An Integrated CO_2 Production and CO_2-NH_3 Cascade Refrigeration System

Project code:	**2016.1038**
Prepared by:	**Cold Logic Pty Ltd**
Date Submitted:	**24/03/2016**
Date Published:	
Published by:	

Research Organisation

Name	Cold Logic Pty Ltd
ABN	63 087 198 249
Street Address	24 Francis Street
	Port Adelaide SA 5015
	Australia
Postal Address	PO Box 74
	Port Adelaide SA 5015
	Australia
Telephone	+61 (08) 8240 3333

Project Leader / Nominated Person:

Name	Michael Riese
E-mail	Michael.Riese@coldlogic.com.au

Report Author:	Adam Pattingale
Reviewer:	Michael Riese

Executive Summary

Liquefied carbon dioxide (CO_2) is used on a daily basis in the red-meat industry to produce dry ice snow for product cooling applications. Traditionally, it has been cost prohibitive for abattoirs to invest in their own CO_2 liquefaction equipment; consequently, it is procured from specialist providers at a significant cost. Liquefied CO_2 can also be used in a cascade refrigeration system with ammonia (NH_3), substituting two-stage NH_3 refrigeration systems more commonly seen throughout Australian abattoirs. As a result, CO_2 refrigeration and liquefaction systems have the potential to be combined, decreasing operational expenses for abattoir operators.

This report has focused on the technical feasibility of combining a closed-loop CO_2-NH_3 cascade refrigeration system with an open-loop CO_2 liquefaction system, along with the financial feasibility of integrating a CO_2 liquefaction system into an existing abattoir. Investigations into these areas were undertaken to outline potential cost reductions for red-meat processors through reducing production/consumable costs, the return on investment for new refrigeration equipment and allowing processors to evaluate additional options for operational cost reductions.

The originally proposed design regarding the integrated closed-loop CO_2-NH_3 cascade refrigeration system and open-loop CO_2 liquefaction system was deemed to be uneconomical. This was a result of a technical feasibility study raising concerns due to contamination between the CO_2 refrigeration and liquefaction systems, along with an oversized plate heat exchanger being used to condense liquefied CO_2. Consequently, an amended system design was developed to address technical concerns. The technical feasibility study also established flue gas from existing steam boilers provide a rich source of CO_2 that can be captured and purified using a stack gas recovery system.

The financial feasibility of integrating the stack gas recovery system to an existing abattoir was investigated using a financial feasibility model. The model incorporated expected costs associated with capital and operational expenditure, along with cost reductions when integrating the stack gas recovery system. Cost reductions were expected to come through substituting currently procured CO_2 with CO_2 captured by the stack gas recovery system, substituting water-based ice cooling applications with dry ice, substituting current cleaning methods with dry ice blasting and selling excess CO_2 captured by the stack gas recovery system back to market. Expected costs were evaluated using standard commercial values and values found through private correspondence

with an existing abattoir, to form baseline values for each variable used in the model. Private correspondence with the abattoir also led to the discovery of excess biogas being produced during regular abattoir operations. As a result, the model also includes approaches to utilise excess biogas as a fuel source for an alternative form of power generation or as a substitute for natural gas currently used in existing steam boilers.

A financial feasibility study was undertaken to investigate the project's payback period when employing different operating scenarios and when changing particular input variables relating to capital expenditure, operational expenditure and cost reductions to ±10% and extreme realistic cases of their baseline value. A sensitivity analysis of the main input variables used in the financial feasibility model was also undertaken to determine which variables would have the largest influence upon the project's payback period when changed from their baseline value by ±1%.

It was determine that operating the SGRS at maximum capacity, solely to substitute currently procured CO_2, provides the lowest payback period for all possible operating scenarios. However, if demand of currently procured CO_2 does not meet the CO_2 capture capacity of the SGRS, excess CO_2 captured can be sold to market to achieve the same payback period. As these operating scenarios are heavily reliant on the market price of liquefied CO_2, a thorough market analysis into liquefied CO_2 must be undertaken to prove their financial feasibility.

Notably, the feasibility of operating the stack gas recovery system at maximum capacity, solely to meet currently procured CO_2 demand or selling excess CO_2, is pivotal when determining the financial feasibility of implementing a CO_2 liquefaction system to an existing abattoir. Additional uses of liquefied CO_2 captured by the stack gas recovery system have not been deemed economical as yet. However, should be investigated on a case-by-case basis, as they have they have the potential to provide significant cost reductions depending on abattoir operations.

Table of Contents

Nomenclature

AUD	Australian dollar
CAPEX	capital expenditure
CO_2	carbon dioxide
COP	coefficient of performance
EURO	European dollar
FFM	financial feasibility model
FFS	financial feasibility study
NH_3	ammonia
NO_x	nitrogen oxides
OPEX	operational expenditure
PHE	plate heat exchanger
SGRS	stack gas recovery system
SO_x	sulphur oxides
WBI	water-based ice

1.0   Introduction

1.1   Project Background

Liquefied carbon dioxide (CO_2) is used on a daily basis in the red-meat industry to produce dry ice snow for product cooling applications. Traditionally, it has been cost prohibitive for abattoirs to invest in their own CO_2 liquefaction equipment; subsequently, liquefied CO_2 is procured from specialist providers at a significant cost. Liquefied CO_2 also has the potential to be used in a cascade refrigeration system with ammonia (NH_3), substituting two-stage NH_3 refrigeration systems more commonly seen throughout Australian abattoirs.

Over the past five years, there has been a significant uptake in CO_2 as a natural refrigerant for low temperatures, often in a cascade system with NH_3 (Shecco 2015). Major installations exist in North America and Europe (Shecco 2015), with only a handful of applications in Australia (CCN 2012). An advantage of CO_2 refrigeration is that it can achieve multi-stage low temperatures at positive charge pressure. Refrigeration equipment is often only run at full capacity during certain parts of the 24-hour day cycle, with particular equipment idle for the remainder as a result of reduced loading.

This project initially aimed to investigate the technical feasibility of combining a closed-loop CO_2-NH_3 cascade refrigeration system with an open-loop CO_2 liquefaction system. CO_2 refrigeration and liquefaction systems were proposed to be co-located on-site; however, investigations into this process deemed the proposal to be uneconomical. Contamination risks between the CO_2 streams of the refrigeration and liquefaction systems, prompted the need for further purification measures. Technical concerns raised led to an amended system design that integrates CO_2 liquefaction and refrigerant systems with an NH_3 refrigerant system through separate plate heat exchangers (PHE), utilising the existing refrigeration capacity at a typical abattoir.

The financial feasibility of integrating a CO_2 liquefaction system was undertaken rather than investigating the financial feasibility of integrating the CO_2 refrigeration and liquefaction systems. As a result, a successful outcome of the project would potentially result in significant cost reductions for abattoir operators.

1.2   Project Objectives

The project objectives have been updated throughout the project's progress as a result of key findings during the technical feasibility study. The original project objectives are stated as follows:

- Investigate the technical feasibility of integrating a closed-loop CO_2-NH_3 refrigeration system together with an open-loop CO_2 liquefaction system co-located on-site, in close proximity.
- Provide red-meat processors with a financial feasibility study outlining potential cost reductions for abattoir operators through reducing production/consumable costs, the return on investment for new refrigeration equipment and allowing processors to evaluate additional new options for operational cost reductions.

The original objectives were revised after investigations into the technical feasibility of integrating a closed-loop refrigeration system with an open-loop CO_2 liquefaction system proved this option to be uneconomical. The newly revised project objectives are:

- Develop a concept design of the amended system that removes the technical and financial concerns of the originally proposed system.
- Develop a financial feasibility model (FFM) capable of assessing all variables associated with capital expenditure (CAPEX), operational expenditure (OPEX) and cost reductions expected with the integration of an open-loop CO_2 liquefaction system to a typical abattoir.
- Determine key variables of the FFM using a thorough sensitivity analysis.
- Provide red-meat processors with a financial feasibility study (FFS) outlining potential cost reductions available when integrating an open-loop CO_2 liquefaction system capable of producing food-grade CO_2 to a typical abattoir.

1.3   Limitations of the Project

Research undertaken during the project was restricted by a number of factors relating to technical and financial issues. Research limitations were as follows:

- CAPEX for all major equipment was based upon private correspondence with an abattoir having a capacity of 5,000 cattle and 52,000 lamb/mutton per week. However, CAPEX values are subject to change depending on a case-by-case basis. CAPEX variables including equipment installation and additional equipment may vary depending upon the abattoir's layout and must be investigated.

- Using dry ice to cool red-meat product has the potential to provide a large cost reduction to Australian abattoirs. A literature review showed there has been minimal research into the physical effects on product quality when using dry ice as cooling media. As a result, dry ice may not be able to be used in this particular method, prompting the need for further research into this topic.

- Dry ice blasting has the potential to replace current cleaning methods used at any abattoir. Dry ice is currently used in the food industry, however, little information regarding its application at an abattoir was found during a review of relevant literature. Further research into this field is needed to ensure it is a practical option.

- A stack gas recovery system (SGRS) has been proposed as the system used to capture CO_2 from steam boiler flue gas. An alternative form of power generation has also been proposed as a use of excess biogas currently produced by the abattoir. These systems are dependent on safe operating levels of nitrogen oxides (NO_x) and sulphur oxides (SO_x) in flue gas and biogas; otherwise, further purification systems are needed. Capital and operation expenses of the SGRS and alternative form of power generation have not included purification systems. As a result, NO_x and SO_x levels must be further investigated prior to making decisions regarding the implementation of the proposed systems.

- The project assumes there is enough available biogas produced by the abattoir to fuel an alternative form of power generation or existing steam boilers. Biogas availability will be dependent upon abattoir operations and should be investigated on a case-by-case basis.

1.4   Scope of the Report

The scope of this project covers investigations into the technical and financial feasibility of integrating a closed-loop CO_2-NH_3 refrigeration system with an open-loop CO_2 liquefaction system. A concept design of a proposed integrated system will be completed, along with a thorough financial feasibility study to determine if the design will be an economical solution for abattoir operators. Information gathered during the completion of the project is aimed to supply red-meat processors with sufficient information outlining: cost reductions through reduced production/consumables cost, the return on investment for new refrigeration equipment and allowing processors to evaluate additional new options for operational cost reductions.

2.0   Methodology

The project methodology has been divided in three main categories including the technical feasibility study, financial feasibility model development and financial feasibility study.

2.1   Technical Feasibility Study

The technical feasibility study was undertaken during early stages of the project to assess the technical feasibility of integrating a closed-loop CO_2-NH_3 cascade refrigeration system with an open-loop CO_2 liquefaction system.

2.1.1   Detailed Description of the CO_2-NH_3 Cascade Refrigeration System

Figure 2.1 shows the layout of the CO_2-NH_3 cascade refrigeration system. The system includes the high temperature NH_3 loop as the working fluid and the low temperature CO_2 loop as the working media. The two loops interact through the PHE, where the NH_3 evaporator absorbs heat from the CO_2 condenser.

In the high temperature loop, NH_3 typically evaporates at -18°C and 104 kPa (g) in the evaporator, to provide the required refrigeration capacity to the CO_2 condenser (Point 10 to 6). The NH_3 vapour is then compressed to 1246 kPa gauge pressure (Point 6 to 7) and condensed at 35°C (Point 8 to 9). The liquefied NH_3 is then expanded to 104 kPa again (Point 9 to 10) to be evaporated.

CO_2 is used as the refrigerant in the low temperature loop and evaporates at -40°C and 903 kPa (Point 5 to 1). Vaporized CO_2 is compressed (Point 1 to 2) from 2300 to 4158 kPa and then condensed at -13 to 7.7°C (Point 3 to 4), depending on the optimised mean temperature of the evaporator-condenser. The condensed CO_2 is then expanded (Point 4 to 5) before it is pumped to the evaporator. A liquid-vapour separator (also referred to as surge drum) is typically installed for the CO_2 loop (Toogood 2012; Danfoss 2014) to allow gas to separate out of the liquid, prior to passing through the compressor, along with allowing the expanded liquid to separate with the gas prior to being pumped to the evaporator. The surge drum works as a buffer to absorb surges in the evaporator that may occur due to the variation of load during operation (Phillips 2015).

The operating parameters of the evaporator-condenser PHE are important as they influence the coefficient of performance (COP) of the system. There are typically two factors to consider when designing the mean temperature of the evaporator-condenser; one aims at maximizing the COP of the system, and the other aims at equalizing the pressure ratio of two compressors to save input power (Liu et al. 2002).
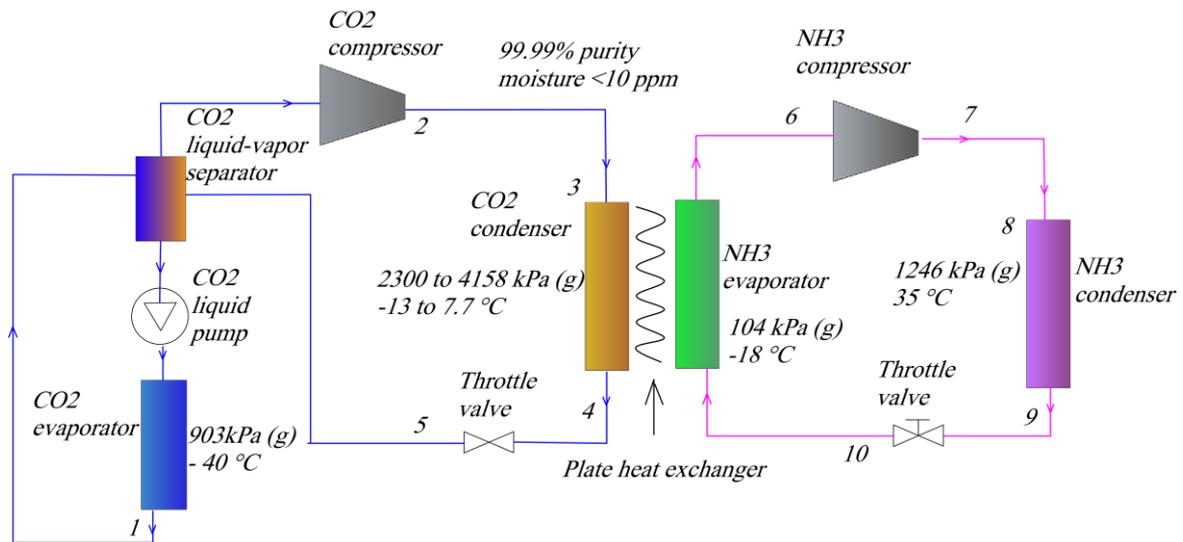
Figure 2.1: CO$_2$-NH$_3$ Cascade Refrigeration System Design - Detailed schematic of the closed-loop CO$_2$-NH$_3$ cascade refrigeration system.

2.1.2   CO$_2$-NH$_3$ Cascade and Two-Stage NH$_3$ Refrigeration System Comparison

In Australia, two-stage NH$_3$ refrigeration systems are relatively common, compared to CO$_2$-NH$_3$ cascade systems. As this project aims to investigate the integration of the CO$_2$ liquefaction system with the cascade refrigeration system, benefits of using the cascade system over the two-stage system were investigated. Pacific Gas and Electric Co. (2009) conducted a comprehensive study to compare a CO$_2$-NH$_3$ cascade refrigeration system against an equivalent two-stage NH$_3$ system. The study investigated the COP of both systems based on their refrigeration capacity (kW) per unit consumption of power (kW). The main outcomes of the study can be seen in Table 2.1.

Table 2.1: Cascade CO$_2$-NH$_3$ vs. Two-Stage NH$_3$ Refrigerant System - COP comparisons of compressors, condensers, air units and the total system for the two refrigerant systems (Pacific Gas and Electric Co 2009).

Refrigeration System Components	COP of Two-Stage NH$_3$ (kW/kW)	COP of Cascade CO2-NH3 (kW/kW)	COP Improvement (%)
-29°C Suction Group	4.40	5.02	14.1
-50°C Suction Group	2.19	3.52	60.7
Combined -29°C and -50°C Suction Groups	2.93	3.91	33.5
-11.7°C Suction Group	5.02	4.40	-12.4
Total System (Compressors)	2.07	2.20	6.28
Total System (Compressors/Condensers)	1.85	1.95	5.41
Total System (Comp./Cond./Air Units)	1.46	1.53	4.79

Taking into account the power consumption of all compressors, condensers and air units of both systems, the cascade system shows a 4.79% increase in COP. Additionally, the cascade system has the following advantages over the two-stage system:

- **Lower Capital Cost** - The volumetric refrigeration capacity of CO$_2$ is eight times that of NH$_3$ (Haar & Gallagher 1978; NIST 2010). This reduces the size of low stage compressors piping and insulation by more than half (M&M Refrigeration of Federalsburg 2014) and the related labour and material cost by 31.5% (Larose 2015).

- **Constant Positive Pressure** - At temperatures lower than -33°C, NH$_3$ has to work below atmospheric pressures (Haar & Gallagher 1978). On the other hand, CO$_2$ always works under positive pressure (NIST 2010), avoiding concern about non-condensable build up and air/moisture invasion through vacuum leaks (Peterson 2014).

- **NH$_3$ Charge Reduction** - In many cases, CO$_2$-NH$_3$ cascade systems can be designed with an NH$_3$ charge below 4.5 tons, giving owners the opportunity to reduce the costs associated with process safety management compliance (Peterson 2014).

- **The NH$_3$ Loop is Separated from the Public Area** - A CO$_2$-NH$_3$ cascade system allows designers to limit NH$_3$ charge to the machine room. Only CO$_2$ is present in the processing and/or storage areas.

