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Ghayur, A., et al. (2019). "Techno-economic analysis of a succinic acid biorefinery coproducing acetic acid and dimethyl ether." *Journal of Cleaner Production* 230: 1165-1175.

Which has been published in final form at:
<https://doi.org/10.1016/j.jclepro.2019.05.180>

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Manuscript Number: JCLEPRO-D-19-01234R1

Title: Techno-economic analysis of a succinic acid biorefinery
coproducing acetic acid and dimethyl ether

Article Type: Original article

Keywords: acetic acid; biorefinery; carbon negative; circular economy;
succinic acid; techno-economic analysis

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Abstract: The production of platform chemicals via carbon negative technologies will play an important role in global efforts to mitigate climate change. Succinic acid biorefineries are commercially mature carbon negative technologies that are plagued with large waste streams in the form of hemicellulose and gypsum. Here, a techno-economic analysis assesses the viability of a succinic acid biorefinery wherein hemicellulose is converted to acetic acid and dimethyl ether, and gypsum generation is avoided. Succinic acid is a feedstock for biodegradable plastics, acetic acid replaces petroleum-derived sources, and dimethyl ether is ideally suited as an energy storage vector. Our novel biorefinery concept presents an innovative integration of commercial technologies including water-splitting bipolar membrane electrodialysis for acid purification. The modelled multiproduct biorefinery (Multi Case) annually consumes 650,000 metric tonnes (t) of pulp logs, 135,000t of methanol, 1,700,000t of water, 42,000t of CO₂ and 89MW of electricity to produce 220,000t of succinic acid, 115,000t of acetic acid and 900t of dimethyl ether. All the parasitic electricity and heat duties are fulfilled within the biorefinery. Results show a CAPEX of AUD \$635,000,000, OPEX of \$180,000,000 and a succinic acid Minimum Selling Price of \$990/t. Sensitivity and uncertainty analyses of the Multi Case biorefinery model show it is also resilient to price fluctuations.

Techno-economic analysis of a succinic acid biorefinery coproducing acetic acid and dimethyl ether

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- Techno-economic analysis of a multiproduct succinic acid biorefinery is presented
- Minimum Selling Price (MSP) for succinic acid is AU\$990 per metric tonne
- Acetic acid and dimethyl ether are produced as coproducts
- MSP is only 6.4% higher than for typical succinic acid biorefineries

Total words=7291

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Abstract

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1. Introduction

Both the Intergovernmental Panel on Climate Change (IPCC, 2018) and the National Academies of Sciences, Engineering, and Medicine of the US (NASEM, 2018) in their latest reports have identified “carbon negative” technologies as playing a role in the CO₂ emissions reduction. Biorefinery production of succinic acid is a commercially mature carbon negative technology with several plants made operational in this decade (table 1).

Succinic acid, or 1,4-butanedioic acid, a four-carbon (C₄) dicarboxylic acid, i.e. HO₂C-CH₂-CH₂-CO₂H, typically derived from petroleum sources and utilised in the chemical, food, pharmaceutical and biodegradable polymer industries. Being one of the few platform chemicals whose bio production is competitive with that from petrochemicals (Mazière et al., 2017; Pinazo et al., 2015) it has attracted a significant amount of research in the last couple of decades. In fact, the US Department of Energy has identified succinic acid as one of the top bio-based chemicals (Werpy et al., 2004). Research in this area has focused on microbial species naturally capable of producing succinic acid such as *Actinobacillus succinogenes*, *Mannheimia succiniciproducens*, *Anaerobiospirillum succiniciproducens*, and on various strains of modified *Escherichia coli* and recombinant *Corynebacterium glutamicum* (Song & Lee 2006; Beauprez et al., 2010; McKinlay et al., 2007; Van-Heerden & Nicol 2013). Among the wild-type succinic acid producers, *Actinobacillus succinogenes*, isolated from bovine rumen, is known as one of the most efficient natural producers of the succinic acid with reported concentrations up to 145.2 g/L (Li et al., 2011a) and volumetric productivities higher than 10 g/L/h

(Maharaj et al., 2014). The other noteworthy characteristic of this species is their CO₂ utilisation during anaerobic succinic acid production, thereby turning the process carbon negative.

Two issues confront succinic acid biorefineries despite their commercial success. They are: i) underutilisation of biomass as microbes only consume glucose; and ii) generation of a large gypsum (calcium sulphate) waste stream during acid purification.

