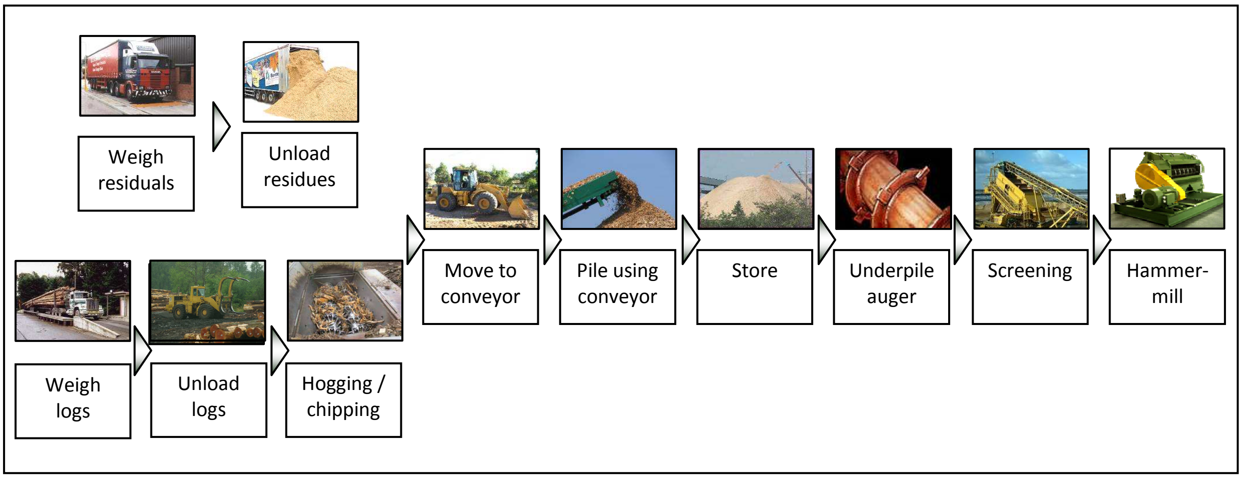

Figure 3: Feedstock handling process

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[8] See for example, http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf

[9] Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass (NREL/TP-510-41168)

3.2.2. Capital costs

Estimates of the capital cost of the feedstock handling system are set out in Table 2. Individual component costs have been multiplied by a factor to account for the labour and incidental costs to build install the components. This installation factor is also intended to cover associated capital costs such as control systems and buildings.

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Table 2: Feedstock handling capital costs

3.2.3. Operating costs

A total of about 7 staff would be required at any one time to run feedstock handling meaning that a total of approximately 35 staff would be required to run a plant 24 hours / 7 days. When other operating costs are added (electricity, maintenance) total operating costs came to approximately $3m per year.

3.3. Biomass gasification

The biomass gasifier will be the single most expensive part of the plant. A considerable amount of time was devoted to exploring options for the gasifier system. This work raised numerous issues about the choice of gasification system, operating performance and capital & operating costs. LanzaTech will continue to work on these in coming months. In order to make progress on a financial model assumptions have been made about the choice of gasifier system. These assumptions will be reviewed and the model iterated as LanzaTech develops its understanding of the technology choices.

3.3.1. Maturity of biomass gasification technology

A survey of biomass gasification technology quickly highlights the technical and commercial immaturity of this equipment. While small scale wood gasifiers have been around for many decades, the large and sophisticated designs appropriate for the size of plant envisaged are still at an early stage. There are no operational gasifiers of the size and type proposed in this study for LanzaTech's plant anywhere in the world. Most gasifiers that approach the design size[10] are located in non-commercial pilot facilities and operate only with government (or EU) grant support. A key part of establishing the viability of LanzaTech's biomass to ethanol process will be to establish one or more partnerships with biomass gasifier developers.

3.3.2. Gasifier types

Biomass gasification references identify a number of different types of gasifiers. These include updraft, downdraft, fluidised bed, circulating fluidised bed. This report won't discuss the differences between the different designs as this is well-documented elsewhere[11].

Updraft and down draft gasifiers dominate those in commercial operation today. Typically their working fluid (see below) is air and they are comparatively simple when compared to fluidised bed and circulating fluidised beds gasifiers. Fluidised bed and circulating fluidised beds gasifiers are preferred for large, modern plants due in part to their better coking performance.

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[10] Meaning within an order of magnitude of capacity

[11] One good review reference is the BTG's (Biomass Technology Group) Handbook on Biomass Gasification. It can be ordered at www.btgworld.com.