2.1.3 CO₂ Capture Methods

CO_2 capture technologies can be distinguished into three main categories, depending on what stage of the combustion process CO_2 is removed (as shown in Figure 2.2).
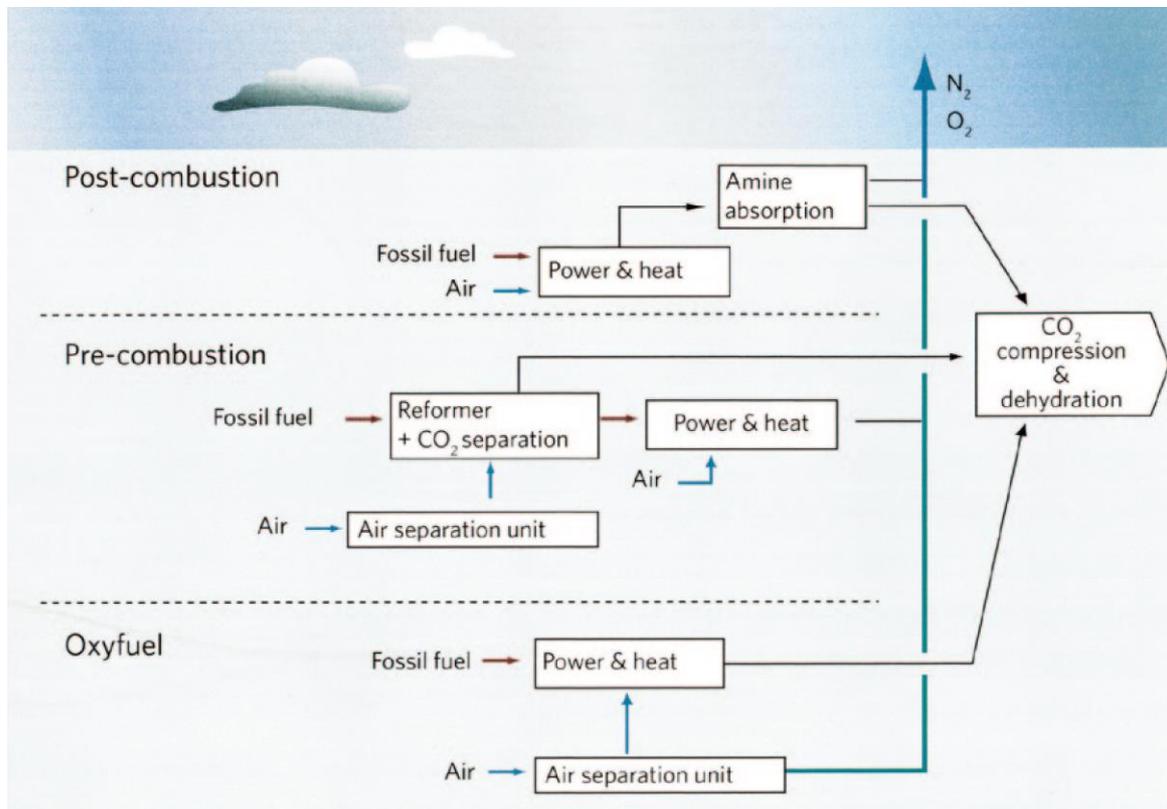
Figure 2.2: Current CO₂ Capture Methods - Illustration of the three main methods used for CO_2 capture (Freund & Kaarstad 2007).

- **Post-Combustion Separation** - This process separates CO_2 from exhaust gas after the combustion of carbon-containing fuels. An amine-based solution is typically used to absorb CO_2 at low temperatures, which can then be released at high temperatures; thus allowing the separation of CO_2 from the other flue gases (Macdowell et al. 2010). This technology is well developed commercially and suitable for both new and retrofitted projects (ASCO 2015; TPI 2015).

- **Pre-Combustion Separation** - This process splits hydrocarbons into hydrogen and CO_2 prior to combustion. Splitting is commonly achieved by gasification of coal or the reforming of natural gas (Zero 2011).

- **Oxy-Fuel Combustion** - Fuel is combusted in pure oxygen to generate exhaust gas that consists of CO_2 and water vapour, when assuming complete combustion. CO_2 is then separated by decreasing the temperature until water vapour condenses, allowing it to be removed (Zero 2011).

Private correspondence with an abattoir found there are significant CO_2 emissions in flue gas produced by steam boilers. This provides a source of CO_2 to be captured and liquefied through post-combustion methods, or a SGRS. Using a SGRS, CO_2 can be separated from flue gas after the combustion of carbon containing fuels. Post-combustion methods present the most financially feasible solution of CO_2 capture at the abattoir, as steam boilers already exists on-site.

2.1.4   Originally Proposed System

Figure 2.3 shows the originally proposed system design that planned to integrate the CO_2-NH_3 cascade refrigeration and CO_2 liquefaction systems. The design had proposed to merge compressed CO_2 streams from both the SGRS and the CO_2 refrigeration system (point 2). The merged compressed CO_2 streams are liquefied by passing through a common CO_2 condenser (point 3) in the cascade refrigeration system. Condensed CO_2 is divided into two branches, one remaining in the closed-loop of the CO_2 refrigeration system, while the other would flow into a storage tank to be later expanded to atmospheric pressure to produce dry ice.

Dry ice is produced by initially compressing gaseous CO_2 captured by the SGRS, then condensing it into a liquid to be stored in pressurised tanks. Liquefied CO_2 is then expanded to a lower pressure, causing some of the remaining liquid to vaporise. The temperature of the remaining liquid is lowered, due to the absorption of latent heat, causing it to solidify into a snow like substance (known as dry ice). It takes approximately 2.5kg of liquefied CO_2 to produce 1 kg of dry ice (ASCO 2015).
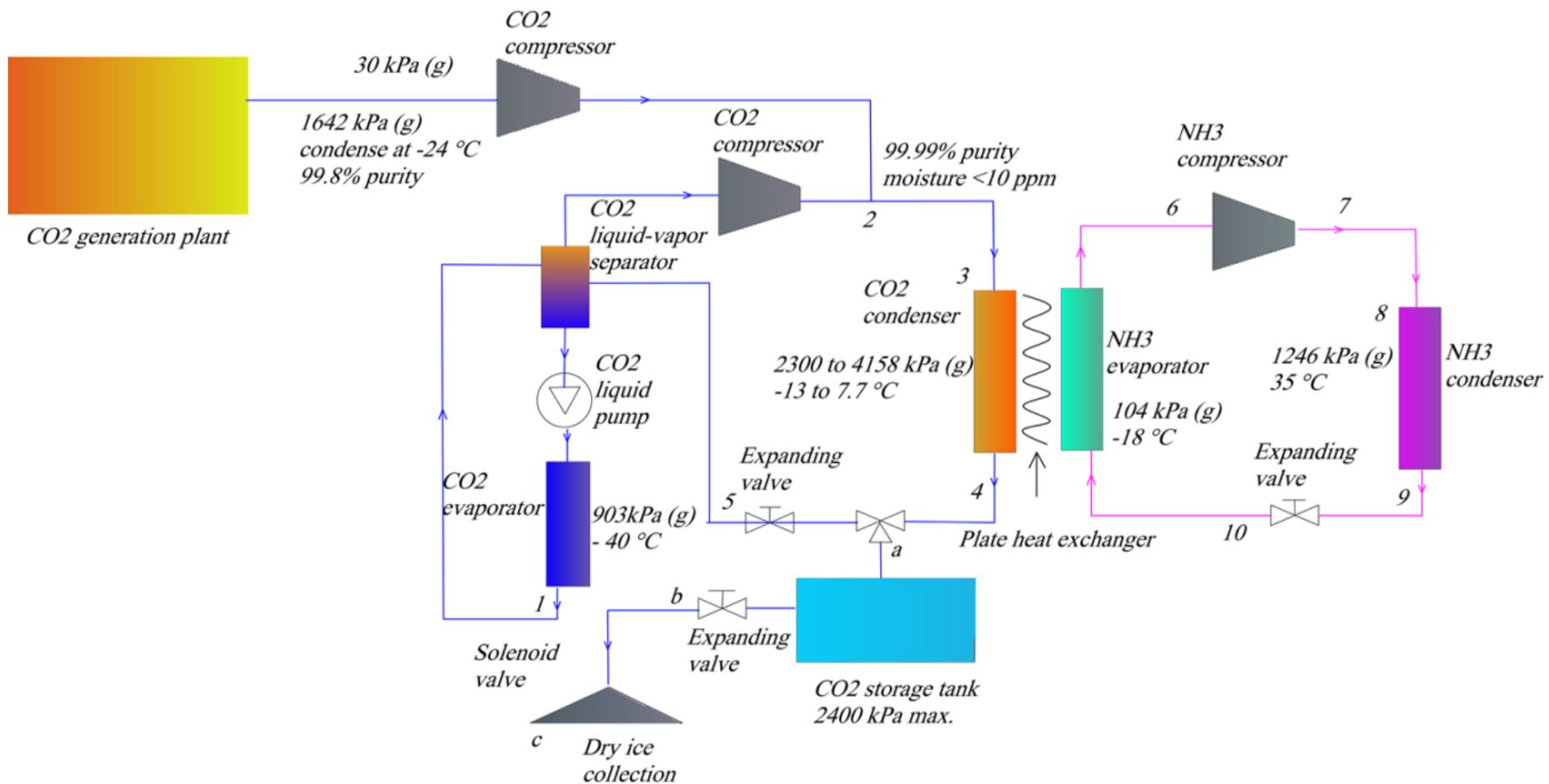
Figure 2.3: Original System Design - Detailed schematic of the integrated closed-loop CO_2-NH_3 cascade refrigeration system and open-loop CO_2 liquefaction system.

2.1.5   Technical and Financial Hurdles Faced by the Originally Proposed System

The proposed system faced two major hurdles when proving its technical and financial feasibility, these included an oversized PHE used to condense compressed CO_2 for dry ice production and contamination concerns between the two compressed CO_2 streams.

2.1.5.1   Oversized Plate Heat Exchanger

- **Cooling Capacity Required to Condense CO_2 as Food-Grade Product**

Assuming CO_2 is condensed at -13°C and 2300 kPa (g), the screw compressor with thermosyphon achieves a discharge temperature of 60°C (73 °C superheat), consistent with the normal operating discharge temperature of commercially available screw compressors (Pacific Gas and Electric CO 2009; Danfoss 2010). In this case, the enthalpy of the superheated gas phase CO_2 is 404.72 kJ/kg and saturated liquid state CO_2 is 57.40 kJ/kg (NIST 2010); hence, the heat rejection of CO_2 at this condition is 347.32 kJ/kg. Assuming a SGRS capacity of 285 kg/h (0.08kg/s), the cooling requirement for condensing CO_2 as food-grade product is 27.50 kW.

- **Cooling Capacity Required to Condense CO_2 as Refrigerant-Grade Product**

Assuming the cooling requirement at the -40°C refrigeration area is 1000 kW, the heat absorption during the evaporation of CO_2 from saturated liquid state to saturated gas phase is 322.64 kJ/kg (NIST 2010). Therefore, the mass flow rate of CO_2 at this load is 3.1 kg/s. As calculated in the paragraph above, the condenser operating at -13°C and 2300 kPa (g) with a superheat of 73°C has a heat rejection of CO_2 equal to 347.32 kJ/kg. Therefore, the cooling requirement for condensing CO_2 as refrigerant is 1076.69 kW at this load.

The comparison between condensing requirements of the two systems shows that the PHE needed for the refrigeration system is approximately 40 times oversized when condensing CO_2 for dry ice production. It is worth noting that the cooling requirement calculated for the above two processes assumes 73 °C superheat of CO_2, which may be lower or higher in the real case. However, as the two systems assume the same degree of superheat, the heat rejection per kilogram of CO_2 is the same. The ratio of the PHE size in the two systems primarily depends on the ratio of the mass flow rate of CO_2, which is constant at approximately 40 for this particular case.

2.1.5.2 Contamination Concerns

As compressed CO_2 streams were proposed to merge into a single stream, their respective CO_2 purity requirements were investigated. Typically, liquid CO_2 captured by the SGRS is of 99.9% purity, reaching the International Purity Standard for food-grade CO_2 (EIGA 2008). Comparatively, refrigerant-grade CO_2 requires a purity of 99.99%, along with a moisture content of less than 10 parts per million by weight. Moisture concentration in CO_2 refrigeration system is strictly controlled because it may create carbonic acid that causes corrosion in steel pipework (Linde 2015). There is also a risk of ice formation that may block small capillary tubing and damage pumps, leading to eventual system failure (Linde 2015). Therefore, contamination exists in the initially proposed system where the refrigerant-grade CO_2 merges with the food-grade CO_2 in the condenser.

One method of removing contamination concerns is to employ additional purification measures to liquefied CO_2 captured by the SGRS. As a result, investigations into the financial feasibility of this method were undertaken to determine if it was a viable option. The cost of purifying food-grade CO_2 to a refrigerant-grade CO_2 standard was estimated to be the price difference between the two. Food-grade and refrigerant-grade CO_2 have a stock price of 2.40 and 5.50 AUD/kg respectively leading to an approximate purification cost of 3.10 AUD/kg. As mentioned in Section 2.1.5.1, the flow rate of the refrigerant-grade CO_2 is 40 times that of food-grade CO_2. This means that for every 1kg of food-grade CO_2 captured, 40kg of CO_2 must be purified to refrigerant-grade, costing 124 AUD/kg. This is approximately 50 times more expensive then producing 1kg of food-grade CO_2 in a non-integrated system and can be considered an uneconomical solution.

2.1.6 Amended System Design

Figure 2.4 details the amended system design developed to eliminate technical and financial hurdles faced by the originally proposed design. By not merging the CO_2 refrigerant and liquefaction systems, contamination concerns have been eliminated. Concerns raised regarding the oversized PHE were also removed by allowing the integration of appropriately sized PHEs for both food-grade and refrigerant-grade CO_2 systems with the NH_3 refrigerant system. An additional PHE has been incorporated for the cooling water of the CO_2 generation plant, shown as "#3 NH_3 evaporator" in Figure 2.4. The PHE has been included as the commercially available SGRS includes a separate refrigeration system to remove heat from high temperature water in its cooling tower. The revised arrangement makes most use out of the abattoir's existing

refrigeration capacity and eliminates the need for a separate refrigeration system. The PHE between the food-grade CO_2 and NH_3 systems serve as a condenser for the CO_2 system, producing liquefied CO_2 to be stored in large storage tanks. Once stored, the liquefied CO_2 is expanded to produce dry ice that can then be collected and used where needed.

2.1.7   Amended Project Direction

Project direction was altered to look primarily into the financial feasibility of solely integrating the CO_2 liquefaction system to a typical abattoir using a FFS, due to the integration between the CO_2 refrigerant and liquefaction systems being deemed uneconomical. The FFS looked into capital and operational expenditure, along with cost reductions expected when implementing proposed additions to an abattoir in private correspondence with the project. Proposed additions to the abattoir consist of the SGRS, alternative form of power generation, excess biogas usage in steam boilers and dry ice blasting equipment. CAPEX, OPEX and cost reductions were investigated to determine operating conditions that would produce the lowest payback period of the project, along with outline which operating variables the payback period would be most sensitive to.
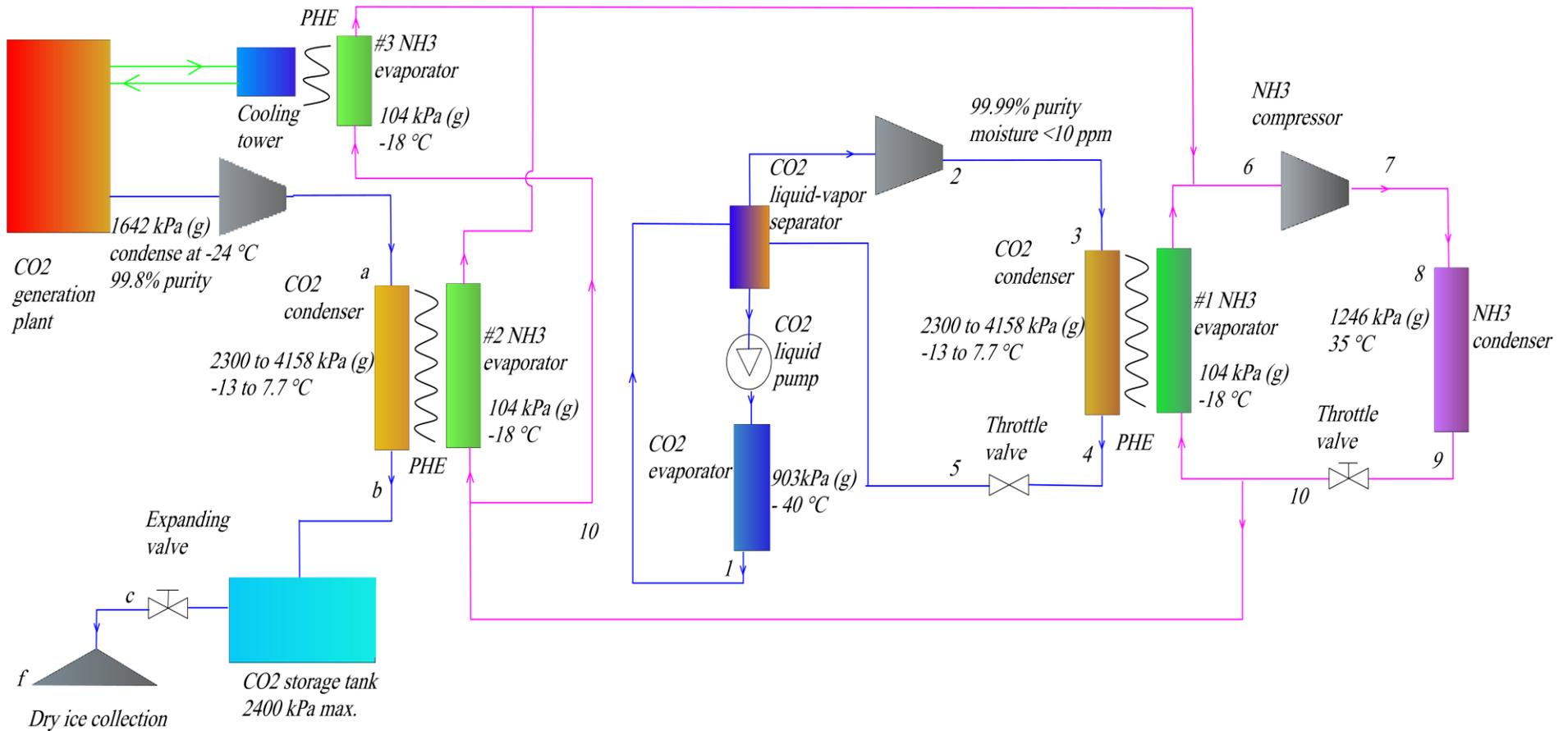
Figure 2.4: Newly Amended System Design - Detailed Schematic of the amended system design of the integrated closed-loop CO_2-NH_3 refrigeration system and open-loop CO_2 liquefaction system.