Bacterial species like *Actinobacillus succinogenes* are able to produce succinic acid from a broad range of carbon sources, such as arabinose, cellobiose, fructose, galactose, glucose, lactose, maltose, mannitol, mannose, sorbitol, sucrose, xylose or salicin under anaerobic conditions (Guettler et al., 1999). However, fermentative microorganisms are unable to assimilate different sugars simultaneously and preferentially consume glucose from a mixed sugar media. Only once the glucose is fully consumed, will the microorganisms consume other sugars such as xylose, a pentose sugar. This phenomenon is referred to as catabolite repression or diauxic growth and leads to inefficient fermentation. A suitable alternative is separation of the C5 and C6 sugars in two streams and carrying out separate fermentations thereby achieving efficient conversion of both sugars.

However, not all microbial species efficiently convert C5 sugars into products. Some acetic acid bacteria are known to digest C5 sugars at high efficiency, such as *Moorella thermoacetica*, previously known as *Clostridium thermoaceticum*. On exposure to a mixture of glucose and xylose, it preferentially consumes xylose over glucose (Andreesen et al., 1973; Balasubramanian et al., 2001; Ehsanipour et al., 2016). The other noteworthy characteristic is its CO₂ utilisation during acetic acid production. These features make it a worthwhile candidate for hemicellulose valorisation in a succinic acid biorefinery.

Acetic acid is mainly produced from petroleum precursors via the carbonylation of methanol, however, recently focus has shifted towards biological sources. Zechem's biorefinery (Verser & Eggeman, 2008) has been successfully producing it for over a decade, value-adding it to ethanol for

1 the market. As a platform chemical (C2) it has a myriad of applications in the chemical, food and
2 medical industries.

3 Gypsum is produced as a waste product in the succinic acid biorefinery during its purification. In this
4 process calcium succinate from the anaerobic digestion tank is passed through an ion-exchanger to
5 protonate it to succinic acid. Subsequently, the calcium loaded ion-exchange resin is regenerated by
6 sulphuric acid for reuse, resulting in the generation of calcium sulphate. It has value in some
7 agricultural and construction markets as a co-product, however, in some countries it would need to
8 be disposed-of, substantially increasing overall cost. Thus, alternative purification technologies such
9 as water-splitting bipolar membrane electrodialysis (BMED) are needed to avoid this waste.

10 In view of these available solutions, a techno-economic analysis is required to study their impact
11 over succinic acid production costs for a commercial scale biorefinery and fill the knowledge gap. A
12 literature search revealed scholarly articles on the techno-economic modelling of stand-alone
13 succinic acid (Efe et al., 2013; Lam et al., 2014; Li et al., 2011b; Pinazo et al., 2015) and acetic acid
14 (Sayar et al., 2018) biorefineries. Some techno-economic studies have also investigated succinic acid
15 as the coproduct of an ethanol biorefinery (Klein et al., 2017; Luo et al., 2010). To-date, however,
16 there has been no investigation of a succinic acid biorefinery coproducing acetic acid and dimethyl
17 ether (DME) using BMED in the purification process. It is important to investigate such integrative
18 biorefinery concepts as they minimise waste generation, promote cleaner production, displace fossil
19 fuels and help mitigate climate change.

20 The above factors have led to this investigation of a multiproduct succinic acid biorefinery concept
21 that can be replicated anywhere with an adequate biomass supply. The novelty of this biorefinery is
22 the innovative integration of commercial technologies for the production of succinic acid, acetic acid
23 and DME. A Latrobe Valley (Victoria, Australia) location was selected for our techno-economic
24 analysis. The Latrobe Valley has unique attributes with a large Forest Value Chain and an existing
25 relevant human resource. These provide the necessary resources for such an ambitious project

which in turn would allow its community to contribute towards mitigating climate change. With this perspective, the aim of this study is to develop a carbon negative biorefinery model that:

- Incorporates CO₂ into platform chemicals via anaerobic processes;
- Utilises all fractions of sugar in the biomass;
- Minimises waste generation;
- Fulfils all the parasitic energy demand from within the biorefinery; and
- Has technical and financial viability.

2. Materials and Methods

Two cases are modelled in this study. The first case produces succinic acid and used as Base Case. The second multiproduct model – Multi Case – produces acetic acid and DME in addition to succinic acid. The two biorefinery models allow for a better comparison of the proposed multiproduct model (Multi Case) with the single product model (Base Case).

2.1 Methodology

Technical simulation and costing methodologies are discussed here. Economic assessment methodology is explained in Section 3.2 alongside the analysis of the two models.

2.1.1 Technical Simulation Methodology

Simulations have been developed and carried out in gPROMS (General Process Modeling System) from Process Systems Enterprise Ltd. (gPROMS, 2018). gPROMS allows users to specify the model via process flow-sheeting and carryout mass-energy calculations. The physical properties of the components are obtained from its library. The simulation is done as zero-dimensional energy model. Simulation parameters are listed in the process description in the next section and all assumptions are duly noted.