3.3.3. Working fluid (oxygen source)

A further variable considered is the choice of working fluid for the gasifier. The main design choices are air (approximately 79% N_2 and 21% 0_2) , enriched oxygen or steam.

Most biomass gasifiers in commercial operation today are air blown. This makes them comparatively simple from an engineering standpoint but they suffer an inherent inefficiency as inert nitrogen is heated in the gasifier with no benefit for the end process. For LanzaTech's process the nitrogen component imposes a number of additional process costs:

- Prior to the fermentation step the syngas needs to be compressed. Including nitrogen would significantly increase the energy and capital costs of the compression step.
- The rate of the fermentation reaction is driven by concentration difference between the reactive species (H_2 and CO) in the gas bubbled through the fermenter and the fermentation media. Including nitrogen in the syngas would reduce the concentration of the reactive species in the gas bubbles thereby increasing the size of the fermenter required.
- Increased gas flow would increase the rate of ethanol loss in the vent gas from the fermenter.
- NO_x formed by the nitrogen in the gasifier may be inhibitory to the fermentation process.

'Back-of-the-envelope' calculations indicated that these costs justify the extra investment in an oxygen or a steam blown system.

Oxygen blown gasification systems are common for coal gasifiers and may be a viable option for LanzaTech. However, the capital cost of an oxygen plant and the extra safety equipment that would be needed are significant compared to the overall plant cost. For example, a 500 tonne per day oxygen plant might cost some $30m dollars to install and then some $3 to 5 million per year to operate. While these costs would be justified by the benefits compared to an air-blown system, a steam blown system appears more favourable still. Using steam as a working fluid would result in low nitrogen gas with intermediate additional capital and operating costs.

3.3.4. Plasma gasification

Plasma gasification[12] provides a different gasification option. Plasma gasifiers operate at much higher temperatures than conventional gasifiers and as a result produce much cleaner syngas. Their major drawback is considerably greater capital costs. Publicly available data about the cost of a number of major plants that use plasma gasifiers suggest that the capital costs compared to conventional gasifiers would be at least twice and probably higher still. As the gasifier is expected to be the most expensive component of the plant even with a conventional gasifier this makes the economics very unattractive.

3.3.5. Description of the modelled system

In order to put a 'stake in the ground' the modelling work was based around a gasifier design developed by Repotec. Repotec are a small engineering firm based in Austria. Their website[13] describes their business as *design and erection of plants on the field of energy and environmental techniques, specialized on biomass power plants.*

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[12] See http://www.westinghouse-plasma.com/technology_solutions/what_is_plasma_gasification.php for a description of the technology

[13] http://www.repotec.at/en/index.php

Repotec's gasification technology uses a steam blown fluidised bed gasifier which produces syngas low in nitrogen and tars (see 0 for more on tar). The system is illustrated schematically in Figure 4.

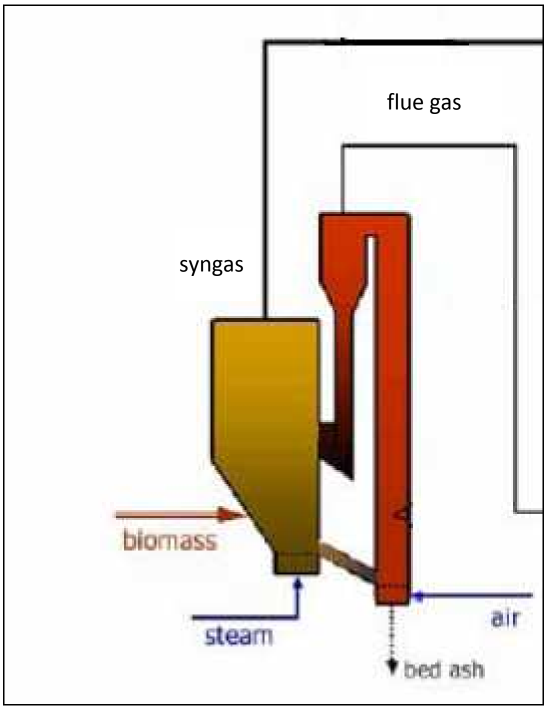

Figure 4: Repotec gasification system

The gasifier consists of two connected fluidised beds. In the gasification zone at approximately 850°C the biomass is gasified with steam. To maintain the energy balance for the gasification process additional heat has to be fed into the gasifier. Partially gasified carbon (charcoal) is fed into the combustion zone together with the circulating bed material, which serves as a heat carrier, and is burned. The exothermic reaction in the combustion zone provides the energy for the endothermic gasification with steam. Two separated gas streams are produced: a flue gas stream, comparable to flue gases from conventional combustion and the product gas stream.