2.2 Financial Feasibility Model Development

A FFM was developed to assess the financial feasibility of the project. The model was developed using information collected during a preliminary financial feasibility study that looked into capital and operation expenditure, along with cost reductions that were expected when integrating the SGRS. Private correspondence with an abattoir found there is generally excess biogas produced at any abattoir. Excess biogas has the potential to fuel a form of alternative power generation or substitute natural gas currently used to fuel steam boilers. Subsequently, capital and operational expenditure, along with cost reductions estimated from these sources were added to the FFM.

Each variable used in the FFM was initially researched to determine its expected range. Values corresponding with current industry rates were then used in the FFS as a baseline case. Private correspondence with an abattoir was used to gather information on regular operations and consumable usages. Information given by the abattoir was averaged against current industry rates, for particular variables, to give a more accurate approximation of the expected baseline case. The FFM was used to estimate the project's payback period based upon particular operating conditions that were possible. The payback period refers to the length of time required for an investment to recover its initial expenditure through savings made by the investment. The payback period, in the case of the FFM, is calculated using Equation 2.1:

$$\textbf{Payback Period (months)} = \frac{\textbf{CAPEX (AUD)}}{\left(\textbf{Cost Reductions }(\frac{\textbf{AUD}}{\textbf{month}}) - \textbf{OPEX}(\frac{\textbf{AUD}}{\textbf{month}})\right)} \qquad (2.1)$$

2.2.1 Project Boundary Conditions

The proposed system design is constrained by a set of boundary conditions surrounding the total amount of CO_2 captured. The amount of CO_2 available in flue gas from steam boilers limits the total CO_2 capture capacity of the system. Private correspondence with an abattoir found a 50/50 mixture of natural gas and biogas is being used as a fuel source to satisfy steam boilers at the abattoir. It is currently estimated that 2.61kg of CO_2 will be produced per kg of fuel consumed; with a maximum of 2.84kg of CO_2 being produced per kg of fuel if a maximum ratio of biogas/natural gas (80/20) is used (seen in Appendix A). There will be excess CO_2 available when considering both operating conditions, even when running the largest commercially available SGRS at maximum capacity. The capacity of the SGRS also limits the amount of CO_2 that can be captured. However, an appropriately sized SGRS should be chosen depending on CO_2 demands of the abattoir; thus, this is not expected to present an issue.

The amount of biogas that can be used for an alternative form of power generation, or as a replacement for natural gas used in steam boilers, is constrained by the amount of biogas currently being produced at the abattoir. The abattoir in question currently uses 62.5% of its total biogas in steam boilers, with the remaining 37.5% not being utilised. The remaining 37.5% is available to be used in an alternative form of power generation or to replace natural gas currently used to fuel steam boilers.

2.2.2   System Inputs

System inputs were used in the FFM to modify operating conditions of the proposed additions to the abattoir. System inputs were designed to be modified to investigate their effect on the project's payback period when different variations of operating conditions are used. System inputs include the following and can be also be seen in Appendix B:

- SGRS CO_2 production capacity;
- Running time per day;
- Days operational per month;
- CO_2 substituted for dry ice snow production;
- Dry ice demand for dry ice blasting;
- Water-based ice replaced by dry ice for cooling red-meat product;
- Alternative form of power generation capacity;
- Alternative form of power generation running time per day;
- Percentage of biogas used in steam boiler;
- Currency exchange rate (EURO-AUD); and
- Interest rates for loan repayments.

Input variables can then be used to determine the main system outputs including: the maximum amount of CO_2 captured, current CO_2 demand (substituted CO_2), possible CO_2 demand (substituted CO_2, dry ice blasting dry ice and water-based ice) and excess CO_2 produced. Outputs for additional cost reduction sources including power generation and substituted natural gas were also calculated. These values were used to determine OPEX and cost reductions detailed in Sections 2.2.4 and 2.2.5 respectively. Excess CO_2 production has been included, since captured liquefied CO_2 has the potential to be sold. Because of this, the SGRS can be used to meet the abattoir's CO_2 demands or produce a maximum amount of CO_2 where excess can then be sold.

2.2.3 Capital Expenditure

CAPEX outlines the initial costs associated with the purchase and installation of all proposed additions to a typical abattoir. CAPEX has been included for each proposed addition to a typical abattoir and currently includes the following inputs that can also be seen in Appendix B:

- SGRS equipment, freight, piping and installation;
- Alternative power generation equipment and installation;
- Infrastructure needed for increased biogas usage in steam boilers; and
- Dry ice blasting equipment (blast machine and pelletiser) and installation.

CAPEX was divided into four main sections to show the individual capital cost of each system. The majority of equipment and installation costs were obtained from commercial providers. However, not all installation costs could be attained; hence, were estimated at 30% of their respective equipment cost. 30% was used as a baseline value, due to installation costs of known equipment being approximately 30% of their respective purchase price. It must also be noted that the SGRS CAPEX has been estimated without a refrigeration system included for its cooling tower as a result of the amended system design outlined in Section 2.1.6.

2.2.4 Operational Expenditure

OPEX was based around utility and consumable usage expected from the SGRS, alternative source of power generation, excess biogas usage in steam boilers and dry ice blasting equipment. OPEX for the proposed additions to the abattoir currently include the following inputs that can also be seen in Appendix B:

- Electricity consumption;
- Water consumption;
- Consumable consumption during SGRS purification;
- Maintenance costs; and
- CO_2 levies.

SGRS utility and consumable usage, along with maintenance costs, was provided by a commercial supplier. OPEX for the other major proposed systems were not supplied by their respective suppliers and were estimated. Maintenance costs were estimated at 4% of CAPEX per year of operation (Sondalini 2001), whilst running costs were estimated at 1% of CAPEX per month based

on the SGRS OPEX. As a result of recent rapid climate change, CO_2 levies are expected to be introduced in the near future. Because of this, CO_2 levies were included as input variables when calculating OPEX while integrating an alternative source of power generation or excess biogas usage, as they will both increase CO_2 emissions.

2.2.5 Cost Reduction

For the proposed system to be economical, cost reductions must be realised by the proposed additional equipment to reduce the project's payback period. Cost reductions are expected from the sources below, with specific FFM input variables being seen in Appendix B:

- Substitution of currently procured CO_2 from specialist providers with CO_2 captured by the SGRS;
- Replacement of water-based ice used for cooling applications with CO_2 captured by the SGRS;
- Sale of excess CO_2 captured by the SGRS;
- Electricity production by the alternative form of power generation;
- Decreased natural gas consumption due to excess biogas usage in steam boilers; and
- Decreased cleaning costs as a result of dry ice blasting.

Prices for CO_2 and water-based ice have been averaged between values found through private correspondence with an abattoir and average market values, to provide an accurate representation of their expected baseline value. Expected consumption rates of dry ice and water-based ice have also been estimated using information provided by the abattoir. The substitution of water-based ice with dry ice was investigated further, due to the increased cooling capacity of dry ice when compared with water-based ice. As stated in Section 2.1.4, 2.5kg of CO_2 is needed to produce 1kg of dry ice. However, dry ice provides an increased cooling capacity of 1.88 times that of water-based ice (Access Science 2014; Elite Soft 1995). Therefore, it was estimated to take 1.33kg of CO_2 to substitute 1kg of water-based ice.

### 2.2.6 Financial Feasibility Model Checks

The FFM was put through rigorous checks to ensure all coding logic used was correct to ensure accurate information was being outputted. Check sums, unit testing and order of magnitude checks were used as methods of checking coding logic.

- **Check Sums** - Additional sums were created throughout the FFM to ensure calculated sums used were producing the correct values. Check sums were designed to calculate the same value as another sum used in the FFM; however, using different equations. This provided a check on major sums that were used throughout the FFM.

- **Unit Testing** - All cells in the FFM that were directly inputted (not calculated using code) were changed to a number that is a power of ten (including 0.01 and 0.1). Errors in coding were found by investigating all calculated values to ensure they were divisible by 10, otherwise there was apparent errors in the code.

- **Order of Magnitude Checks** - All code was checked to ensure values being calculated were approximately what were expected when using particular values for input variables.

2.2.7   Project Process Flow Chart

The flow chart as seen in Figure 2.5 outlines the main components of the project that have been developed to summarise the project into an easy-to-read format. The main components of the flow chart include:

- **Fuel Source** - Includes both natural gas and biogas that is currently used to fuel steam boilers. Biogas may also be used to fuel an alternative source of power generation.

- **Systems Inputs** - The post-combustion of CO_2 provides a source of CO_2 to be captured by the SGRS.

- **Refrigerant Systems** - Both the CO_2-NH_3 cascade and two-stage NH_3 refrigerant systems have been included; however, only the cascade system has been included in the amended system design.

- **Project Expenditure** - This includes capital and operational expenditure for the SGRS and dry ice blasting.

- **System Outputs** - This shows all expected physical outputs from the proposed additions to the abattoir.
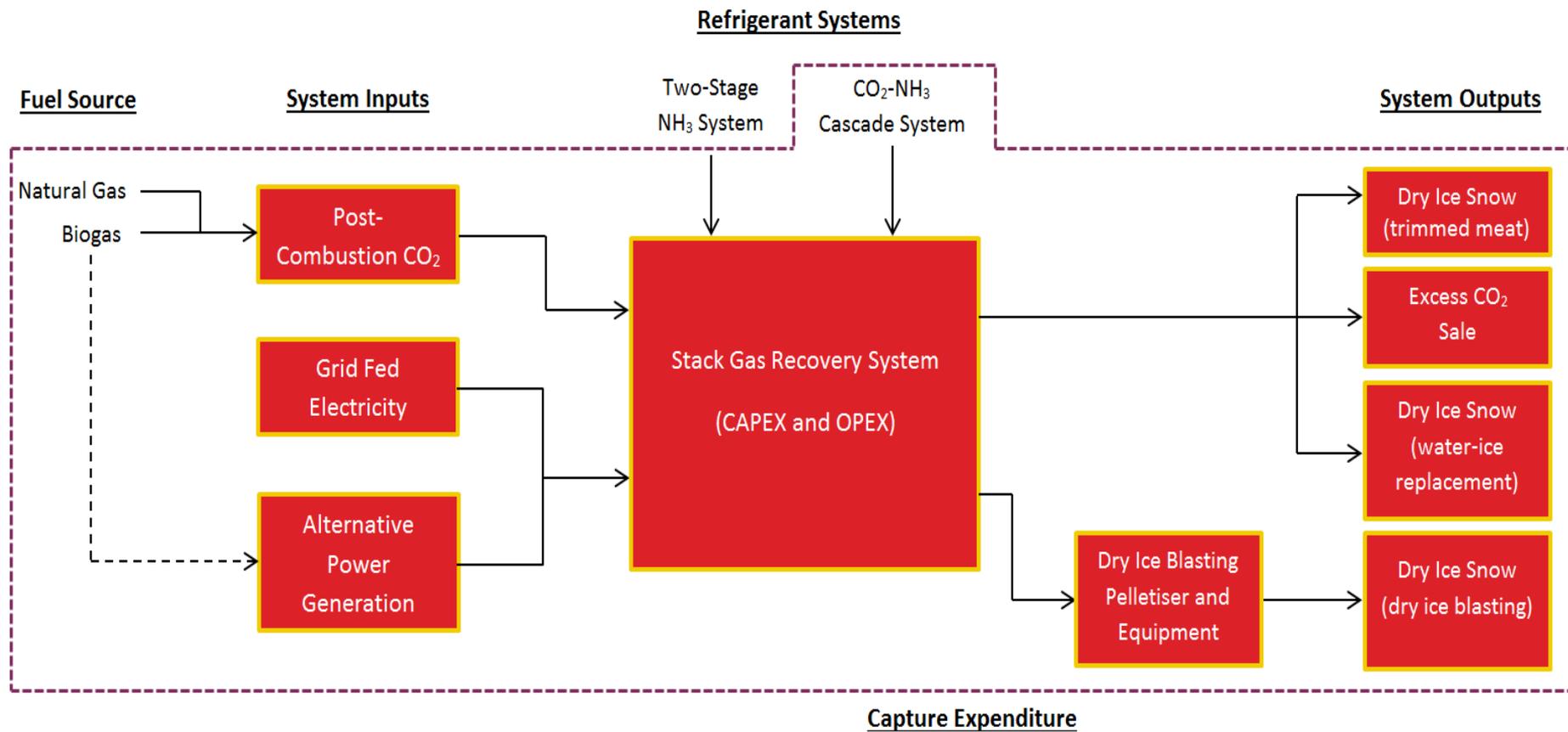
Figure 2.5: Project Process Flowchart – Summary of the main process components for the proposed CO_2 liquefaction system. Items included within the dashed line outline components that have been included in the project's amended design.

2.3   Financial Feasibility Study

The FFS was undertaken to investigate the impact of all major variables included in the FFM on the payback period of the project. The study was divided into two major sections, including the investigation of different operating conditions (scenarios) and a sensitivity analysis of major variables included in the FFM. Six separate scenarios were explored for the first section of the study, whilst the sensitivity analysis examined the main FFM variables for each scenario.

2.3.1   Scenario Summary

Private correspondence with an abattoir was used to determine six separate operating scenarios that were deemed possible when integrating the proposed additions to the abattoir. The FFS looked into each scenario, with results being detailed in the following points:

- **Scenario 1** – Solely operating the SGRS to meet current CO_2 demands of the abattoir. Current demands include the substitution of CO_2 currently procured from specialists providers with CO_2 captured from the SGRS.
- **Scenario 2** – Solely operating the SGRS to meet possible CO_2 demands of the abattoir. Possible demands include the substitution of currently procured CO_2, replacing water-based ice cooling applications with dry ice and replacing current cleaning methods with dry ice blasting.
- **Scenario 3** – Solely operating the SGRS to maximum capacity to meet **possible** CO_2 demands along with selling excess CO_2 captured back to market.
- **Scenario 4** – Operating the SGRS as per Scenario 3 along with running an alternative form of power generation using excess biogas produced by the abattoir.
- **Scenario 5** - Operating the SGRS as per Scenario 3 along with using excess biogas to substitute natural gas used in steam boilers at the abattoir.
- **Scenario 6** – Solely operating the SGRS to maximum capacity to meet **current** CO_2 demand along with selling excess CO_2 captured back to market. Note, this scenario can also be considered operating the SGRS to maximum capacity to solely substitute currently procured CO_2 if demand is high enough.

These scenarios were used as they depict the possible combinations of operating conditions when integrating the proposed additions to the abattoir. The additional source of power generation and excess use of biogas in steam boilers were not combined into a singular scenario, as there was not enough biogas available to satisfy the demands of both.

2.3.2 Scenario Operating Conditions

All six scenarios were investigated to find their respective payback periods under a range of operating conditions. The major variations to operating conditions included changing the SGRS capacity and changing major variables of the FFM by ±10% and to extreme realistic cases.

- **SGRS Capacity** - Commercially available SGRSs are offered in capacities of 285, 500 and 1000kg/h of CO_2 captured. Specialised systems ranging up to 11,000kg/h can be purchased; however, at a greatly increased cost (ASCO 2015). As a result, only commercially available SGRS capacities were investigated. Different SGRS capacities were explored, as there is excess CO_2 available from steam boilers, even when running the 1000kg/h system to maximum capacity. The 285kg/h system has the capacity to meet possible CO_2 demand; however, increased excess CO_2 can be captured and sold when using the larger systems, leading to increased cost reductions.

- **10% Change in Major Variable Values -** Values for major variables of the FFM described in Appendix C for each scenario were altered by ±10% of their baseline value estimated in the FFMs development. The payback period for each scenario was then calculated for the three SGRS production capacities. This analysis gave insight into which variable provided the largest change in payback period when all were changed by the same percentage amount.

- **Extreme Change in Major Variable Values** - Baseline values for particular variables used in the FFM were susceptible to large increases or decreases when compared to others. This occurrence can be attributed to rough estimates for their baseline values being made. Values for extreme maximum and minimum values of each variable can be seen in Table 2.2.

Table 2.2: Extreme Changes in Input Variables – Percentage change in the baseline values used for input variables when changed to extreme cases.