2.1.2 Costing Methodology

Economic analysis is done in Australian dollars (AUD \$) for the 2018 year. Costing of the models was carried out using National Renewable Energy Laboratory's (NREL) reports (Davis et al., 2013; Humbird et al., 2011) and market prices. The equipment prices were from different years, thus they were indexed up to the year 2018. This indexing was based on the Producer Price Index of Australia (ABS, 2018). Increase in Producer Price for the "Metal Container Manufacturing", "Other Fabricated Metal Product Manufacturing", "Pump, Compressor, Heating and Ventilation Equipment Manufacturing", "Specialised Machinery and Equipment Manufacturing" and "Other Machinery and Equipment Manufacturing" were calculated as "Total" via the tool available at the Australian Bureau of Statistics website (ABS, 2018). The online database calculates all index numbers. From March 2009 to March 2018 the total percentage Increase in Producer Price Index was 10.75%.

Pulp log price was used for biomass feed. According to Australian Pine Log Price Index, maximum pulp log price in 2017 was \$23.51 per metric tonne (t) (KPMG, 2015). Typical, pulp log transport costs average at \$0.10/t/km. Based on this, an average biorefinery gate-price of \$50/t for the pulp log is used in the study. Results for feed and utilities consumption from the simulation are used for calculating costs based on market rates and tariffs. An average water cost of \$0.6/t is used based on industrial water rates ranging from \$0.4/t to \$0.8/t in Victoria (ESC, 2018).

2.2 Facility Process Description

The biorefinery model is divided into nine sections, described below. The Multi Case has all nine sections (figure 1), while the Base Case does not have the two acetic acid related sections, namely: Acetic Acid Digestion (A700) and Acetic Acid Purification (A800).

2.2.1 Feedstock Handling Area (A100)

Pulp logs are subjected to proper pretreatment conditions including cleaning and comminution in this section. Logs are stored in the open and transferred to the washing area. Washed logs are then

reduced to 1 mm size. Comminution allows for size reduction which increases the efficiency of infiltration of the chemical reagents used in the subsequent processes.

2.2.2 Fractionation Area (A200)

Biomass from comminution is transferred to screw extruder for fractionation. It is a four-stepped process (Humbird et al., 2011). First, in a pre-steamer the solids enter at 30% weight (wt.) concentration and the temperature is kept above 100 °C for 10 minutes. Next, the slurry enters the screw extruder and the temperature is raised to just under 160 °C for five minutes. 18 kg of sulphuric acid per 1,000 kg of biomass is added. In the third step 4.1 kg of sulphuric acid per 1,000 kg of biomass is added and the temperature is kept at 130 °C for 30 minutes. In the final step biomass concentration is lowered to 20% (wt.) and the temperature is lowered to 75 °C for another 30 minutes. Ammonia gas is added, raising the pH to 5. Slurry is then flash-cooled, vaporising 10% (wt.) of water. The flash vapour is condensed and sent to Water Treatment (A600). The extruded biomass is cooled in the wash tank and centrifuged into separate solid and liquid streams. Solid stream (30% moisture) comprising cellulose, lignin, mineral/inorganics and 10% of the hemicellulose is transferred to Succinic Acid Digestion (A300). Liquid stream containing 90% of the hemicellulose is sent to Water Treatment (A600) in Base Case or to Acetic Acid Digestion (A700) in MultiCase.

2.2.3 Succinic Acid Digestion Area (A300)

Separated cellulose, ash and lignin enter one of the hydrolysis tanks at 10:90 cellulose to water ratio (wt.). Hydrolysis is conducted in a batch system of five vessels. Synergetic actions of three cellulose enzymes, namely: endo-b-glucanase, exo-b-glucanase and b-glucosidase are used, working together to convert cellulose into glucose monomer ($(C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6$). Cellulase loading is 20 kg enzyme protein per 1,000 kg cellulose to achieve over 90% conversion rate. Temperature is kept at 48 °C with a residence time of 48 hours. At the end, glucose with the rest of the slurry is batched to one of the five anaerobic digesters.

Actinobacillus succinogenes are used for glucose's conversion to succinic acid ($7C_6H_{12}O_6 + 6CO_2 \rightarrow 12C_4H_6O_4 + 6H_2O$). This bacterial species is capnophilic (CO_2 loving) and requires a CO_2 feed into the anaerobic digester. Di-Ammonium Phosphate (DAP) is added as a nutrient at a rate of 7.65 kg per 1,000 kg glucose. Ammonium hydroxide is fed to the digester as a pH buffer. Temperature is controlled at 37 °C at which optimum growth of *Actinobacillus succinogenes* occurs (Pateraki et al., 2016). Residence time is kept at 36 hours.