Repotec developed the system for use in a combined heat and power plant (CHP) and in that application the sensible heat of the two gas streams can used for the production of district heat. In LanzaTech's process this heat can be used to separate ethanol by distillation, to generate the steam and to pre-dry the wood before it enters the gasifier. Although it is not necessary to dry the wood prior to gasification for the Repotec gasifier pre-drying the wood makes use of heat that would otherwise be lost and makes the overall process more thermally efficient.

Figure 5 illustrates typical syngas composition from a Repotec gasifier. The low nitrogen production is well suited for LanzaTech's process. Methane production for this gasifier is higher than most air blown gasifiers.

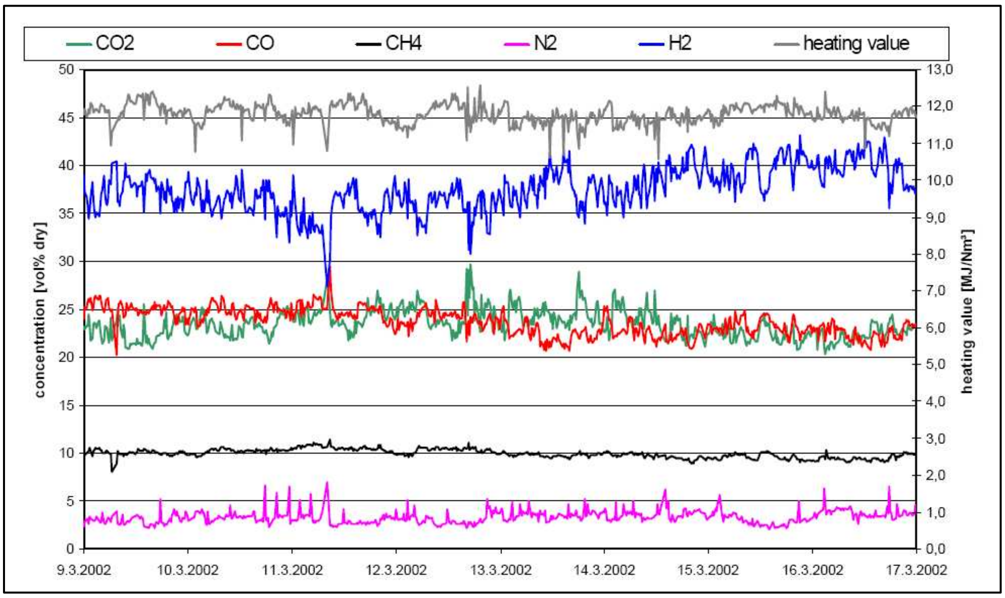

Figure 5: Producer gas composition from a Repotec gasifier

As with almost all of the gasifiers that LanzaTech would consider, Repotec's technology is still at an early stage of development. Repotec have only one gasifier installed in an operational plant (a CHP plant in Güssing, Austria) although this gasifier has been operating for over five years and so Repotec has, at least, built up some experience of this gasifier in operations. The size of the gasifier is much less than LanzaTech would need for a 150m litre ethanol plant (approximately 8MW_{gas} vs approximately 200MW_{gas}). Repotec say that their technology would scale up easily and that their target size (up to 40MW_{gas}) is limited by the geographic distribution of biomass in Europe rather than technical considerations. However, this has yet to be demonstrated in practice.

3.3.6. Engineering model for biomass gasification

In order to create some flexibility in the financial model a thermodynamic model was created for the gasification step. In theory it should be possible to develop a thermodynamic equilibrium model for the gasification process given a known set of process inputs. However, feedback from gasifier manufacturers and evidence from the literature show that thermodynamic models require considerable empirical tweaking for them to provide reasonable predictions of syngas composition, exit temperatures and energy balances.

After an investigation of more elegant approaches, and attempts to source existing models[14], it was concluded that the most robust approach was to create a simple empirical model that fitted mass and energy balances to experimentally derived values of exit temperatures and syngas composition. The syngas composition shown in Figure 5 was used in the base case.