	Running Time	Days Operational	Currency Exchange Rate	SGRS CAPEX	Dry Ice Blasting OPEX	CO_2 Price	Cleaning Costs	Water-Based Ice Price	Biogas Usage
Minimum	-10.0%	-10.0%	-6.45%	-10.0%	-10.0%	-30.0%	-30.0%	-80.0%	-30.0%
Maximum	+5.00%	+10.0%	+3.23%	+10.0%	+30.0%	+10.0%	+30.0%	+100%	+30.0%

Large variations in water-based ice price can be seen due to large discrepancies in prices found through private correspondence with an abattoir and an Australian water-based ice provider. Relatively large changes in cleaning costs and dry ice blasting were also given. This was a result of limited information being given on both input variables, leading to rough approximations having to be used for their baseline case. CO_2 price was given a low minimum value due to the possibility of the CO_2 market being flooded in the near future. Maximum and minimum values for currency exchange rate were based on extreme rates seen over the past six months.

2.3.3   Sensitivity Analysis

The sensitivity analysis was divided into two main sections including the initial sensitivity analysis and a focused sensitivity analysis.

- **Initial Sensitivity Analysis** - The initial sensitivity analysis was undertaken to determine the sensitivity of all variables used in the FFM. The analysis looked into the change in payback period per 1% change in a particular variable in the FFM. This analysis was completed for all six scenarios; however, only the 285 kg/h SGRS was examined. Once the sensitivities of all variables were found, variables that changed the total payback period by 0.5% per 1% change of their baseline value were deemed as significant. These variables were then analysed further in the three conditions listed in Section 2.3.2 and the focused sensitivity analysis.

- **Focused Sensitivity Analysis** - All six scenarios for each SGRS capacity on the variables listed in Table 2.2 were analysed. Variables were only analysed if they were applicable to the scenario being tested (e.g. biogas usage tested only in scenario 5). The analysis consisted of calculating the change in payback period when changing each variable by 1%, as undertaken in the initial sensitivity analysis. However, unlike the initial sensitivity analysis, sensitivity was calculated using the change in payback period seen when using the extreme case condition. This method was undertaken to determine which variables could be considered 'show stoppers'. 'Show stoppers' refer to significantly sensitive variables that could single-handedly alter the decision to implement the SGRS when their baseline value is altered over a realistic range.

3.0   Project Outcomes

The section provides results found during the technical and financial feasibility studies. Technical concerns have been outlined along with relevant results from the individual studies undertaken during the FFS.

3.1   Technical Feasibility Study Outcomes

The technical feasibility study outlines work that was undertaken to prove the technical feasibility of integrating a closed-loop CO_2-NH_3 cascade refrigeration with an open-loop CO_2 liquefaction system. The original proposal met certain issues due to the combination of the two systems including:

- **Contamination Concerns** - The proposed SGRS will capture and liquefy CO_2 from steam boiler flue gas, producing food-grade CO_2 (99.9% purity), whilst the CO_2 refrigeration system requires refrigerant-grade CO_2 (99.99% purity). Purity requirements of the CO_2 refrigeration system led to food-grade CO_2 needing to be purified before being combined with the refrigerant stream. Also, due to the different flow rates seen between the two systems, for every 1kg of food-grade CO_2 captured, 40kg of CO_2 must be purified to a refrigerant-grade standard. When using stock prices for food and refrigerant grade CO_2, it can be estimated that this method is 50 times more expensive then producing 1kg of food-grade CO_2 to be used in a non-integrated system.

- **Oversized Condenser** - The originally proposed system incorporated a singular PHE between the integrated CO_2 stream and the NH_3 refrigeration system for the purpose of condensing high-pressure gas. It was found that the PHE necessary to meet the cooling requirements of the CO_2 refrigeration system was 40 times oversized for condensing CO_2 for dry ice production.

This showed that the addition of a purification system to the CO_2 liquefaction system and the use of a single PHE for both CO_2 streams proved to be an uneconomical design. As a result, the originally proposed design was replaced by the amended system design detailed in Section 2.1.6. The amended design removes the integration of the two CO_2 streams to eliminate the contamination concerns raised by the original proposal. Concerns raised by the oversized PHE have also been removed by integrating separate PHEs for both CO_2 streams with the NH_3 refrigeration system. A PHE has also been included between the cooling tower of the SGRS and the NH_3 refrigeration system to make the most out of the NH_3 refrigeration system's capacity.

3.2 Financial Feasibility Study Outcomes

The outcomes of the financial feasibility study can be divided into five main categories including the results when completing the initial sensitivity analysis, scenario payback period comparison, changing major variables by ±10%, changing variables to extreme realistic cases and the focused sensitivity analysis.

3.2.1 Omitted Result from Financial Feasibility Study

Results were gathered for all six scenarios when using the 285, 500 and 1000kg/h SGRS. However, certain results were omitted from this report as they provided minimal information on the financial feasibility of the project. The following result were omitted from the report:

- **Scenario 1** - This scenario was omitted from the report as the payback period was approximately 2.5 times larger than any other scenario investigated. Also, interest rates from CAPEX loans outweighed any cost reductions the proposed system could make, producing a net loss per month. This was attributed to a relatively small amount of procured CO_2 to substitute with CO_2 captured by the SGRS.
- **Scenario 2 from 500kg/h SGRS** - As the 285kg/h SGRS already met possible CO_2 demand, the 500kg/h system only increased CAPEX without increasing cost reductions.
- **1000kg/h SGRS for all Scenarios** - Decreased payback periods were seen for all scenarios when employing the 1000kg/h SGRS. However, this option was deemed unfeasible as a result of excessive CO_2 being captured, with all CO_2 not being expected to be sold back to market.

3.2.2 Initial Sensitivity Analysis

Prior to undertaking other forms of result analysis, a sensitivity analysis on all variables in the FFM was undertaken. This analysis was used to determine which variables could provide significant changes to payback period when changed by ±1% for all scenarios, when running the 285kg/h SGRS. The results from the initial sensitivity analysis can be seen in Table 3.1.

Table 3.1: Initial Sensitivity Analysis Results - Results show the expected change in payback period (months) per ±1% change in input variables. Outputs were deemed significant if they were above 0.5% of the payback period. N/A refers to an input variable which will not impact that particular scenario.
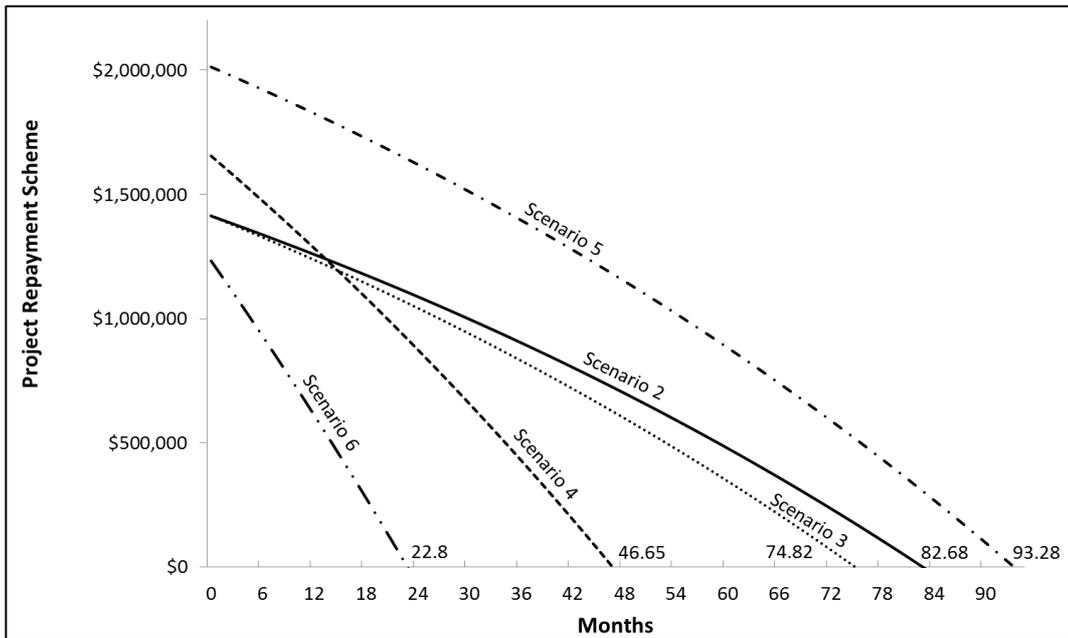
Input	Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
SGRS Running Time	N/A	N/A	1.52	-1.27	0.60	-0.54	1.45	-1.25	0.23	-0.21
Days Operational	N/A	N/A	1.88	-1.14	0.97	-0.65	1.98	-1.24	0.25	-0.20
Substituted Snow	0.25	-0.23	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Dry Ice for Dry Ice Blasting	-0.05	0.05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Water-Based Ice Substitution	0.18	-0.16	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Turbine Capacity	N/A	N/A	N/A	N/A	0.18	-0.17	N/A	N/A	N/A	N/A
Turbine Running Time	N/A	N/A	N/A	N/A	0.19	-0.17	N/A	N/A	N/A	N/A
Biogas Usage	N/A	N/A	N/A	N/A	N/A	N/A	0.93	-0.57	N/A	N/A
Currency Exchange Rate	-0.50	0.50	-0.46	0.46	-0.33	0.33	-0.38	0.38	-0.19	0.19
SGRS CAPEX	-0.54	0.54	-0.50	0.50	-0.29	0.29	-0.41	0.41	-0.21	0.21
Dry Ice Blasting CAPEX	-0.09	0.10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Turbine CAPEX	N/A	N/A	N/A	N/A	-0.06	0.06	N/A	N/A	N/A	N/A
Biogas CAPEX	N/A	N/A	N/A	N/A	N/A	N/A	-0.24	0.25	N/A	N/A
Electricity Price	-0.20	0.21	-0.18	0.19	0.14	-0.13	-0.17	0.18	-0.02	0.02
Dry Ice Blasting OPEX	-0.37	0.49	-0.32	0.42	-0.14	0.16	-0.32	0.40	N/A	N/A
SGRS Maintenance	-0.09	0.09	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CO_2 Levies	N/A	N/A	N/A	N/A	-0.01	0.01	-0.02	0.02	N/A	N/A
CO_2 Price	0.29	-0.27	0.30	-0.27	0.12	-0.11	0.29	-0.27	0.29	-0.23
Current Cleaning Costs	1.32	-0.58	1.09	-0.51	0.35	-0.23	0.95	-0.51	N/A	N/A
Water-Based Ice Price	0.60	-0.22	0.49	-0.19	0.15	-0.09	0.42	-0.20	N/A	N/A
Natural Gas Price	N/A	N/A	N/A	N/A	N/A	N/A	0.18	-0.17	N/A	N/A
Expected Payback Period	**61.45 months**		**57.10 months**		**39.24 months**		**66.92 months**		**20.89 months**	

| Colour Guide	
Not Significant	
Significant	

Table 3.1 shows a summarised version of the initial sensitivity analysis. The original sensitivity analysis included variables such as SGRS consumable consumption rates, individual CAPEX costs for all proposed additions (e.g. SGRS freight, SGRS piping, etc.) and maintenance costs for proposed additions excluding the SGRS. However, these were omitted from Table 3.1 as they had minimal impact on the payback period for each scenario. It can be seen that running time, days operational, currency exchange rate, SGRS CAPEX and current cleaning costs showed significant changes in the payback period; hence, were included in further analysis. Dry Ice blasting OPEX was seen to be significant in majority of the scenarios and was included in further analysis. Biogas usage was only relevant to scenario 5; hence, it was only included for this scenario. CO_2 and water-based ice price was not found to be significant for majority of the scenarios. However, they were included as large changes to their baseline values were expected.

3.2.3   Scenario Payback Period Comparison

Results gathered during the FFS were summarised to compare all relevant scenarios for both the 285 and 500 kg/h SGRS. Results seen in Figures 3.1 and 3.2, show the baseline payback periods when implementing the 285 and 500kg/h SGRS respectively.

Figure 3.1: Project Repayment Scheme - 285kg/h SGRS - Displays the estimated payback for each scenario when baseline values are used for input variables. Scenario 2: Running the SGRS to meet possible CO_2 demand (substituting currently procured CO_2, substituting water-based ice with dry ice and substituting current cleaning methods with dry ice blasting); Scenario 3: Running the SGRS to meet possible demand along with selling excess CO_2 to market; Scenario 4: Running SGRS as per Scenario 3 along with running an alternative form of power generation off excess biogas; Scenario 5: Running SGRS as per Scenario 3 along with substituting natural gas used in steam boilers with excess biogas; and Scenario 6: Running SGRS to solely substitute currently procured CO_2 along with selling excess CO_2 to market.
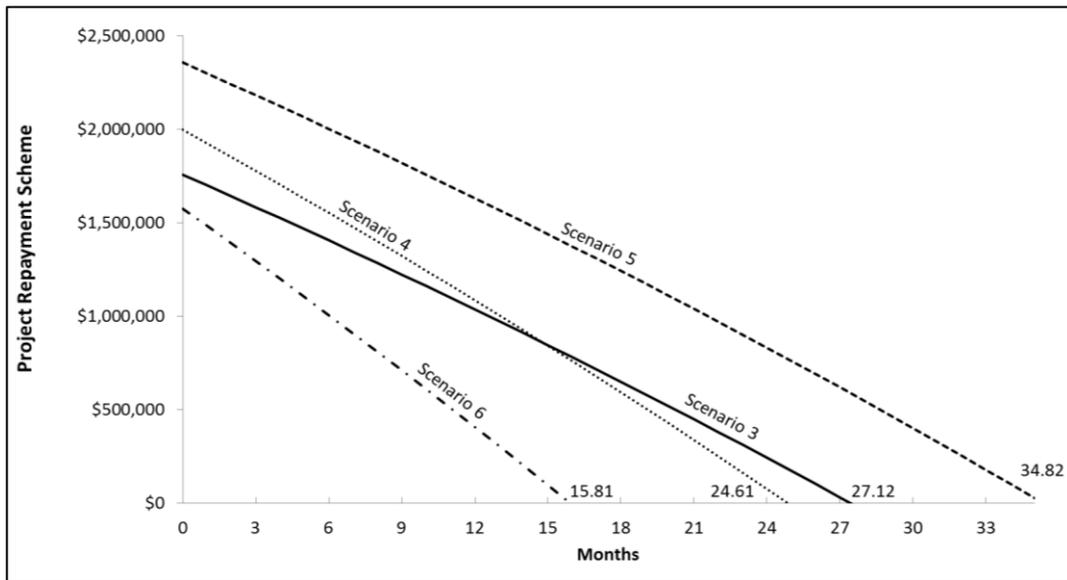
Figure 3.2: Project Repayment Scheme - 500kg/h SGRS - Displays the estimated payback for each scenario when baseline values are used for input variables; Scenario 3: Running the SGRS to meet possible demand (substituting currently procured CO_2, substituting water-based ice with dry ice and substituting current cleaning methods with dry ice blasting) along with selling excess CO_2 to market; Scenario 4: Running SGRS as per Scenario 3 along with running an alternative form of power generation off excess biogas; Scenario 5: Running SGRS as per Scenario 3 along with substituting natural gas used in steam boilers with excess biogas; and Scenario 6: Running SGRS to solely substitute currently procured CO_2 along with selling excess CO_2 to market.