As anaerobic digestion is conducted around neutral pH (i.e. pH=7.0), the product is largely a succinate salt $C_2H_4(CO_2H)_2 + 2NH_4OH \rightarrow C_2H_4(CO_2^-NH_4^+)_2 + 2H_2O$. The overall conversion rate from cellulose to ammonium succinate is 80%. Broth exiting the digester contains salts of succinic acid, colouring matter, metabolic by-products, bacterial cell and cell materials, heavy metals, and other inorganic materials. Disk stack centrifuge is used to separate out solids and liquids. The insoluble stream (30 wt. % moisture) containing nearly all the lignin, undigested biomass, microbial biomass, other solid contaminants and a small percentage of ammonium succinate is sent to the boiler (A500). The liquid stream is sent to purification (A400).

2.2.4 Succinic Acid Purification Area (A400)

The crude ammonium succinate stream is micro-filtered to remove residual solids. Next, this liquid stream passes through an electrodialyser (ED) and then through BMED (Glassner & Datta, 1992; Zeikus et al., 1999). ED is able to purify and concentrate ammonium succinate 3 to 4 folds in the aqueous stream (Glassner & Datta, 1992). In this study, 4-fold concentration is assumed. This stream then passes through the BMED unit that produces a nearly cation free succinic acid stream and an ammonium hydroxide stream, for recycle to the digester (Glassner & Datta, 1992).

The aqueous succinic acid stream from the BMED is passed through an ultrafiltration membrane to further remove any impurities. This stream is then treated with cation and anion exchangers, further purifying the succinic acid including the removal of any nitrogenous impurities (proteins and amino acids). This clean stream then goes through an evaporator and finally a drier. The result is a high

1 purity succinic acid product comprising 99.5% succinic acid and 0.5% water. On dry basis, less than
2 1% nitrogenous impurities and less than 10 ppm of contaminating ions are left in this stream.

3 **2.2.5 Turbogenerator Area (A500)**

4 Solids (at 30% moisture) from Succinic Acid Digestion (A300) and Acetic Acid Digestion (A700) enter
5 the boiler in the Multi Case simulation. In Base Case; only solids from A300 are sent to the boiler as
6 there are no acetic acid areas. The system produces 239 t/h of steam at 454 °C and 61 atm. Boiler
7 efficiency, defined as the percentage of the feed heating value that is converted to steam heat, is
8 ~80%. Steam from the boiler is sent to the turbogenerator with a multistage turbine with two
9 extraction ports and a final condenser (Davis et al., 2013; Humbird et al., 2011). Of the superheated
10 steam leaving the boiler, 12% is extracted from the turbine at 13 atm. and 268 °C for feeding the
11 fractionation reactor and the boiler feed water economiser. An additional 2.5% is extracted at 9.5
12 atm. and 164 °C for the succinic acid drier. The rest of the steam is condensed at 0.1 atm. and
13 pumped back to the boiler. The generator produces a total of 53.1 MW of power. Makeup water
14 demand of this area is 0.91 t/t of steam generated. This is the only area of the biorefinery that
15 consumes utility water.

16 **2.2.6 Water Treatment Area (A600)**

17 All the wastewaters generated in the biorefinery are combined enroute to the wastewater
18 treatment system. This includes condensed fractionation flash vapour, boiler blowdown, cooling
19 tower blowdown, and the liquid streams from anaerobic digestion. The water treatment differs in
20 both cases. In Base Case - the Water Treatment Area consists of anaerobic digestion, aerobic lagoon,
21 membrane filtration, reverse osmosis, evaporation, dewatering, and gravity belt thickening based on
22 NREL's proposed wastewater treatment system (Davis et al., 2013). In the anaerobic digester, 91% of
23 its carbon burden is assumed either mineralised or converted to methane; i.e. 86% is converted to
24 biogas, which is sent to the Solid Oxide Fuel Cell (SOFC) Area (A900). Liquid slurry from the anaerobic
25 digester is sent to aerobic activated-sludge lagoons with floating aerators where 96% of the

remaining soluble organic matter is removed. Ammonium ions pass through to the aerobic lagoons where they are converted to nitrate by nitrifying bacteria, consequently lowering the pH by forming nitric acid. Sodium hydroxide is added to the lagoons for neutralisation. The fully digested material stream passes through micro and ultra-filtration to remove remaining particles. The treated water finally passes through reverse osmosis. Reverse osmosis removes dissolved salts and the water is recycled.

In Multi Case - the combined wastewater stream passes through reverse osmosis only. In both cases, the simulations assume near full water recovery, suitable for reuse.