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[14] One model in the public domain is Gasify (see http://www.gasification.higman.de/programs.htm). The model was developed for coal rather than biomass and proved difficult to use for biomass. Chris Higman, the author, was approached but didn't want to share the workings behind the model. This meant that the model couldn't have been integrated into the Excel model used for this work even if did work for biomass.

The thermodynamic model respects energy and mass balances for changes of chemical species, but takes no account of any reaction dynamics or equilibrium. The chemical composition, enthalpy and elemental mole numbers of the reactants are calculated in a straightforward manner from the inputs to the gasifier, which are some combination of wood, air, oxygen and water.

Gasifier manufacturers supply figures for the composition of the exit gas from their equipment under a range of conditions and a similar calculation could be performed for the gasifier products based on these numbers. However, while this could be used for a rough energy balance, the mole numbers for the reactants and products won't match.

To match the mole numbers of reactants and products, the manufacturer's figures for H_2 and CO, the two species with the largest effect on the performance of the fermentation process are used as is. For the other products, N_2 is passed through unchanged, CO_2 and CH_4 are present in the product stream along with one of H_2O, O_2 or C. The fractions of CO_2, CH_4 and the third product are chosen to satisfy the mole balance, the third product being chosen so that the mole balance implies all positive mole fractions.

For the Repotec gasifier, with a steam equivalence ratio of 0.27, the manufacturer specifies a 40% mole fraction of H_2 and a 20% mass fraction of CO. The mole balance implies 22% CO_2, 15% CH_4, while the last product is, not surprisingly given that it's a steam reformer, 2.5% H_2O.

3.3.7. Capital cost

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3.3.8. Operating costs

[REMOVED FROM THIS VERSION OF THE REPORT]

3.4. Gas clean-up

3.4.1. Requirement for gas clean-up

All biomass gasifiers produce a range of impurities in the syngas. By mass the main impurities are 'tars'. In the context of biomass gasification 'tars' describe a complex range of high molecular weight hydrocarbons, typically aromatic. Other important impurities are alkali metals, halides, sulphur and chlorine.

3.4.2. Clean-up technologies

A wide variety of different technologies are employed to clean-up syngas. Tar removal technologies can be categorised into physical technologies and chemical processes. Physical technologies in turn can be separated into wet scrubbing processes and dry separation devices. Impurities such as sulphur require additional clean-up steps. The choice of clean-up technologies employed depends on purpose for which the syngas is used. Direct firing of syngas gas for, say, steam generation in a boiler, allows syngas to be used without much clean-up. At the other extreme, synthesis of liquid fuels from syngas using a catalytic process requires a number of expensive steps to remove impurities.

The tolerance of LanzaTech's process to impurities is thought to be much better than for catalytic synthesis of liquid fuels. However, exactly what clean-up steps will be required remains unknown. In the base case modelled here the clean-up steps based on those required for gas production for use in internal combustion engines. According to a review paper prepared by the National Renewable Energy Laboratory[15] internal combustions can tolerate up about 30mg per m^3 of gas produced for which wet scrubbing will typically be an adequate clean-up step.

3.4.3. Description of the modelled system

The gas cooling and clean-up system modelled in the base case is shown in Figure 6. In this model syngas from the gasifier is cooled from 850^{o}C to 300^{o}C after passing through two heat exchangers to recover syngas heat. The syngas then passes through a wet venturi scrubber and a quench chamber. Water used in the scrubber and quench chamber is circulated through a tank and cooler. Two waste streams are produced (sludge and wastewater) which require external treatment.