3.2.4   ±10% Change in Input Variables

Once baseline cases were established, each variable was individually altered by ±10% to determine the impact upon the payback period for each scenario when running either the 285 or 500kg/h SGRS. Examples of the study can be seen in Figures 3.3 and 3.4 respectively, showing scenario 6 for both SGRS capacities. The remaining results of the study can be found in Appendix D.
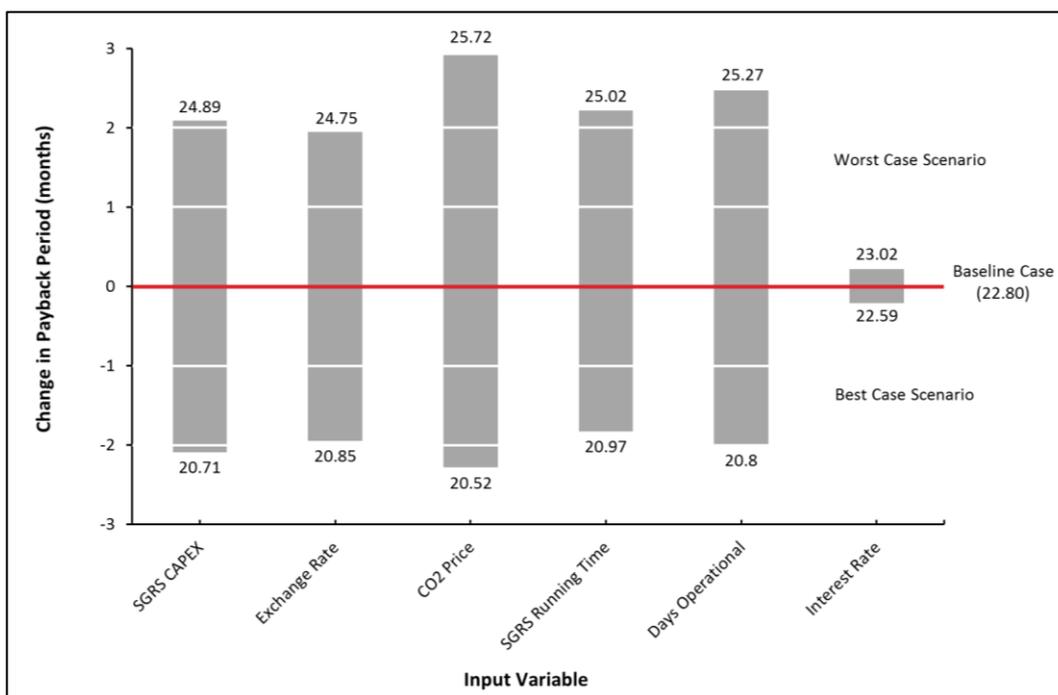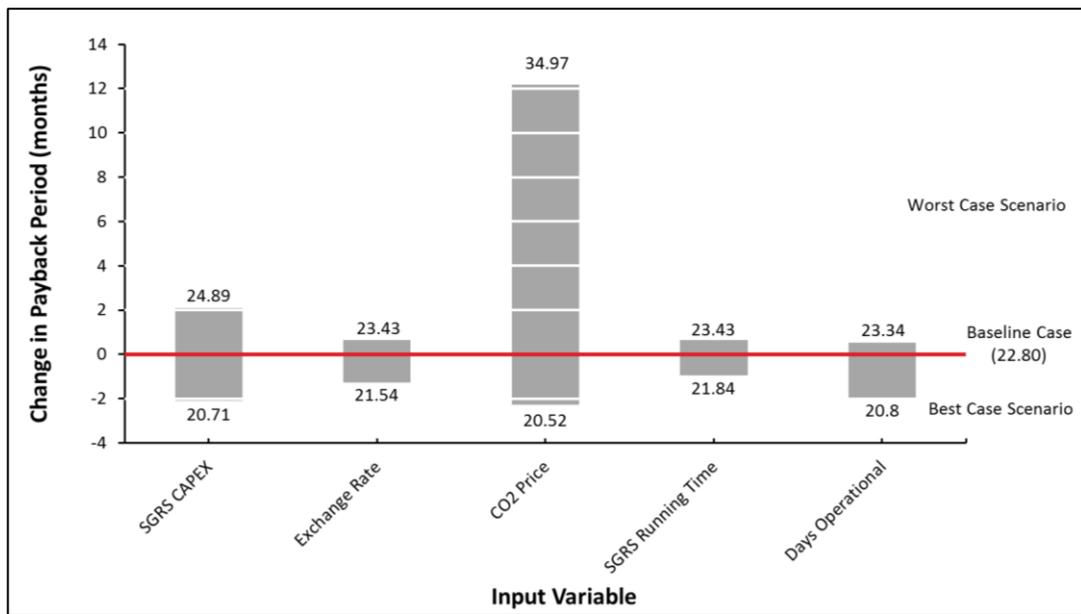
Figure 3.3: 10% Change in Input Variables - Scenario 6 (285kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±10%. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered by ±10%.
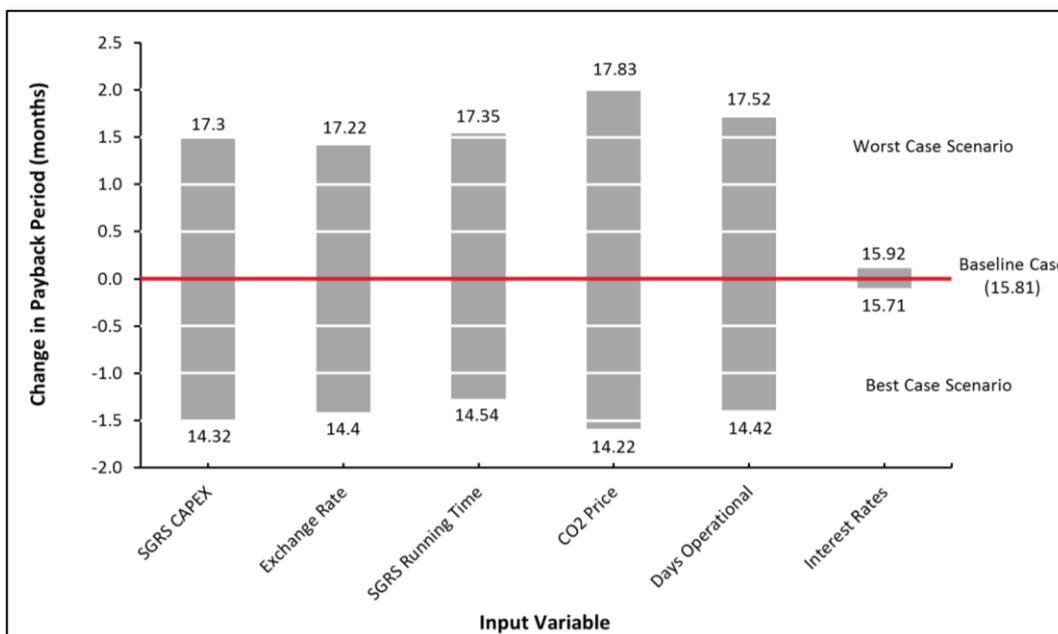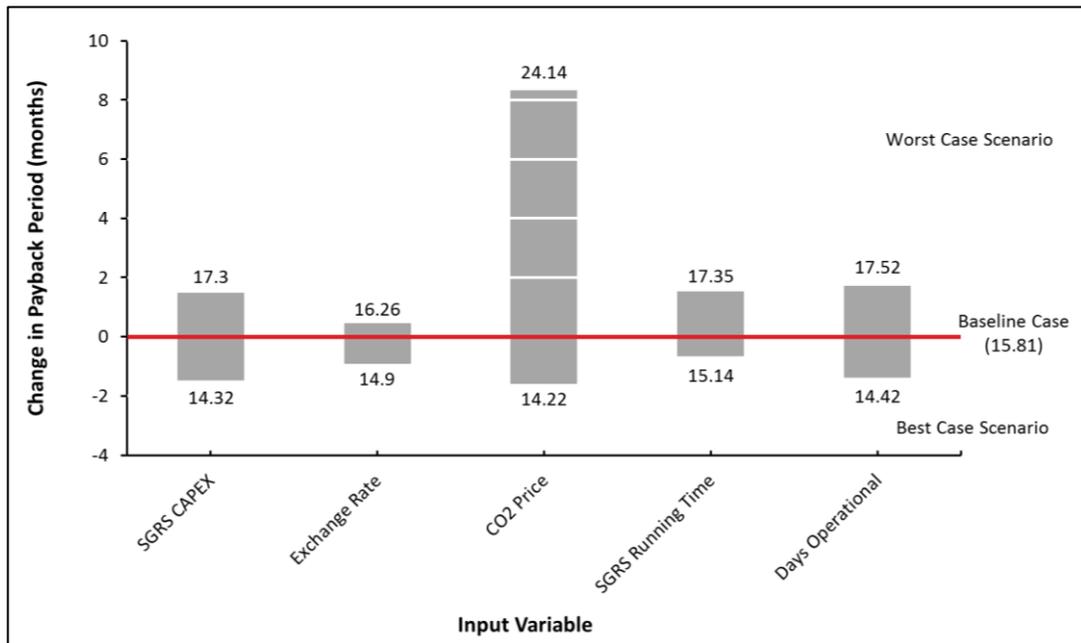

Figure 3.4: 10% Change in Input Variables - Scenario 6 (500kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±10%. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered by ±10%.

3.2.5   Extreme Change in Input Variables

Table 2.2 showed that baseline values for particular input variables are susceptible to large increases or decreases when compared to others. Extreme cases were analysed to determine maximum and minimum paybacks that were deemed realistically possible when running either the 285 or 500 kg/h SGRS. Examples of the study can be seen in Figures 3.5 and 3.6, whilst the remaining results of the study can be found in Appendix E.

Figure 3.5: Extreme Change in Input Variables - Scenario 6 (285kg/h SGRS) - Expected change in project payback period when individual input variables are altered to possible extreme cases. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered to extreme cases.
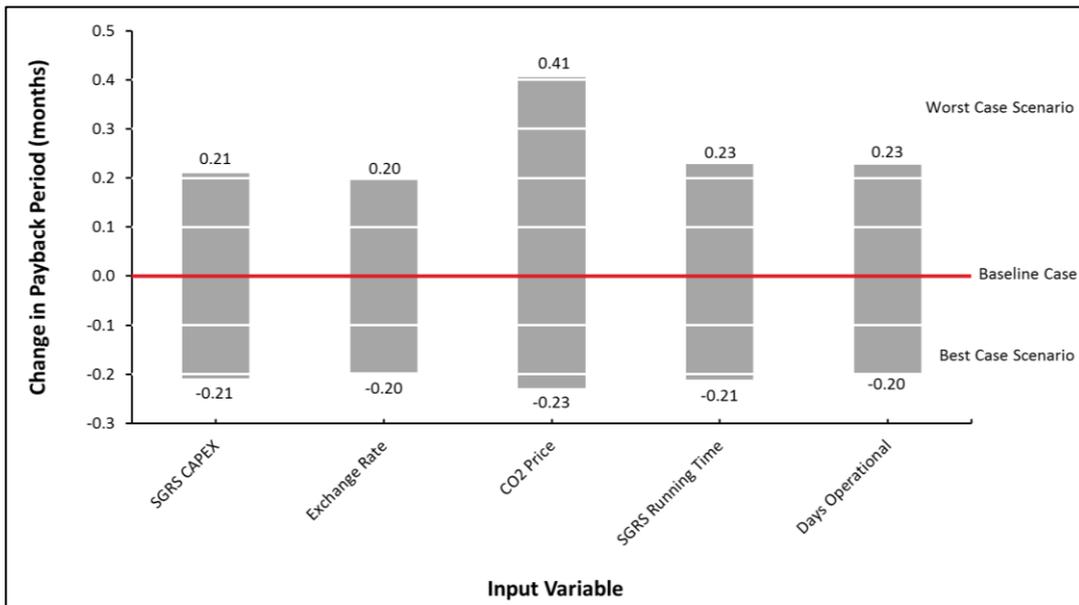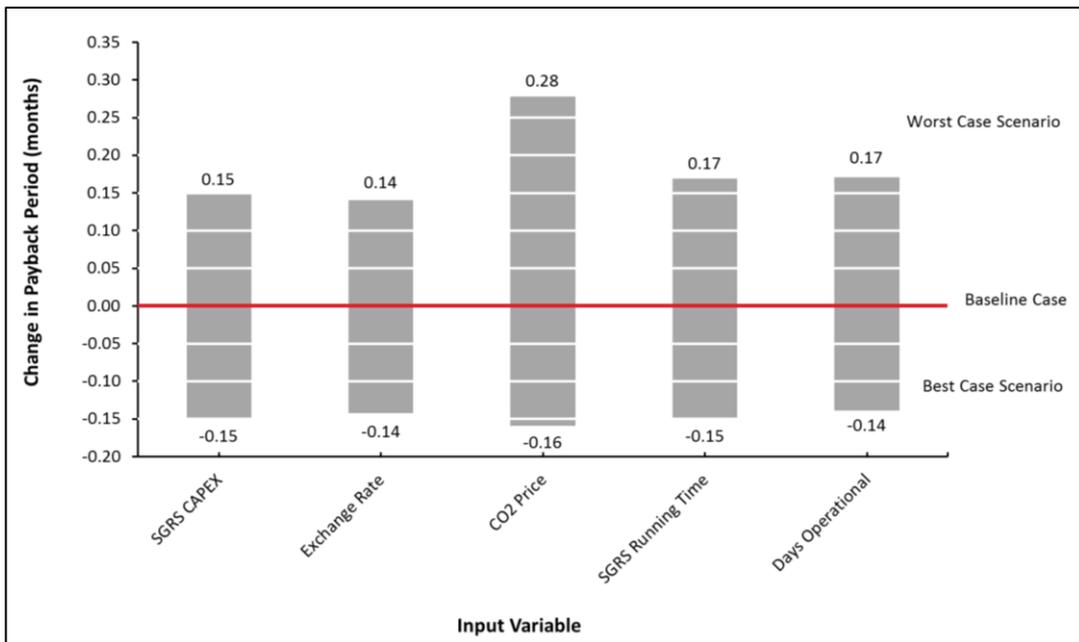
Figure 3.6: Extreme Change in Input Variables - Scenario 6 (500kg/h SGRS) - Expected change in project payback period when individual input variables are altered to possible extreme cases. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered to extreme cases.

3.2.6 Focused Sensitivity Analysis

Results from the extreme change in input variables study were used to determine the expected change in payback period per ±1% change in input variable. This result was investigated to find input variables that would have the largest impact upon the payback period of the project. Examples of this study can be seen in Figures 3.7 and 3.8, whilst the remaining results of the study can be found in Appendix F.

Figure 3.7: Focused Sensitivity Analysis - Scenario 6 (285kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±1% when based on extreme case results. The baseline case represents project payback period when baseline values for input variables are used.

Figure 3.8: Focused Sensitivity Analysis - Scenario 6 (500kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±1% when based on extreme case results. The baseline case represents project payback period when baseline values for input variables are used.

4.0   Discussion

The following section provides an in-depth analysis of the results found throughout technical and financial feasibility studies. Details outlining the integration of the amended system design to a typical abattoir, along with recommendations realised from the FFS regarding the implementation of proposed additions to a typical abattoir, have been included.

4.1   Implementation of the Amended System Design

The amended system design (outlined in Section 2.1.6) provides a method of integrating a closed-loop CO_2-NH_3 refrigeration system with an open-loop CO_2 liquefaction system. The current system design proposes to integrate PHEs between evaporators of the NH_3 refrigeration system with condensers of the CO_2 refrigeration system, CO_2 liquefaction system and cooling tower of the SGRS. This is only an initial design and requires further investigation to determine its technical feasibility. Items to be addressed in further study include:

- **NH_3 Refrigeration System Cooling Capacity** - As there are three PHEs proposed to be integrated to the NH_3 refrigeration system, the refrigeration capacity of the system must be investigated to ensure the condensing requirements of all three condensers will be met when they are run simultaneously.
- **Cooling Tower PHE Technical Feasibility** - The company supplying the SGRS has stated that it cannot assure food-grade CO_2 production if the cooling tower refrigeration system is replaced by a PHE between the cooling tower and the NH_3 refrigeration system. Because of this, further investigations must be made to assure food-grade CO_2 will still be produced by the SGRS if this design is used.
- **Specific Implementation Details** - Investigations into specific design challenges and conditions of integrating the SGRS with the NH_3 refrigeration system must be made.

4.2   Financial Feasibility Study Analysis

An analysis was undertaken into results gathered during the FFS, including relevant scenario comparisons, impacts of changing input variables by ±10% or to extreme realistic cases and the sensitivities of key input variables. Key findings of each study were discussed, with conclusions being made on the most financially feasible operating scenarios and the most sensitive input variables that have the potential to significantly affect the project's payback period.

4.2.1 Scenario Payback Period Analysis

Scenarios for both the 285 and 500kg/h SGRS systems were analysed to determine the most applicable operating conditions when implementing proposed additions to the abattoir. Comparisons between the individual scenarios, along with the two SGRS capacities were included.

4.2.1.1 Integrating the 285kg/h SGRS

Scenarios 2-6 were investigated when running the 285kg/h SGRS as scenario 1 (current CO_2 demand) was omitted due to yielding an uneconomical payback period. It can be seen in Figure 3.1 that scenario 6 yields the smallest payback period of 22.80 months, providing a 23.85 month decrease in payback period when compared to the second smallest payback period, scenario 4. The large decrease in payback period can be attributed to the increased sale of excess CO_2 or increased substitution of currently procured CO_2. This was expected, as the baseline price per kg of CO_2 is higher than water-based ice, whilst 1.33kg of CO_2 is needed to replace 1kg of water-based ice with dry ice as stated in Section 2.2.5.

Scenarios utilising excess biogas produced by the abattoir (4 and 5), unexpectedly show large variations in payback period. Scenario 4 shows the second smallest payback period of 46.63 months, whilst scenario 5 yields the largest payback period of 93.28 months (seen in Figure 3.1). Integrating an alternative form of power generation yields a relatively small payback period of 46.63 months, primarily as a result of its greatly reduced CAPEX compared to substituting natural gas currently used in steam boilers. Additionally, an alternative form of power generation provides a 49.5% increase in cost reduction per kg of biogas when compared to using biogas in steam boilers, as seen in Appendix G.

Operating the SGRS to solely meet possible CO_2 demand (scenario 2) can be seen to yield an uneconomical payback period. This can be attributed to a low sale price of water-based ice and minimal cost-reductions being made through the substitution of current cleaning methods. This also applies to scenario 3, although this scenario includes the sale of excess CO_2. This can be attributed to a small amount of excess CO_2 being captured when running the 285kg/h, leading to a small cost reduction for excess CO_2 sold.

4.2.1.2   Integrating the 500kg/h SGRS

Only scenarios 3-6 were investigated when running the 500kg/h SGRS, as scenario 2 only yields a larger payback period when compared to using the 285kg/h SGRS. Results displayed in Figure 3.2 display the respective payback periods of each scenario when running the 500kg/h SGRS. Similar trends can be seen when comparing Figure 3.2 to Figure 3.1; however, all scenarios show reduced payback periods. This can be attributed to the increased capture of excess CO_2, assumed to be sold back to market or used to substitute currently procured CO_2.

Scenario 6 yields the lowest estimated payback period of 15.81 months, with all other scenarios being significantly decreased compared to the 285kg/h SGRS. Integrating the 500kg/h SGRS appears to be the obvious option; however, it heavily relies on the sale of excess CO_2 or current CO_2 demands meeting the production capacity of the SGRS; thus, must be investigated further.