2.2.7 Acetic Acid Digestion Area (A700)

In Multi Case, liquid stream from the Fractionation Area (A200) containing mostly hemicellulose at 6.7% concentration (wt.) enters one of the four hydrolysis tanks. α -L-arabinofuranosidase and α -glucuronidase are used for arabinose and glucuronic acids respectively while the xylose backbone is hydrolysed using endo- β -1,4-xylanase and β -xylosidase ($(C_5H_8O_4)_n + nH_2O \rightarrow nC_5H_{10}O_5$). Enzyme loading is 20 kg per 1,000 kg hemicellulose. After 48 hours the slurry is batched to one of the four anaerobic digesters. *Moorella thermoacetica* converts monosaccharides to acetic acid ($2C_5H_{10}O_5 + H_2O \rightarrow 5CH_3CO_2H + H_2O$). CO_2 is added to the digester to achieve the desired yield of 90+% conversion of the sugars. DAP is added at a rate of 7.65 kg per 1,000 kg hemicellulose. Anaerobic digestion is conducted at pH 7 and maintained at 58 °C for 72 hours (Balasubramanian et al., 2001; Barker & Kamen, 1945; Ehsanipour et al., 2016). Ammonium hydroxide is added to achieve neutralisation. Subsequently, nearly all of the acetic acid is generated as ammonium acetate ($CH_3CO_2H + NH_4OH \rightarrow CH_3CO_2NH_4 + H_2O$).

Broth exiting the digester contains ammonium acetate, colouring matter, metabolic by-products, bacterial cell and cell materials, heavy metals and other inorganic materials. Disk stack centrifugation is used to separate out solids and liquids. The insoluble solid (30 wt.% moisture)

stream contains the majority of solids and a small percentage of ammonium acetate. It is sent to the boiler (A500), while the liquid stream is sent for purification (A800).

2.2.8 Acetic Acid Purification Area (A800)

The liquid stream from Acetic Acid Digestion (A700) containing nearly all of the ammonium acetate goes through a micro-filter which helps remove the leftover solids. Next, this aqueous stream passes through an ED, enabling 4-folds concentration of ammonium acetate. This stream then passes through the BMED that produces a nearly cation free acetic acid stream and an ammonium hydroxide stream, for recycle to the digester.

The aqueous acetic acid stream from the BMED is passed through ultrafiltration to remove the remaining impurities. This stream is further treated with ion exchange to remove the charged ions.

The clean aqueous acetic acid stream is sent to the first reactive distillation column. Here, aqueous acetic acid is reacted with methanol (methylation) in a reactive distillation process ($\text{CH}_3\text{CO}_2\text{H} + \text{CH}_3\text{OH} \rightarrow \text{CH}_3\text{CO}_2\text{CH}_3 + \text{H}_2\text{O}$) generating methyl acetate and water. The reaction is carried out at a temperature of 85 °C and a pressure of 5 atm. (Tong et al., 2013; Tong et al., 2014). Methyl acetate is distilled out and in the next column it reacts with methanol to produce DME and acetic acid ($\text{CH}_3\text{CO}_2\text{CH}_3 + \text{CH}_3\text{OH} \rightarrow \text{CH}_3\text{OCH}_3 + \text{CH}_3\text{CO}_2\text{H}$). Reaction parameters are 120 °C of temperature and 5 atm. of pressure (Akkaravathasinp et al., 2015; Hoyme & Holcomb, 2003; Prapainainar et al., 2014). In both columns the conversion rate is 90%. DME is distilled out and sent to the SOFC while the separated acetic acid is stored for sale.

2.2.9 SOFC Area (A900)

In Multi Case - DME is used to generate electricity in the SOFC. Waste heat is used to heat steam for the distillation processes. In the Base Case - methane from Water Treatment Area (A600) is used to generate electricity. CO_2 exiting the SOFC is used to fulfil the anaerobic digestion CO_2 demands.

3. Results and Discussion

2,000 metric tonnes per day (t/d) of local pulp log (dry weight) trees are used as biomass feedstock comprising cellulose (37.47%), hemicellulose (23.83%), lignin (30.03%) and minerals/others (8.67%). This composition is an average of the values given in the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) studies (Dekker, 1987; Dekker et al., 1987) and has been used (Ghayur & Verheyen, 2018) to represent the Victorian feedstock.

The two cases are simulated based on the parameters listed in the previous section. Results are presented in the following table (2) and individual stream data for Multi Case is provided in the figure (1). Figure (1) is a simplified flow sheet for the Multi Case, showing only the essential equipment without pumps and other auxiliary parts and the Water Treatment Area.

3.1 Technical Simulation Results

In the Base Case, the hemicellulose stream from fractionation (A200) is sent to the Water Treatment Area (A600) instead of the Acetic Acid Digestion Area (A700) as discussed earlier. This change has an impact on the total energy requirements of the two models and their coproducts (table 2). Other than the coproducts listed in the table (2) both cases also produce ash at a rate of 4.5 t/h.