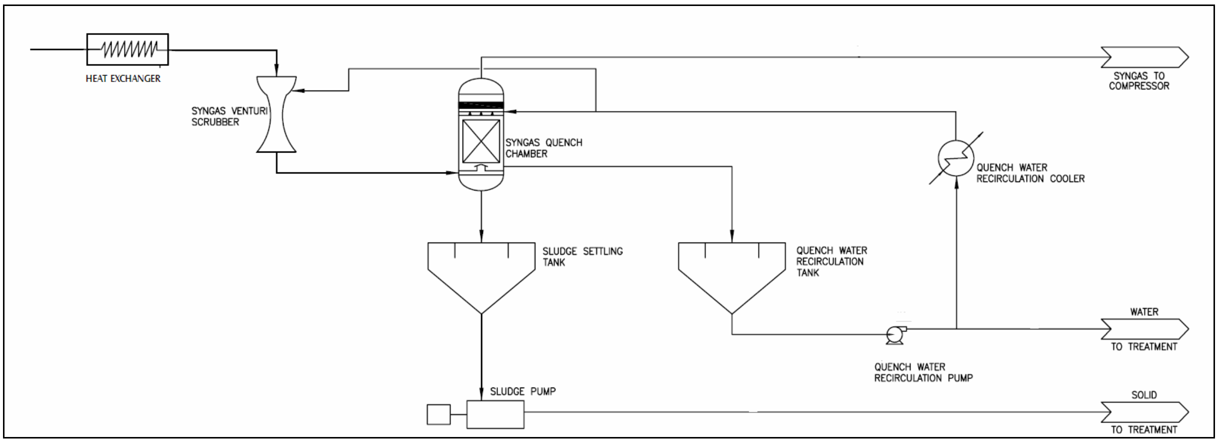

Figure 6: Gasification clean-up system

3.4.4. Capital costs

Capital cost estimates were drawn from published reports and from conversations with manufacturers. In most written sources the capital cost was expressed as a proportion of the gasification costs. Estimates ranged from 30% to 300% of the gasifier costs. For the comparatively basic clean-up system modelled here the lower end of this range is appropriate. In the base case a value of 50% is used to provide some degree of conservatism. Sensitivities analyses show the financial impact of being required to add a catalytic tar reformation process (assumed to cost 100% of the cost of the gasifier) or an acid removal step (assumed to cost 50% of the cost of the gasifier).

3.4.5. Operating costs

The model assumes that one person is required to operate the clean-up system at any time (five for all shift) and the waste water treatment costs are **[REMOVED FROM THIS VERSION OF THE REPORT]** in the base case.

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[15] Biomass Gasifier "Tars": Their Nature, Formation, and Conversion (NREL/TP-570-25357)

3.5. Fermentation

LanzaTech's fermentation process is centred on a single large fermentation tower. The process requires the syngas to be compressed before it is injected at the base of a fermentation vessel. Gas bubbles rise through a media that contains LanzaTech's proprietary microbes. The microbes convert energy from the gas into ethanol, which goes into solution in the media. Not all of the energy in the syngas is recovered – some leaves as vent gas at the top of the fermenter. This vent gas stream will also include some ethanol vapour. The process also produces heat which is removed using a heat exchanger and cooling tower. The overall energy efficiency of this process is modelled at 51%.

3.6. Separation

The ethanol is separated from the fermentation media using a two step process. Fermentation media containing ethanol is distilled using a process only slightly modified from that employed by maize ethanol production. In this process the ethanol is concentrated to approximately 95% pure. The distillation process would employ heat from the syngas and possibly from the flue gas heat exchangers. After distillation the ethanol is dehydrated using molecular sieves.

3.7. Energy balance

An energy balance for the plant was determined and is illustrated in Figure 7 and Table 3. Given the conceptual nature of the engineering design the values presented should be taken as indicative rather than as detailed design values.

[REMOVED FROM THIS VERSION OF THE REPORT]

Figure 7: Energy balance and energy flows (see

[REMOVED FROM THIS VERSION OF THE REPORT]

Table 3 for key)

[REMOVED FROM THIS VERSION OF THE REPORT]

Table 3: Key to [REMOVED FROM THIS VERSION OF THE REPORT]

Figure 7

3.8. Utilities and overheads

3.8.1. Capital costs for general facilities

Assumptions made about the capital cost of general facilities and plant are set-out in **[REMOVED FROM THIS VERSION OF THE REPORT]**

Table 4. These values have been taken from LanzaTech's previous analysis of a maize ethanol facility and are in turn based on estimates from costings from North American maize ethanol facilities.

[REMOVED FROM THIS VERSION OF THE REPORT]

Table 4: Utility and general capital costs

3.8.2. Labour overhead

[REMOVED FROM THIS VERSION OF THE REPORT]

3.8.3. Utility and other overheads costs

Assumptions made about annual utility costs and other overhead costs are set-out in Table 5. As with the capital costs described above, these values have been taken from LanzaTech's previous analysis of a maize ethanol facility and are in turn based on costs from North American maize ethanol facilities. One exception is the value for water usage where the estimate for a maize ethanol plant has been multiplied by ten. This reflects the additional water loss expected as a result of the gas clean-up step.