4.2.2   Scenario Practicality Analysis

The practicality of implementing each scenario must be assessed when comparing the payback periods for each scenario. Scenarios 2-5 all include the substitution of water-based ice with dry ice and current cleaning methods with dry ice blasting. These substitutions have been included in the FFS; however, raise the following concerns that must be addressed along with the sale of excess CO_2.

4.2.2.1   Water-Based Ice Replacement with Dry Ice

It has been proposed to replace water-based ice used for cooling applications of red-meat product with dry ice from the SGRS. However, dry ice has the potential to decrease the quality of the red-meat product due to frostbite. Frostbite can occur when dry ice is in contact with product as it has an extremely low temperature of -78.5°C (Helmenstine 2014), possibly decreasing its value. As a result, research into the direct physical effects of dry ice when contacting particular red-meat product currently being cooled by water-based ice must be researched in further detail.

The cooling capacity of dry ice compared to water-based ice is known and has been incorporated into the FFS. However, this only provides an estimate value with further investigation needed to determine the exact amount of CO_2 needed to substitute water-based ice when cooling red-meat product.

The price of water-based ice needs to be investigated further, due to large discrepancies in prices given in private correspondence with an abattoir and an Australian water-based iced supplier.

The procurement cost of water-based ice must equal or outweigh the procurement cost of liquefied CO_2 for this to be a feasible option.

4.2.2.2 Current Cleaning Methods Replaced with Dry Ice Blasting

It has been proposed to replace particular cleaning methods used at a typical abattoir with dry ice blasting. However, the practicality of implementing dry ice blasting as a primary cleaning method has not yet been justified as a technically or financially feasible option.

Dry ice blasting is a method of cleaning similar to that of sand-blasting, as it uses compressed air to project fine granules of dry ice on a surface to be cleaned (Cold Jet 2011). However, as the dry ice sublimates on impact with cleaning surface, it is considered a dry cleaning process, providing an improved solution compared to water-based cleaning and abrasive blasting methods. Dry ice blasting is currently used as a cleaning method in the food-processing industry (Cold Jet 2016); however, information regarding dry ice blasting in abattoirs was not found during a review of relevant literature. The thoroughness of dry ice blasting as a primary cleaning option must be investigated, as there are stringent health regulations that govern abattoir operations.

Financial information regarding current cleaning methods and prices was roughly estimated, leading to a rough approximation of its baseline value. As current cleaning methods are needed to help provide an estimate for dry ice blasting costs, the baseline value for this was also roughly approximated. As a result, Specific investigation into current cleaning costs and expected costs for dry ice blasting must be made on a case-by-case basis.

4.2.2.3 Sale of Excess CO_2

It can be seen that the sale of excess CO_2 has the potential to provide the project with a greatly reduced payback period. However, it is currently unknown if the sale of excess CO_2 is a practical option due to potentially flooding of the CO_2 market with the imminent introduction of a large CO_2 capture facility at the Torrens Island Power Plant in South Australia.

The CO_2 capture facility is expected to be operational in late 2016, capturing an estimated 50,000T of CO_2 per year that will be used to carbonate drinks and treat waste water (ABC 2015). Because of this, the market price of CO_2 may be driven down due to lack of demand. If this is the case, scenarios 3-6 will have increasing payback periods, depending on the drop in the market price of CO_2.

The sale of excess CO_2 can also be considered as there being enough CO_2 currently procured from specialist providers to operate the SGRS at maximum capacity. If captured CO_2 is used solely for this purpose, the payback period will be the same as the one found in scenario 6. It is more practical to consider scenario 6 as there being enough demand to operate the SGRS to maximum capacity to solely substitute currently procured CO_2, due to feasibility concerns of selling excess CO_2 being raised.

4.2.3 ±10% Change in Input Variable Analysis

A ±10% change in input variables was implemented in the FFS to investigate the effects on the project's payback period when changing input variables by the same amount.

4.2.3.1 ±10% Change - 285kg/h SGRS Analysis

The following points outline the main findings when input variables were changed by ±10% when the 285kg/h SGRS was employed. Further information regarding this study can be found in Appendix D.

- **Days Operational** - Apart from scenario 2 and 6, days operational will deliver the largest changes in payback period. This is a result of this variable having the largest impact upon the amount of excess CO_2 produced that can then be sold to market.

- **SGRS Running Time** - This variable also produced large changes in payback period due to the same reasons stated for days operational.

- **Cleaning Costs** - For scenarios 2-5, a ±10% change in cleaning costs offers significant changes in payback period, especially in scenario 2. This is due to it providing majority of the cost reductions for this particular scenario.

- **CO_2 Price** - The payback period for scenario 6 sees its largest variations when the price of CO_2 is varied by ±10%. This is due to all cost reductions being based upon the market price of CO_2.

4.2.3.2 ±10% Change - 500kg/h SGRS Analysis

The results found when analysing a ±10% change in input variables for the 500kg/h SGRS showed similar trends to the 285kg/h SGRS study. However, minor alterations can be seen and are discussed in the following points. Further information regarding this study can be found in Appendix D.

- **SGRS CAPEX** - As a result of the increased CAPEX of the 500kg/h SGRS, this variable now becomes significant.

- **Currency Exchange Rate** - Since the quote for the SGRS was given in EURO, the currency exchange rate also becomes a significant variable as a result of the increased SGRS CAPEX.

4.2.4 Extreme Change in Input Variable Analysis

Extreme realistic values for input variables were researched and implemented in the FFS to investigate their effect on payback period. Particular baseline values were given more extreme changes then others, as they were found difficult to estimate or had seen large fluctuations in the past.

4.2.4.1 Extreme Case - 285kg/h SGRS Analysis

The following points outline the main findings when extreme changes were made to input variables when the 285kg/h SGRS was employed. Further information regarding this study can be found in Appendix E.

- **Water-Based Ice Price** - For scenarios 2-5, water-based ice price proved to have the largest impact upon payback period. This was expected, as the substitution of water-based ice provides one of the main cost reductions for each scenario. Such large changes in payback period can be attributed to large discrepancies in price being given through private correspondence with an abattoir and an Australian water-based ice supplier.

- **Cleaning Costs** - For scenarios 2-5, cleaning costs also proved to have a large impact upon payback period. This was also expected due to costs for current cleaning methods being roughly estimated, leading to ±30% changes of its baseline value being used as the extreme cases.

- **Biogas Usage** - For scenario 5, biogas usage in steam boilers also provided a significant change in payback period. The steam boilers investigated are currently fuelled by 50%

biogas; however, this could be increased to 80% if all available biogas is used. As a result, the baseline value given was 65% usage, with extremes being 50% and 80% of biogas usage.

- **CO$_2$ Price** - CO$_2$ price had the largest impact upon payback period in scenario 6. This was due to the heavy reliance scenario 6 has on the price of CO$_2$ as all cost reductions are based on the sale of excess CO$_2$. A 30% drop in CO$_2$ price was given as the worst case scenario, to allow for the introduction of the Torrens Island Power Plant that may flood the CO$_2$ market, possibly lowering the market price of CO$_2$.

4.2.4.2   Extreme Case - 500kg/h SGRS Analysis

The 500kg/h SGRS showed similar trends to the 285kg/h system; however, showed a much greater reliance on CO$_2$ price, days operational and SGRS running time. The following points outline the main findings when extreme changes were made to input variables when the 500kg/h SGRS was employed. Further information regarding this study can also be found in. Appendix E.

- **CO$_2$ Price** - All scenarios are primarily affected from an extreme change in CO$_2$ price. This can be attributed to all scenarios producing an increased amount of excess CO$_2$ to be sold back to market.
- **Days Operational** - This variable was only given extreme changes of ±10% of the baseline case; however, still showed significantly impact on the payback period of the project. This can also be attributed to days operational heavily influencing the amount of excess CO$_2$ produced to be sold back to market.
- **Running Time** - Running time also has a significant effect on the amount of excess CO$_2$ produced. It has a similar effect on payback period as days operational; however, to a lesser extent. Running time was not found to be significant when running the 285kg/h SGRS, since running time could only drop to a minimum of 21.39hr/day as possible CO$_2$ demands of the abattoir had to be met.

4.2.5   Focused Sensitivity Study Analysis

The focused sensitivity analysis was undertaken to determine which input variables could be considered 'show stoppers' when regarding the payback period of the project. The analysis looked into the change in payback period per 1% change in input variable when based on results found in the extreme cases study.

4.2.5.1 285kg/h SGRS Sensitivity Analysis

The following points detail the major sensitivities of each scenario for the 285kg/h SGRS. The results of the sensitivity analysis can be seen in Appendix F.

- **Scenario 2** - The worst case scenario for cleaning costs proved to be the most sensitive input variable for the second scenario. This is due to the substitution of current cleaning costs contributing the majority of cost reductions for this scenario. However, A large difference in sensitivity between the best and worst case scenarios for cleaning costs can be seen. This is a result of the payback period being less sensitive to an increase in cost reductions when compared to a decrease.

- **Scenario 3** - Running time and days operational were found to be the most sensitive variables for the third scenario. This was expected due to these variables heavily influencing the amount of excess CO_2 captured by the SGRS. Cleaning costs were also deemed to be a sensitive variable for the same reasons outlined for scenario 2.

- **Scenario 4** - Similar trends can be seen between scenarios 3 and 4; however, scenario 4 shows a heavier reliance on days operational. This was expected, as the power generated through an alternative form of power generation is reliant on days operational. The form of alternative power generation was also quoted in EURO, leading to the currency exchange rate becoming more sensitive.

- **Scenario 5** - Once again, similar trends can be seen between scenario 5 and 3. However, biogas usage in steam boilers prove to be another sensitive input variable as a result of it being a major contributor to cost reduction.

- **Scenario 6** – The worst case scenario for CO_2 price was found to be the most sensitive input variable, with all other input variables showing similar sensitivities for both best and worst case scenarios. As all cost reductions for scenario 6 are dependent upon the price of CO_2, this was expected.

4.2.5.2 500kg/h SGRS Sensitivity Analysis

Results found in the 500kg/h SGRS study (seen in Appendix F) show similar trends to the 285kg/h system. However, results show a heavier reliance on running time and days operational for scenarios 3-5, along with the following points:

- **CO_2 Price** - The increase in excess CO_2 sale when using the 500kg/h SGRS leads to scenarios 3-5 being more sensitive to CO_2 price.

- **SGRS CAPEX** - As the SGRS CAPEX is increased when purchasing the larger system, SGRS CAPEX now becomes a significantly sensitive variable.

- **Currency Exchange Rate** - As the SGRS CAPEX quote was supplied in EURO, the currency exchange rate has also become a more significantly sensitive variable when compared to the 285kg/h SGRS.

4.2.6 Summary of the Financial Feasibility Study

The financial feasible study has provided a detailed insight into the payback period for the main six operating scenarios deemed applicable when implementing the proposed additions to an abattoir in correspondence with the project. Investigations into ±10% and extreme realistic changes to input variables used in the FFM were made, along with the sensitivity of each variable also being explored. The key findings of the FFS are outlined in the following points:

- The SGRS cannot be economically run to meet current CO_2 demand (substitution of currently procured CO_2) as CAPEX loan interest repayments outweigh any cost reductions to be made from the substitution of currently procured CO_2.

- As a result of the high sale price of liquefied CO2, scenario 6 provides the smallest payback period for both the 285 and 500kg/h SGRS, when assuming currently procured CO_2 demand is high enough to operate the SGRS at maximum capacity. Note that scenario 6 can be considered the same as operating the SGRS to maximum capacity when substituting current demands of procured CO_2, with excess CO_2 captured then being sold to market.

- Integrating the SGRS to meet possible CO_2 demand (substituting currently procured CO_2, substituting water-based ice used for cooling red-meat product and substituting current cleaning methods with dry ice blasting) has the potential to provide an economical solution, if prices for water-based ice and cleaning substitutions correspond with best-case scenarios.

- The 500kg/h SGRS will produce decreased payback periods when compared to the 285kg/h SGRS if demand to substitute currently procured CO_2 is high enough, or excess CO_2 can be sold to market.

- With current input variables, it is more economical to integrate an alternative form of power generation compared to increasing biogas usage in steam boilers. This is due to the alternative form of power generation's CAPEX being approximately half that of the latter option, with it also producing a larger cost reduction per kg of biogas used.

- The payback period of the project is most sensitive to changes in the market price of CO_2 when assuming demand to substitute currently procured CO_2 is high enough or excess CO_2 can be sold to market.

5.0   Conclusions

The project successfully investigated the technical feasibility of integrating a closed-loop CO_2-NH_3 refrigeration system and an open-loop CO_2 liquefaction system and the financial feasibility of integrating the CO_2 liquefaction system to a typical abattoir. A summary of the key findings from the project are as follows:

- The integration of a closed-loop CO_2-NH_3 cascade refrigeration system with an open-loop CO_2 liquefaction system is a technically feasible option for a typical abattoir.

- The integration of these two systems proves to be an uneconomical solution due to the following issues:
    - CO_2 liquefaction systems produce food-grade CO_2 that requires further purification to be integrated with the CO_2 refrigeration system.
    - The plate heat exchanger to be used for condensing the refrigerant system is 40 times oversized when condensing CO_2 for dry ice production.

- On-site steam boilers provide a rich source of CO_2 emissions in flue gas that can be captured and purified for dry ice production. Stack gas recovery systems (SGRS) provide a method of capturing CO_2 emissions to produce food-grade CO_2 for dry ice production.

- It was determine that operating the SGRS at maximum capacity, solely to substitute currently procured CO_2, provides the lowest payback period for all possible operating scenarios. However, if demand of currently procured CO_2 does not meet the CO_2 capture capacity of the SGRS, excess CO_2 captured can be sold to market to achieve the same payback period.

- Additional uses of dry ice at a typical abattoir (substituting water-based ice cooling methods and current cleaning methods with dry ice based methods) have proven to be an uneconomical use of liquefied CO_2, unless their prices correspond with best-case scenarios.

- The payback period of the project is most sensitive to changes in the market price of CO_2 when assuming the SGRS is operated to solely substitute CO_2 currently procured from specialist providers.

6.0   Recommendations

On completion of this report, the following aspects of research have been recommended for further investigation. They have been recommended with the aim of providing a more thorough review into the amended system design of the integrated CO_2 refrigeration and liquefaction systems and the feasibility of integrating a closed-loop CO_2 liquefaction system to a typical abattoir.

- The amended system design requires further investigation into the following points:
    - The NH_3 refrigeration system's capacity to provide condensing requirements to the CO_2 refrigeration system, CO_2 liquefaction system and CO_2 capture systems cooling tower using separate PHEs.
    - The technical feasibility of integrating a PHE between the CO_2 capture system's cooling tower and NH_3 refrigeration system when producing food-grade CO_2.
    - Investigations into specific design challenges and conditions of integrating the CO_2 capture system with the NH_3 refrigeration system.

- Research into the substitution of water-based ice with dry ice to cool red-meat product must be undertaken to determine if this is a technically feasible use of captured CO_2.

- Research into the technical feasibility of replacing current cleaning methods with dry ice blasting should be made, as it proved to be one of the most sensitive variables in the FFS. Specific areas of interest include which cleaning processes can be replaced, possible impacts on red-meat product quality and if dry ice blasting methods can meet stringent health requirements of the red-meat processing industry.

- A thorough CO_2 market analysis should be completed to determine if the sale of excess CO_2 is a viable option. Specific investigation into the impacts of the Torrens Island Power Plant and other large CO_2 capture operations expected to be undertaken in the near future should be researched. Potential sale avenues should also be included in the analysis to outline how excess CO_2 will be effectively distributed.

7.0   Bibliography

ABC 2015, *French company to carbon capture in Adelaide in Australia's first commercial attempt to burn emission-free fossil fuels*, viewed 27th January 2016, <http://www.abc.net.au/news/2015-06-04/agl-to-carbon-capture-in-adelaide/6521422>

Access Science 2014, *Dry Ice*, viewed 29th January 2016, <http://www.accessscience.com/content/dry-ice/205900>

ASCO 2015, *CO_2 Production Plants*, viewed November 2015, <http://www.ascoco2.com/en/products/co2-production-plants/>.

CCN 2012, *CO_2 makes a 21st century comeback*, viewed December 2015, <http://www.climatecontrolnews.com.au/news/c02-makes-a-21st-century-comeback>.

Cold Jet 2011, *What is dry ice cleaning?*, viewed 14th January 2016, <http://www.coldjet.com.au/what-is-dry-ice-cleaning.aspx>.

Cold Jet 2016, *Industry overview; Food processing and packaging*, viewed 15th March 2016, <http://www.coldjet.com.au/media/2640/Food-and-Packaging%202011.pdf>.

Danfoss 2010, *Cascade HC/HFC – CO_2 system*, viewed December 2015, <http://www.r744.com/web/assets/companybrochure/file/Cascade_HC_HFC_CO2_system.pdf >.

Danfoss 2014, *Danfoss Industrial Refrigeration*, Industrial Refrigeration Workshop Charlotte, NC.

EIGA 2008, *Carbon dioxide source qualification quality standards and verification*, viewed December 2015, <http://www.ascoco2.com/fileadmin/user_upload/ascoco2.com/Bilder_und_Dokumente/CO2-_und_Trockeneislieferungen/EIGA_Spezifikationen_CO2.pdf>.

Elite Soft 1995, *Cooling a house with ice*, viewed 29th January 2016, <http://www.elitesoft.com/sci.hvac/iticehou.html>

Energy.Gov 2016, *How has turbine power plants work*, viewed 25th January 2016, <http://energy.gov/fe/how-gas-turbine-power-plants-work>.

Engineering Toolbox 2016, *Fuel gases and heating values*, viewed 28th January 2016, <http://www.engineeringtoolbox.com/heating-values-fuel-gases-d_823.html >.