Base Case produces 5.38 t/h of methane and 14.27 t/h of CO₂ as biogas. Of this 2.61 t/h of methane is consumed to generate 14.9 MWh of electricity via SOFC, leaving behind 2.77 t/h. Multi Case has higher electricity demand due to the addition of Acetic Acid Purification Area (A800). While it produces 10.05 t/h of DME, 9.94 t/h is consumed to generate 36.9 MWh of electricity via the SOFC, leaving behind 0.11 t/h. In both cases an additional 53.1 MW of electricity is generated via the turbogenerator.

Succinic acid purification consumes the most power in both cases at 48.5 MW. In Multi Case, Acetic Acid Purification is the second largest consumer of power at 27.8 MW (figure 2). Water Treatment has higher power consumption in Base Case at 7.38 MW due to the requirements of the anaerobic digester and the aerobic lagoon (figure 3), which are missing in Multi Case.

The succinic and acetic acid production rates modelled in this study are based on typical values. Due to their commercial status, it is reasonable to assume that these may rise in future as technologies get more efficient. Despite this, an investigation into the variation of production rates was carried out. A combined impact of $\pm 10\%$ efficiency variation on the conversion and purification processes was simulated with results provided in figure (4). Results show succinic acid production varying between 22.84 t/h and 34.18t/h while acetic acid rates varying between 11.77t/h and 17.98 t/h (figure 4).

3.2 Economic Assessment

All the areas in the biorefinery process are considered Inside Battery Limits (ISBL) for both cases. This puts the Installed Equipment Cost of Base Case at \$288,249,717 (figure 5) and Multi Case at \$343,956,973 (figure 6). The Total Direct Cost (TDC) of Base Case is \$345,899,660 and Multi Case is \$412,748,367 (table 3).

Total Indirect Costs (TIC) are taken as 40% of the TDC, accounting for Prorateable Expenses (10% of TDC), Field Expenses (10% of TDC), Contractor's Fee (10% of TDC) and Contingency (10% of TDC).

Owner's Cost is calculated as including Working Capital and Commissioning Costs thus bringing the Total Capital Expenditure (CAPEX) of Base Case to \$532,685,476 and Multi Case to \$635,632,485 (table 4).

The biorefinery is assumed to operate for 90% of the year, a typical uptime used in biorefinery modelling (Davis et al., 2013). Thus the variable operating expenditure was calculated for 90% load factor equalling 328 working days per year (table 5). Rest of the days the biorefinery is shut for scheduled cleaning and maintenance. The cleaning process includes sanitisation, disinfection and reduction of the amount of soil to an acceptable level. Soil is any unwanted material left on a surface that needs to be cleaned and can be composed of sugars, salts, fats, proteins, microbes, scales and other mineral components (Larson & Power, 2003). Cleaning ensures smooth operations of the biorefinery for the next year.

Fixed operating costs will be incurred in full whether or not the plant is producing at full capacity. These are calculated for labour and overhead items. The total number of employees for both cases is 50 and their salaries come to \$4,680,000. These are based on 12-hours shifts. The total number of employees along with their associated positions and salaries are provided in the table (6). With a 90% labour burden, other overheads as 3% of ISBL and property insurance as 0.7% of ISBL the Fixed Operating Costs of Base Case and Multi Case amount to \$20,929,309 and \$23,255,643 respectively. The total Operating Expenditure (OPEX) of the two cases are provided in the following table (7). CAPEX and OPEX are used to populate the table (8) for calculating Minimum Selling Price (MSP) of succinic acid. MSP is calculated using the data in table (8) by iterating the selling cost of succinic acid until the net present value of the project reaches zero. The two additional factors included in MSP calculations are plant depreciation costs and coproduct sales. Plant depreciation cost is carried out using a previously published methodology (Humbird et al., 2011). Methane sale price is taken as \$750/t while DME is taken as \$430/t based on their lower heating values. Acetic acid price is taken 55% higher than methanol, at \$930/t. MSP for succinic acid is nearly the same in both cases. In Base Case it is \$926.79/t while in Multi Case it is \$990.15/t with a difference of only 6.4%. This requires some criteria for the selection of the superior model. As Multi Case displaces a significant quantity of fossil fuel derived acetic acid (115,797 t/a), it presents itself as the superior option to help mitigate climate change. Additionally, acetic acid can be value-added into a portfolio of green products in the local economy, creating valuable jobs in the process. The Latrobe Valley currently has high unemployment at 8.9% (DJSB, 2018) making this approach more attractive. As acetic acid purification process consumes 135,792 t/a of methanol, the biorefinery's green credentials can be increased by using CO₂ hydrogenated methanol. This hydrogenation process would consume 135,792 t/a of CO₂ and 25,628 t/a of H₂. Such a strategy opens the opportunity for an industrial symbiosis between the biorefinery and the existing CO₂ producing and future's H₂ producing industries of the region. Such symbiosis has already been

1 proposed for the Latrobe Valley (Ghayur & Verheyen, 2018). Another option is the utilisation of
2 turbogenerator flue gas CO₂ for renewable methanol generation. The turbogenerator produces
3 nearly 0.577 million t/a of CO₂.