[REMOVED FROM THIS VERSION OF THE REPORT]

Table 5: Annual utility costs

3.9. Overall modelling assumptions

3.9.1. Modelling the effect of changing plant size

In order to assess the financial impact of changing plant size the simple scaling rule described by Equation 1 was applied to most capital costs. As an example, this rule determines that doubling the size of the plant would increase capital costs by approximately 50%.

$$\frac{COST}{COST_{base}} = \left(\frac{SIZE}{SIZE_{base}}\right)^{0.6}$$

Equation 1: Scaling rule used to model changes in costs for different plant scales

For some components individual values for the exponent used are available. Mainly this applies to standard equipment such as compressors and heat exchangers. Where these are available they have been used in place of the default value of 0.6.

3.9.2. Operating levels

The plant is assumed to run 24 hours, 7 days for 350 days per year. Feedback from gasifier manufacturers was that this level of utilisation was not only possible but was in fact desirable for minimising the operating cost of the gasifiers. All other parts of the plant have been proven in 24/7 operation in many other plants.

3.9.3. Building timetable

The model starts 2.5 years ahead of first production. Land is purchased at this point and detailed design begins. Site improvements continue over the following year. The construction and commissioning of the plant proper is assumed to take 15 months.

4. Financial modelling

4.1. Methodology

The financial model is centred on a cash flow forecast for the plant. All of the modules in the model relating to plant components feed into the cash flow forecast via analyses that summarise revenues, costs, investment & depreciation. The cash flow forecast is used to derive a full balance sheet for the plant on a quarter-by-quarter basis and this is used to determine the total cash requirement for the project.

Free cash flows are discounted using rate of return to arrive at a project NPV. In the base case the required rate of return is 15%. For a given set of assumptions, including ethanol sales price, the project NPV value is the model's main output. For illustration purposes, however, the breakeven sales price is a more convenient metric. Consequently, for any given set of input conditions the model was run to find the ethanol price that returns a zero NPV.

In many of the charts that follow the selling price is broken down into variable, fixed and capital costs. To prepare this breakdown the variable costs are totalled and subtracted from the selling price. The fixed costs are divided by total production volumes and these subtracted from the remainder of the previous step. The remainder is then the proportion of the selling price required to cover capital costs. In calculations in which this amount is split across different parts of the plant the split is made in proportion to the total capital cost regardless of the timing of the spend.

4.2. Required selling price

In the base case the required selling price is NZ$0.72 per litre.

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Unsurprisingly feedstock (i.e. wood) costs are the most significant single cost element for the plant although, at under a 1/3 of the selling price, feedstock costs are less significant than they would be for a maize ethanol plant[16]. The capital costs of gasification and gas clean-up are over half of the total capital costs and these are the next most significant elements of the total selling price.

4.3. Total investment requirement

The total investment requirement in the base case is **[REMOVED FROM THIS VERSION OF THE REPORT]**.

4.4. Sensitivity to changes in key inputs

The effect of changes to key model inputs is shown in Figure 8. It is evident that the assumptions play a significant part in determining the selling price.

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Figure 8: Sensitivity of the breakeven selling price to key inputs (NZ$ per litre)

4.5. Economies of scale

The effect of changing plant size on economics of scale is shown in Figure 9 & Figure 10. For a plant size smaller than the base case capital cost economies of scale are much more important than the diseconomy created by the need to transport residues further to the plant. At a scale of 150m litres or more these effects largely cancel out although it is possible to see from Figure 10 that capital economies are still more important right up to a 300m litre plant.

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Figure 9: Effect on the breakeven selling price as plant size changes (NZ$ per litre)

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Figure 10: Effect on the breakeven selling price as plant size changes (NZ$ per litre)

5. Comparison to other price benchmarks

5.1. Coskata

LanzaTech's nearest direct rival is Coskata. Like LanzaTech, Coskata is developing technology to convert syngas to ethanol using a fermentation process.

Coskata have publicly stated that they expect to be able to make fuel ethanol for US$1.00 per gallon (NZ$0.33 per litre) using their process. A quick comparison suggests that Coskata is much better placed than LanzaTech but a more careful reconciliation suggests that the economics of the two companies' processes are similar. Most significantly when undertaking a reconciliation exercise, Coskata's stated target neglects the amount required to cover the capital cost of the plant[17]. The other major different is an assumption that dry biomass will cost US$50 per US ton. The value used by LanzaTech is equivalent to US$70 per tonne.

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[16] For a North American maize ethanol plant the maize (corn to North Americans) typically makes up 60% of total costs. For the maize ethanol plant modelled by LanzaTech for New Zealand the proportion would be been even higher.