Freund, P & Kaarstad, O 2007, *Keeping the lights on*, Universitetsforlaget, Oslo, Norway

Haar & Gallagher 1978, 'Thermodynamic properties of ammonia', *Journal of Phys. And Chem. Reference Data*, vol. 7, no. 3, pp. 635.

Helmenstine, A 2014, *Touching dry ice*, viewed 28th of January 2016, <http://chemistry.about.com/od/howthingswork/f/touch-dry-ice.htm>.

Larose, C 2015, *Food grade CO_2*, viewed November 2015, <http://www.r744.com/web/assets/companybrochure/file/252_Linde_R744.pdf>.

Liu, H, Gu, Z & Li, Y 2002, *Simulation of NH_3/CO_2 two-stage low temperature refrigeration system*, Purdue University, Purdue e-pub

M&M Refrigeration of Federalsburg 2014, *Considering a CO_2 refrigeration-counting costs and comparing options*', viewed November 2015, < http://www.achrnews.com/articles/127234-considering-a-co2-refrigeration-system>.

Macdowell, N, Florin, N, Buchard, A, Hallett, J, Galindo, A, Jackson, G, Adjiman, C, Williams, C, Shah, N & Fennell, P 2010, 'An overview of CO_2 capture technologies', *Energy and Environmental Science*, vol. 3, no. 11, pp. 1645-1669.

NIST 2010, *NIST reference fluid thermodynamic and transport database (REFPROP): version 7*, National Institute of Standards and Technology, <www.nist.gov/srd/nist23.htm>.

Pacific Gas and Electric Co 2009, *Cascade CO_2/NH_3 refrigeration system efficiency study*, VaCom Technologies, viewed December 2015, <http://www.etccca.com/sites/default/files/OLD/images/stories/pg26e20et20project20report20uscs20fresno2030mar091.pdf>.

Peterson, R 2014, *Six reasons to consider a CO_2-NH_3 cascade refrigeration system*, viewed 25th November 2015, <http://stellarfoodforthought.net/six-reasons-to-consider-a-co2nh3-cascade-refrigeration-system/>.

Phillips, R 2015, *Surge Drums*, viewed December 2015, <http://www.haphillips.com>.

Shecco 2015, 'Guide to natural refrigerants in North America - State of the industry', Accelerate.

Sondalini, M 2001, *The cost of maintenance destroys your capital investments returns*, viewed 18th February 2016, <http://www.maintenanceresources.com/referencelibrary/ezine/thecostofmaint.htm>.

The Biogas 2009, *Biogas Composition*, viewed 25th January 2016, <http://www.biogas-renewable-energy.info/biogas_composition.html>.

Toogood, C 2012, *Cascade CO_2/NH_3 refrigeration – A sustainable system for the PRW industry*, Chicago, M&M Refrigeration Inc.

TPI 2015, *CO_2 – Production plant*, viewed December 2015, <http://www.tecnoproject.com/eng/CO2-Production-Plants-from-fuelcombustions.asp?target=2>.

Zero 2011, *Carbon capture and storage*, Zero Enussuib Resiyrce Organisation, Norway

8.0   Appendices

Appendix A - CO_2 Available in Steam Boiler Flue Gas

Values:

CO_2 produced per 1 million BTU (m_{co2}) = 53.07kg   (EIA 2015)

Energy released from natural gas (E_{ng}) = $20,000 \frac{BTU}{lb}$ (Engineering Toolbox 2016)

SGRS extraction efficiency (η_s) = 0.95

Analysis:

Amount of natural gas needed to produce 1 million BTU:

$$m_{ng} = \frac{1,000,000}{E_{ng}} = \frac{1,000,000}{20,000} = 50 \text{ lb} = 22.68\text{kg}$$

Amount of CO_2 extracted using the SGRS:

$$m_c = (m_{co2})(\eta_s) = (53.07)(0.95) = 50.42 \text{ kg}$$

Amount of CO_2 emitted per kg of natural gas combusted:

$$m = \frac{m_c}{m_{ng}} = \frac{50.42}{22.68} = 2.22 \text{ kg of } CO_2 \text{ per kg of natural gas combusted}$$

It is known that there is a 36% higher CO_2 content in biogas compared to natural gas. Therefore, the CO_2 content of biogas is:

$$m_b = (0.36)(m) + m = (0.36)(2.22) + 2.22 = 3.00 \text{ kg of } CO_2 \text{ per kg of biogas combusted}$$

Therefore, running the steam boiler at a biogas/natural gas ratio of 50/50 and 80/20 yield:

50/50: $\frac{2.22+3.00}{2} = 2.61$ kg of CO_2 per kg of fuel consumed

80/20: $(0.8)(3.00) + (0.2)(2.22) = 2.84$ kg of CO_2 per kg of fuel consumed

Appendix B – Input Variables of the Financial Feasibility Model

System Input Variables - Input variables used in the financial feasibility model regarding the operating conditions of the SGRS, alternative form of power generation, dry ice blasting equipment and when using excess biogas in steam boilers.

Item	Unit	Value
SGRS CO_2 Capturing Capacity	kg/h	285
SGRS Running Time	hr/day	22.0
Days Operational	day/month	21.0
CO_2 Substituted for Snow Production	T/month	19.0
Dry Ice for Dry Ice Blasting	T/month	10.1
Water-Based Ice Replaced by Dry Ice for Skins	T/month	63.0
Power Generation Turbine Capacity	kW	200
Power Generation Turbine Running Time	hr/day	20.0
Biogas used in Steam Boilers	%	65.0
Currency Exchange Rate	EURO/AUD	1.55

Capital Expenditure Input Variables - Input variables used in the financial feasibility model regarding the capital expenditure when integrating the SGRS, alternative form of power generation, dry ice blasting equipment and excess biogas in steam boilers.

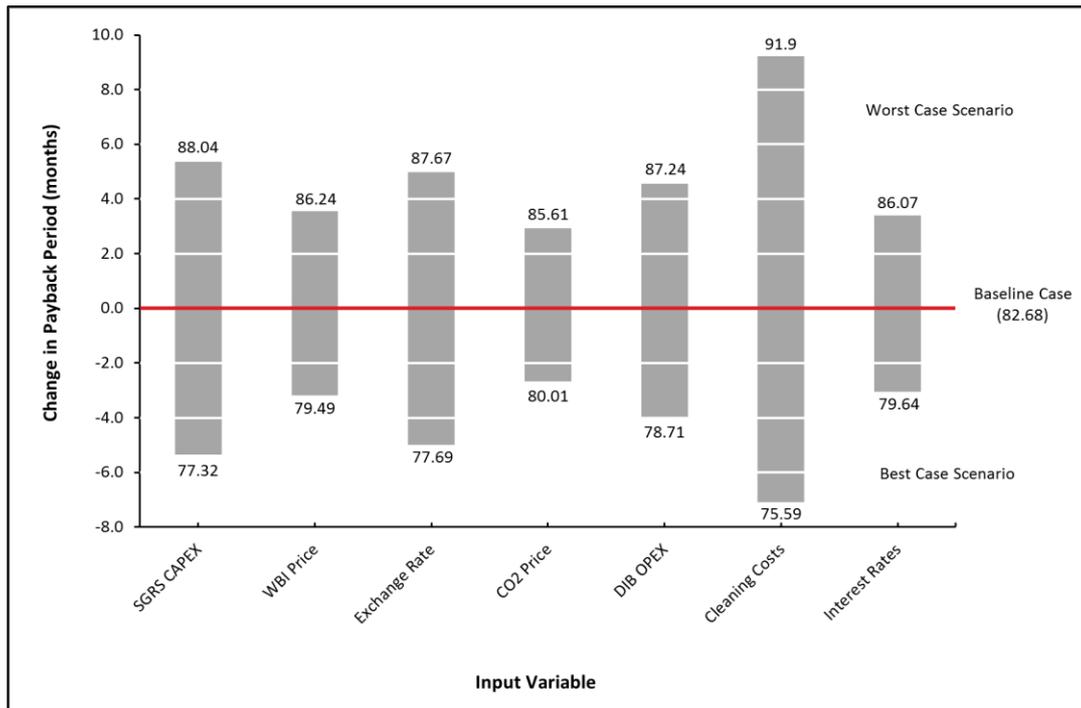| Item	Unit	Value
SGRS	EURO	720,000
Equipment Freight	EURO	21,000
Steam Boiler Exhaust Tapping	AUD	25,000
Flue and Liquid CO_2 Piping	AUD	5,000
Installation	AUD	54,000
Power Generation Turbine Equipment	EURO	120,000
Power Generation Turbine Equipment Installation	EURO	36,000
Increased Biogas in Steam Boilers	AUD	600,000
Dry Ice Blasting Machine	AUD	44,000
Dry Ice Pelletiser	AUD	95,000
Dry Ice Blasting Equipment Installation	AUD	41,700

Operational Expenditure Input Variables - Input variables used in the financial feasibility model regarding the operational expenditure when operating the SGRS, alternative form of power generation, dry ice blasting equipment and excess biogas in steam boilers.

Item	Unit	Value
Electricity Price	AUD/kWh	0.26
Water Price	AUD/kL	3.36
Monoethanolamine Price	AUD/kg	23.1
Soda Ash Price	AUD/kg	21.2
Potassium Permanganate Price	AUD/kg	18.8
SGRS Electricity Consumption	kWh/T CO_2	200
SGRS Water Consumption	kL/T CO_2	1.05
SGRS Monoethanolamine Consumption	kg/T CO_2	0.56
SGRS Soda Ash Consumption	kg/T CO_2	0.22
SGRS Potassium Permanganate Consumption	kg/T CO_2	0.12
SGRS Maintenance	AUD/month	3,430
Dry Ice Blasting Electricity Consumption	kW	8.50
Dry Ice Blasting Maintenance	% of CAPEX	4.00
Dry Ice Blasting Labour Costs	AUD/month	14,900
Power Generation Turbine Running Costs	% of CAPEX	1.00
Power Generation Turbine Maintenance	% of CAPEX	4.00
CO_2 Levies	AUD/T of CO2	10.0
Increased Biogas Maintenance	% of CAPEX	4.00

Cost Reduction Input Variables - Input variables used in the financial feasibility model that had the potential to affect cost reductions made by the SGRS, alternative form of power generation, dry ice blasting equipment and using excess biogas in steam boilers.

Item	Unit	Value
CO_2 Price	AUD/kg	0.55
Water-Based Ice Price	AUD/kg	0.20
Natural Gas Price	AUD/kg	0.26
Current Cleaning Costs	AUD/month	30,000

Appendix C – Input Variables Altered for Each Scenario

Input Variables used in the FFS - Displays which input variables were altered for each individual scenario when testing ±10% changes, extreme changes and input sensitivity.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
SGRS CAPEX	✓	✓	✓	✓	✓	✓
Currency Exchange Rate	✓	✓	✓	✓	✓	✓
CO_2 Price	✓	✓	✓	✓	✓	✓
SGRS Running Time	✗	✓	✓	✓	✓	✓
Days Operational	✗	✓	✓	✓	✓	✓
Interest Rates	✓	✓	✓	✓	✓	✓
Water-Based Ice Price	✓	✓	✓	✓	✓	✗
Dry Ice Blasting OPEX	✓	✓	✓	✓	✓	✗
Cleaning Costs	✓	✓	✓	✓	✓	✗
Biogas Usage	✗	✗	✗	✗	✓	✗

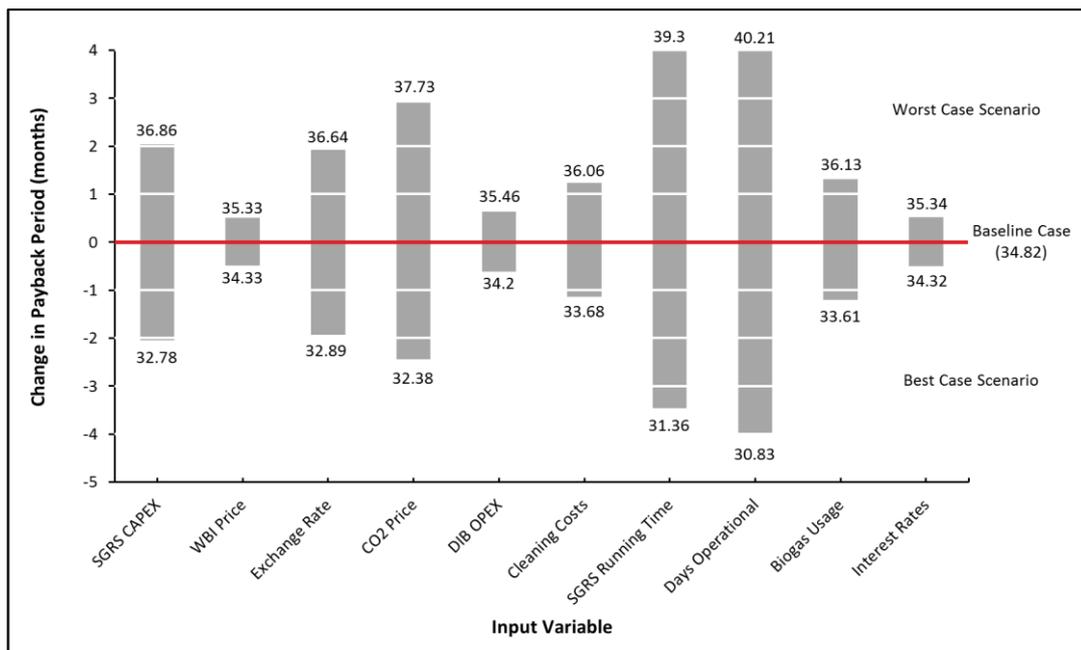## Appendix D - ±10% Change in Input Variable Plots

10% Change in Input Variables - Scenario 2 (285kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±10%. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered by ±10%.
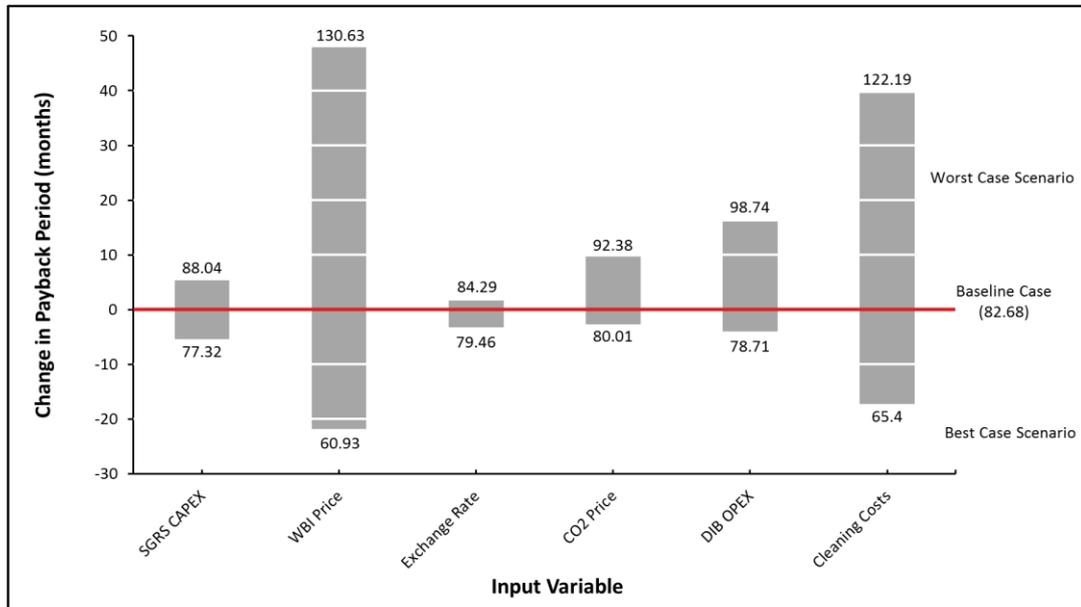
10% Change in Input Variables - Scenario 3 (285kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±10%. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered by ±10%.