4 DME is suited as an energy storage vector in the Latrobe Valley, helping to stabilise the grid as the
5 country transitions to renewable resources. Biofuels have already been proposed as ideally suited
6 for peak and backup power (Ghayan, 2018a; Ghayur, 2019; Ghayur & Verheyen, 2017) for a
7 renewable energy grid. Multi Case produces 866 t/a of DME, enough to generate nearly 3.1 GWh
8 electricity via SOFC.

9 A sensitivity analysis of the Multi Case has been carried out as well. Holding all other process
10 variables constant, the value of the variable in question was changed by a percentage and the
11 change in the unit cost of succinic acid was determined. The variation of MSP with percentage
12 change of different factors is provided in the figure (7). Succinic acid MSP increases to \$991.84/t in
13 the absence of DME sales and increases to \$1476.95/t in the absence of sale of both coproducts. The
14 sensitivity analysis shows doubling of the CAPEX leads to 67% increase in the MSP to \$1651.76/t.
15 Succinic acid's market price typically ranges between three to four times the price of acetic acid. Its
16 current market price is around \$2,500/t.

17 An uncertainty analysis has been carried out to evaluate the impact of stochastic variations between
18 multiple costs and revenues on the calculated MSP. All revenue prices and feedstock costs including
19 discount cash flow rate are used as the key parameters. The Monte-Carlo simulation in this study is
20 constructed based on the feedstock and revenue parameter values with -50% and +100% limits
21 while ± 5 limit is used for the discount cash flow rate. The resulting MSP has an average of \$1067/t
22 with a standard deviation of 32. It has a 50% probability of MSP being less than \$1067/t. The
23 probability distribution of the MSP based on variations in the costs and revenues is shown in figure
24 (8).

Succinic acid biorefinery's capacity to sequester CO₂ is another notable characteristic. If succinic acid is incorporated into construction materials such as building cladding, false ceilings and insulation panels, CO₂ can be sequestered for a period of decades. If recycling processes for these building materials are developed, this CO₂ could then potentially be locked in a continuous cycle (Ghayan, 2018b).

Succinic acid's other application as a precursor for biodegradable plastics opens the avenue for locking-in CO₂ in easily recyclable plastics. This has the additional benefit of replacing single-use plastics and reducing environmental pollution.

4. Conclusions

In this study techno-economic analyses of two succinic acid biorefinery concepts were carried out. In Base Case succinic acid and methane, and in Multi Case succinic acid, acetic acid and DME are produced. For both models the succinic acid MSP is nearly the same at \$927/t for the Base Case and \$990/t for the Multi Case. In terms of climate change mitigation potential, the Multi Case has an advantage, as its acetic acid production displaces fossil fuel derived product and DME is useful for power generation.

Results of this research provide sufficient data to conclude that a multiproduct succinic acid biorefinery is technically and economically viable, it has carbon negative potential and a capacity for regional economic activity generation. Succinic acid's application as a feedstock for biodegradable plastics paves the way for the transition to a circular economy.

The next cogent step is working towards a pilot manufacturing plant to de-risk the novel synergies required for such an approach. Another future area in this research is studying the economic impact of such a bio-refining industrial infrastructure on a regional economy. These would require concerted efforts of researchers, businesses and the government, nonetheless, once the efforts

come to fruition, the project would generate jobs and revenue at local level, provide for a large quantity of backup power at national level and help reduce CO₂ emissions at global level.

Acknowledgements

This work was supported by the financial assistance of Brown Coal Innovation Australia Limited, a private member-based company with funding contracts through Australian National Low Emissions Coal Research and Development Ltd (ANLEC R&D) and the Victorian State Government; and by an Australian Government Research Training Program (RTP) Stipend and RTP Fee-Offset Scholarship through Federation University Australia.