[17] See, for example, http://news.cnet.com/8301-11128_3-9913192-54.html?tag=bl

Putting Coskata's input assumptions into the LanzaTech's model yields the results shown in [REMOVED FROM THIS VERSION OF THE REPORT]

Figure 11 (expressed in US$ per gallon for ease of comparison). The sum of the fixed and variable cost contribution to the required selling price is US$0.96. This suggests LanzaTech's process will be about the same or even slightly better than Coskata's.

[REMOVED FROM THIS VERSION OF THE REPORT]

Figure 11: Coskata's assumptions in LanzaTech's model (US$ per gallon)

5.2. Imported ethanol

For a plant built on LanzaTech's process to be viable in New Zealand it would need to be able to sell at or below import parity (see discussion in section 6.1). Figure 12 shows the history of this import parity value for the past five years. For almost all of this time an ethanol cost of NZ$0.72 would be been highly competitive.

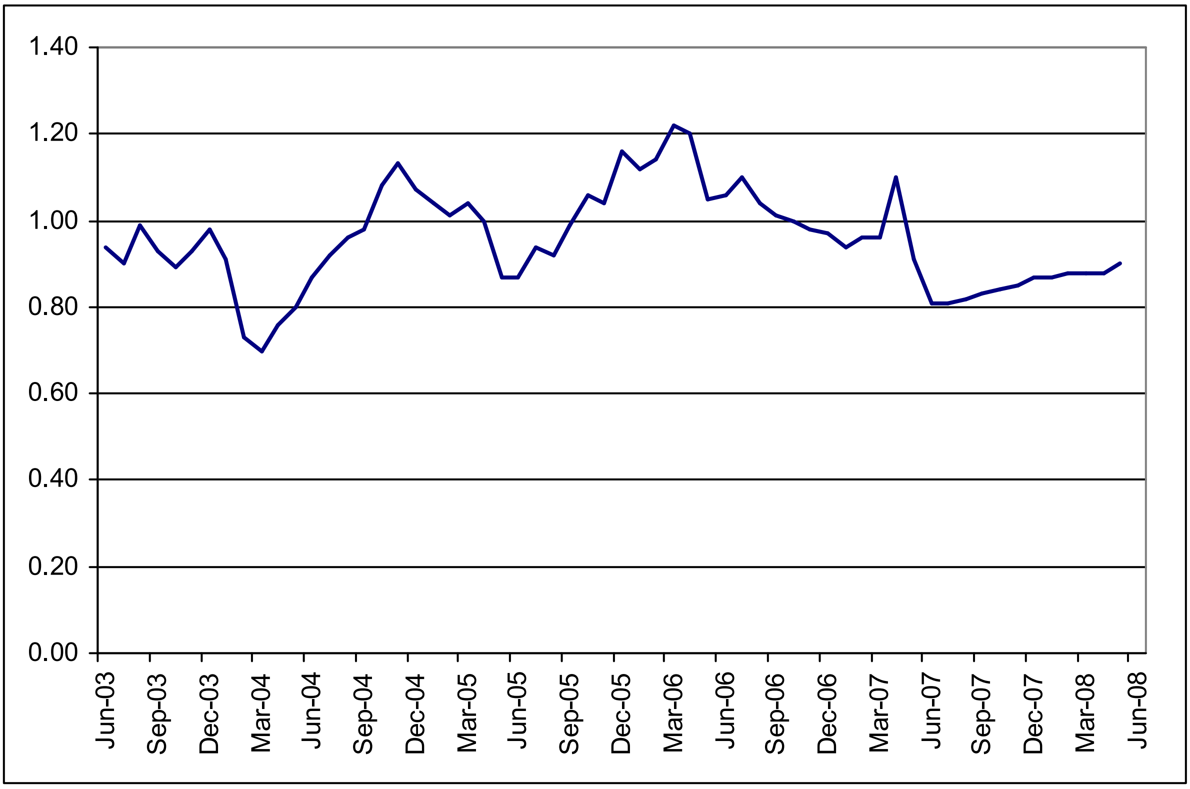

Figure 12: Historic cost to import ethanol into New Zealand (NZ$ per litre)

5.3. Domestically produced maize ethanol

In 2007 LanzaTech determined that maize ethanol would cost approximately NZ1.00 per litre to produce in New Zealand.