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Table 1: Succinic Acid Biorefineries in the World

Corporation	Succinic Acid (t/a)	Location
PTT MCC Biochem	20,000	Thailand
BioAmber	30,000	Sarnia, Ontario
BioAmber, ARD	17,000	Pomacle, France
Reverdia	10,000	Cassano, Spinola, Italy
Succinity	10,000	Montmélo, Spain
Myriant	13,600	Lake Providence, Louisiana

Table 2: Hourly Consumption and Production Rates

	Base Case	Multi Case
<i>Products</i>		
Succinic Acid	28.2 t	28.2 t
Acetic Acid	-	14.71 t
Dimethyl Ether	-	0.11 t
Methane	2.77 t	-
Electricity	68 MW	90 MW
<i>Feedstock</i>		
Biomass	83.33 t	83.33 t
Water	217 t	217 t
Electricity	67.98 MW	89.27 MW
CO ₂	5.25 t	5.35 t
Methanol	-	17.25 t

Table 3: Total Direct Costs (\$)

Area	Base Case	Multi Case
Feedstock Handling	21,165,168	21,165,168
Fractionation	41,109,672	41,109,672
Succinic Acid Digestion	23,482,362	23,482,362
Succinic Acid Purification	42,797,558	42,797,558
Acetic Acid Digestion	-	20,022,335
Acetic Acid Purification	-	34,126,165
Turbogenerator	74,644,946	74,644,946
Solid Oxide Fuel Cell (SOFC)	26,250,000	64,750,000
Water treatment	51,654,964	14,713,720
Clean in Place	7,145,047	7,145,047
Warehouse & Office (5% of ISBL)	14,412,486	17,197,848
Site Development & Land (10% of ISBL)	28,824,971	34,395,698
Additional Piping (5% of ISBL)	14,412,486	17,197,848
Total Direct Costs (TDC)	345,899,660	412,748,367

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Table 4: Total Capital Expenditure (CAPEX)

	Base Case (\$)	Multi Case (\$)
Total Direct Costs (TDC)	345,899,660	412,748,367
Total Indirect Costs (TIC)	138,359,864	165,099,347
Owner's Cost (10% of TDC+TIC)	48,425,952	57,784,771
Total Capital Expenditure (CAPEX)	532,685,476	635,632,485

Table 5: Annual Variable Operating Expenditure

Feed	t/h	t/a	\$/t	Base Case (\$)	Multi Case (\$)
Pulp log	83.33	656,000	50	32,800,000	32,800,000
Sulphuric Acid	1.5	11,808	135	1,594,016	1,594,016
Ammonia	1.05	8,265	400	3,306,240	3,306,240
Cellulose Enzymes	0.624	4,915	4,250	20,889,926	20,889,926
Hemicellulose Enzyme	0.36	2,834	4,250	-	12,044,160
Methanol	17.25	135,792	600	-	81,475,200
DAP	0.38	2,991	580	1,095,782*	1,734,988
Water	217	1,708,224	0.6	1,024,934	1,024,934
CaOH	0.19	1,496	950	1,420,896	1,420,896
NaOH	2.25	17,712	850	15,055,200	-
Total				77,186,994	156,290,360

* In Base Case DAP consumption is 0.24 t/h

Table 6: Employees and Associated Salaries

	Position Salary	Positions	Total Salaries
Plant Manager	200,000	1	200,000
Plant Engineer	150,000	2	300,000
Maintenance Supervisor	100,000	1	100,000
Maintenance Technician	80,000	12	960,000
Lab Manager	100,000	1	100,000
Lab Technician	80,000	2	160,000
Shift Supervisor	120,000	4	480,000
Shift Operator	100,000	20	200,0000
Yard Employee	50,000	4	200,000
Clerk and Secretary	60,000	3	180,000
Total		50	4,680,000

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Table 7: Total Annual Operating Expenditure (OPEX)

	Base Case (\$)	Multi Case (\$)
Fixed OPEX	20,929,309	23,255,643
Variable OPEX	77,186,994	156,290,360
Total OPEX	98,116,303	179,546,003

Table 8: Minimum Selling Price (MSP) for Succinic Acid

	Base Case	Multi Case
CAPEX (\$)	532,685,476	635,632,485
OPEX (\$)	98,116,303	179,546,003
Construction Year 1	40%	40%
Construction Year 2	60%	60%
Load Factor Year 1	70%	50%
Load Factor Year 2	90%	90%
Load Factor Rest of Plant Life	90%	90%
Plant Life Years	30	30
Tax Rate on Taxable Income	30%	30%
Discount Cash Flow Rate	10%	10%
Minimum Selling Price (\$/t)	926.79	990.15

Figure 1: Multi Case Process and Stream Flows

Figure 2: Multi Case Electricity Demand (89.27 MW)

Figure 3: Base Case Electricity Demand (67.98 MW)

Figure 4: Impact of $\pm 10\%$ Variation on Production Rate

Figure 5: Base Case Installed Equipment Cost (\$288,249,717)

Figure 6: Multi Case Installed Equipment Cost (\$343,956,973)

Figure 7: Multi Case Sensitivity Analysis for Succinic Acid MSP (\$/t)

Figure 8: MSP Probabilities based on Uncertain Costs and Revenues