6. Discussion and recommendations

6.1. The market for fuel ethanol in New Zealand

The breakeven selling price and production volumes for any New Zealand-based ethanol plant need to be considered in the context of the market for biofuels in New Zealand. The New Zealand market will be created by the Biofuels Bill which is now expected to come into effect in October 2008.

6.1.1. Demand for fuel volumes

At the time of writing (June 2008) the demand outlook for fuel ethanol in New Zealand is highly uncertain. In the past year changes to the proposed legislation and world commodity prices have dramatically changed both the quantum of the biofuels sales obligation and fuel companies' strategies to meet the obligation.

One year ago:

- The sales obligation was expected to be set at 3.4% on an energy basis. At that level fuel companies expected to sell both ethanol and biodiesel to meet the obligation. A mid-case planning scenario determined demand for ethanol up to 200m litres per year by 2012
- Ethanol was expected to be exempt from excise duty until 2012
- Biodiesel was cheaper for fuel companies to introduce than ethanol
- A litre of ethanol would have cost fuel companies 5-10c less than a litre of petrol. If the costs to switch infrastructure were neglected ethanol would have been a low cost alternative to fossil fuel.

Today, the situation has changed in a number of ways:

- The sales obligation is expected to be set at 2.5% on an energy basis (returning to the level first proposed in 2006). At this level fuel companies could meet their obligation with either biodiesel or ethanol
- Ethanol is likely to be subject to excise duty from 2010
- Ethanol is cheaper for fuel companies to introduce biodiesel
- Ethanol is substantially cheaper than petrol at wholesale pricing (over 50c per litre).

While commodity prices could easily flip the relative attractiveness of ethanol and biodiesel again it seems less likely that the government will once again change its position on the level of the obligation. LanzaTech would need the New Zealand demand outlook to stabilise before it makes a commitment to a New Zealand plant.

6.1.2. Pricing

Discussions with fuel companies held as a part of the maize ethanol plant evaluation provided some clarity on the pricing mechanism that would apply. Fuel companies would be happy to purchase from a New Zealand plant if, but only if, the price was competitive with import parity. Based on the results of this study and historic import parity (see Figure 12) it appears that LanzaTech would be well-placed in this regard.

6.1.3. Offtake contracts

Fuel companies would consider fixed-term offtake contracts that could provide greater security of demand for an ethanol producer. However, fuel companies would expect a price discount in return for any 'take or pay' obligations such a contract imposes. However, there appears to be scope for such as discount between import parity pricing and LanzaTech's breakeven price of NZ$0.72 per litre.

6.2. Project risks

Three key risks to the project are discussed below.

6.2.1. New Zealand market

The recently proposed amendments to the Biofuels Bill have made the New Zealand market much less attractive for a domestic ethanol producer. The shape of legislation beyond 2012, and the possibility of a change of government later this year add further uncertainty. LanzaTech should delay making any commitment to a New Zealand plant until it is clearer what New Zealand ethanol demand will be.

6.2.2. Technology risks

LanzaTech's core process needs to be developed further before the input assumptions used in this study are matched by demonstrated results. In particular this applies to the syngas to ethanol conversion efficiency and to microbial tolerance for syngas impurities. There is significant technical risk around these parameters.

6.2.3. Competitor risks

LanzaTech's technology competes against other technologies on a range of levels:

- Coskata
- Other ethanol technology developers using a thermo-chemical pathway
- Other second generation ethanol technologies (particularly enzymatically produced, cellulosic ethanol)
- First generation ethanol suppliers
- Other biofuels

LanzaTech has little control over any of these but will continue to evaluate these competitive threats.

6.3. Recommendations

6.3.1. Become a broader integrator

In parallel to work on its core process, LanzaTech should invest in acquiring the skills to become a technology integrator. LanzaTech's first plant will feature a wide range of technologies which have limited use in commercial facilities including, in particular, biomass gasification and syngas clean-up. These technologies will have to work well with LanzaTech's core process.

6.3.2. Deepen relationships with biomass gasification groups

Biomass gasification will be as critical to the success of an operational plant as LanzaTech's own process. In order to design a plant well LanzaTech should increase its involvement with leading gasification groups. LanzaTech's proposed collaboration with Range Fuels is an excellent start but supplementary relationships with other manufacturers would be valuable

6.3.3. Undertake further engineering modelling

The engineering modelling on which this work is based is rudimentary. Further engineering modelling using process engineering tools are required in order to refine the financial analysis.