10% Change in Input Variables - **Scenario 4 (285kg/h SGRS)** - Expected change in project payback period when altering individual input variables by ±10%. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered by ±10%.
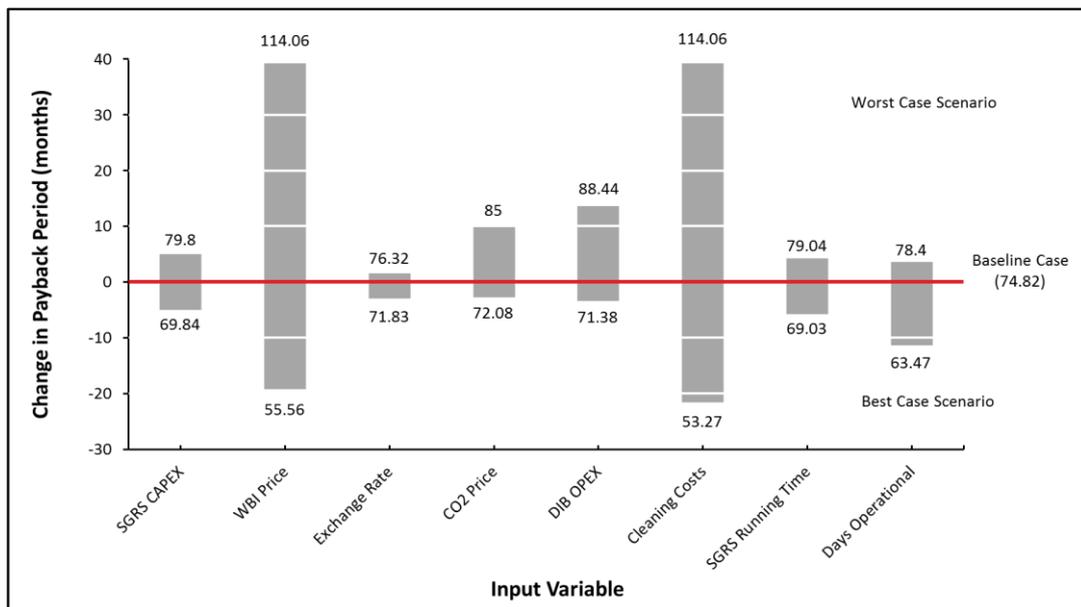
10% Change in Input Variables - Scenario 5 (285kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±10%. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered by ±10%.
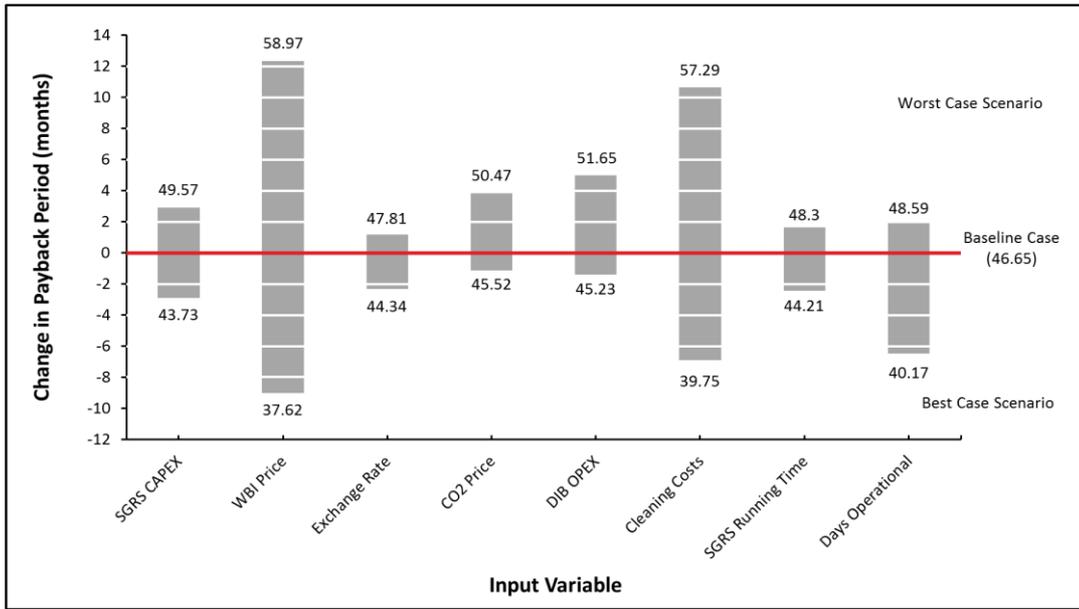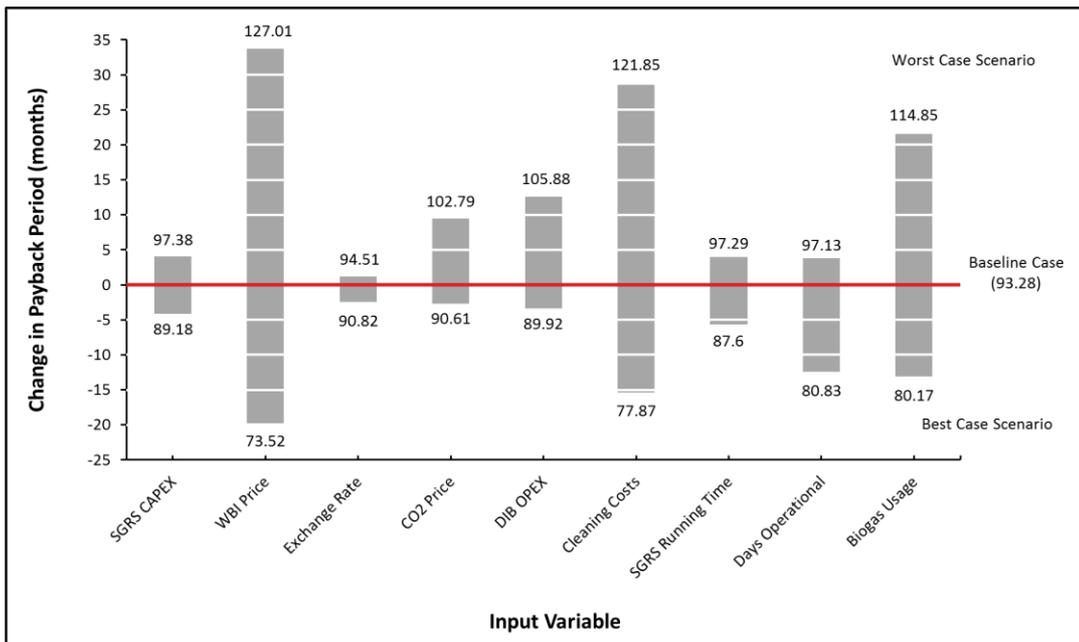

10% Change in Input Variables - Scenario 3 (500kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±10%. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered by ±10%.

10% Change in Input Variables - Scenario 4 (500kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±10%. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered by ±10%.

10% Change in Input Variables - Scenario 5 (500kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±10%. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered by ±10%.

Appendix E - Extreme Change in Input Variable Plots

Extreme Change in Input Variables - Scenario 2 (285kg/h SGRS) - Expected change in project payback period when individual input variables are altered to possible extreme cases. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered to extreme cases.
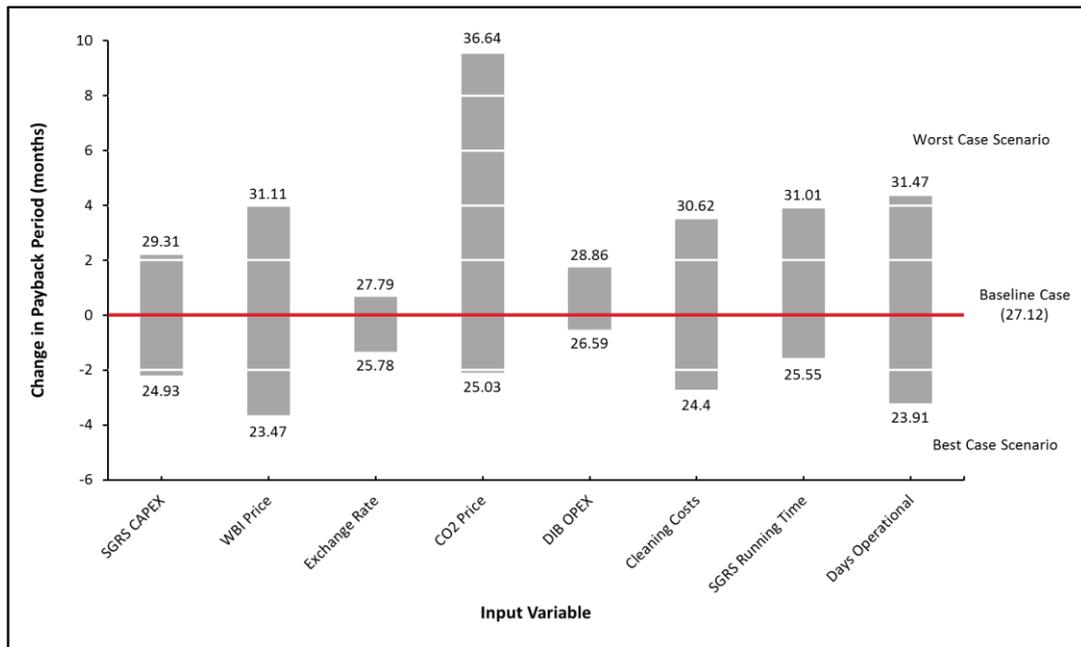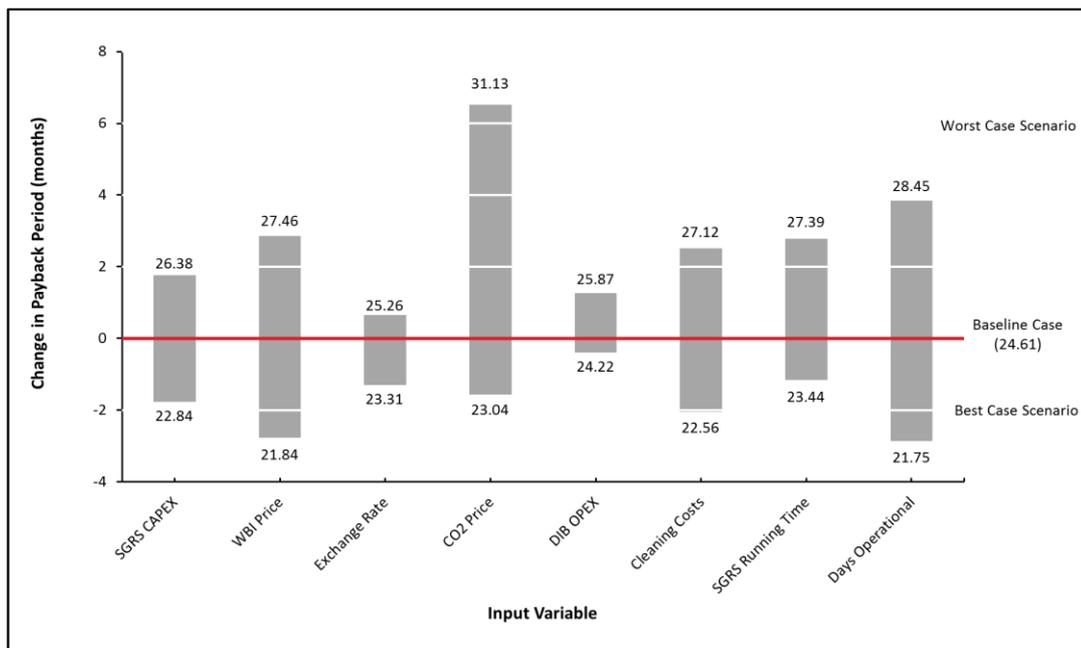

Extreme Change in Input Variables - Scenario 3 (285kg/h SGRS) - Expected change in project payback period when individual input variables are altered to possible extreme cases. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered to extreme cases.
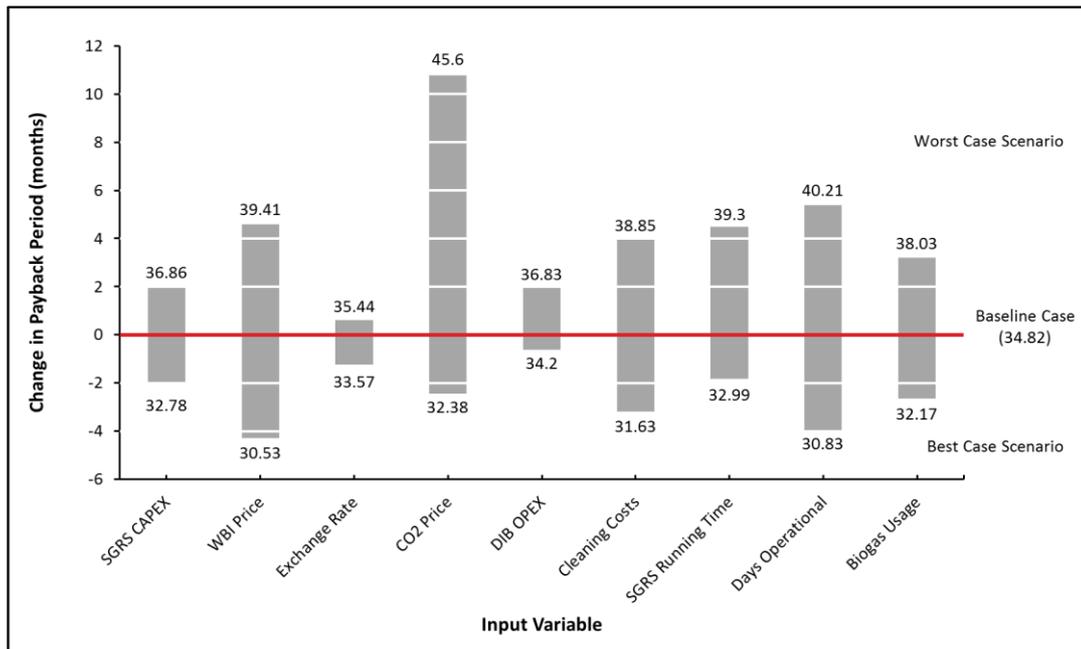
Extreme Change in Input Variables - Scenario 4 (285kg/h SGRS) - Expected change in project payback period when individual input variables are altered to possible extreme cases. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered to extreme cases.

Extreme Change in Input Variables - Scenario 5 (285kg/h SGRS) - Expected change in project payback period when individual input variables are altered to possible extreme cases. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered to extreme cases.
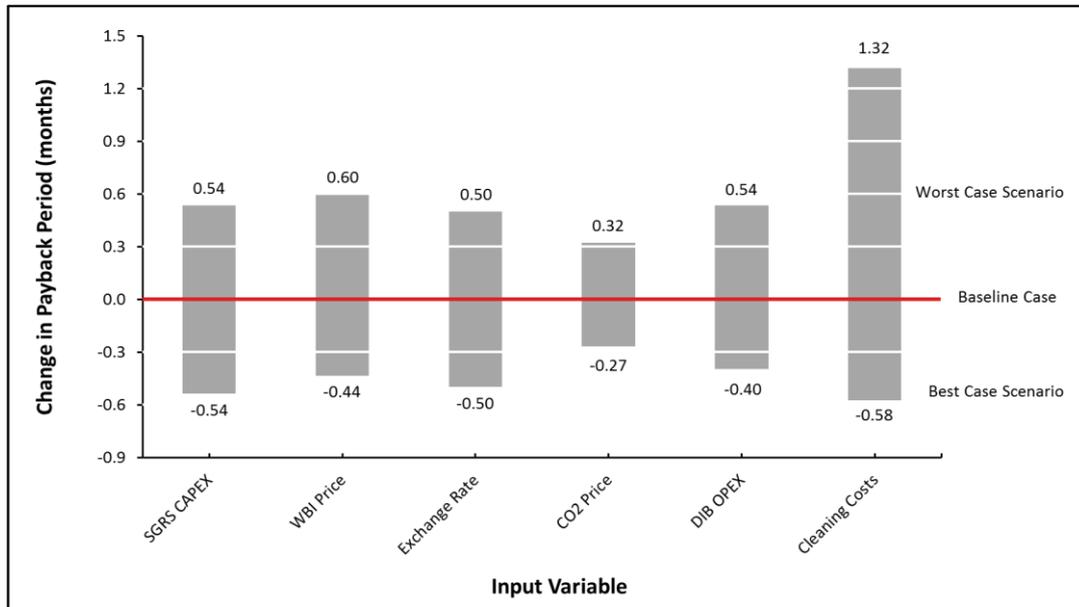
Scenario 3 (500kg/h SGRS) - Expected change in project payback period when individual input variables are altered to possible extreme cases. The baseline case represents project payback period when **baseline** values for input variables are used, whilst data labels represent project payback period when input variables are altered to extreme cases**.**
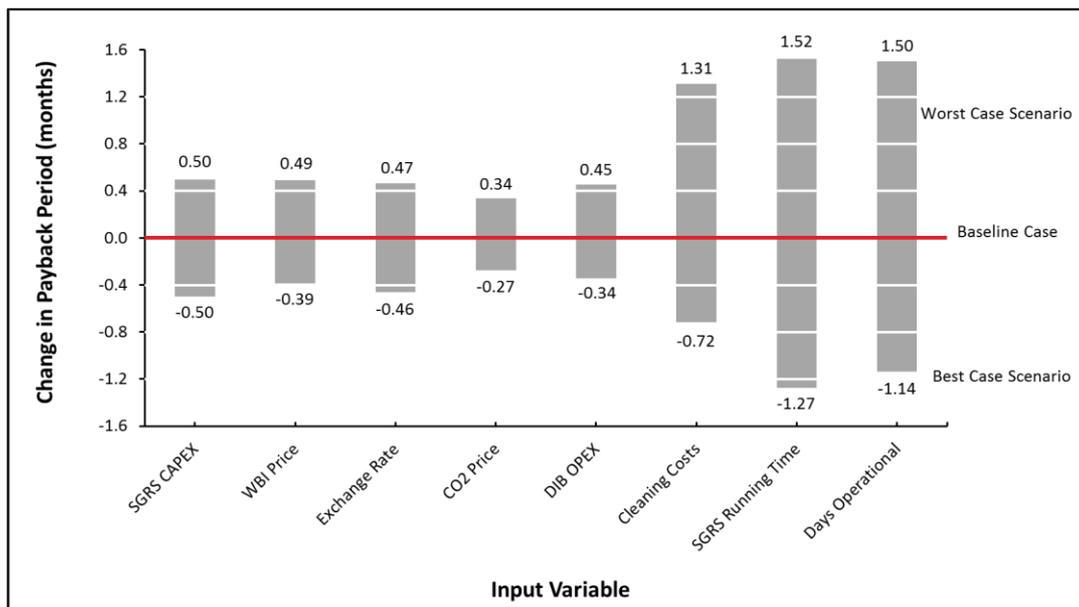

Extreme Change in Input Variables - Scenario 4 (500kg/h SGRS) - Expected change in project payback period when individual input variables are altered to possible extreme cases. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered to extreme cases.
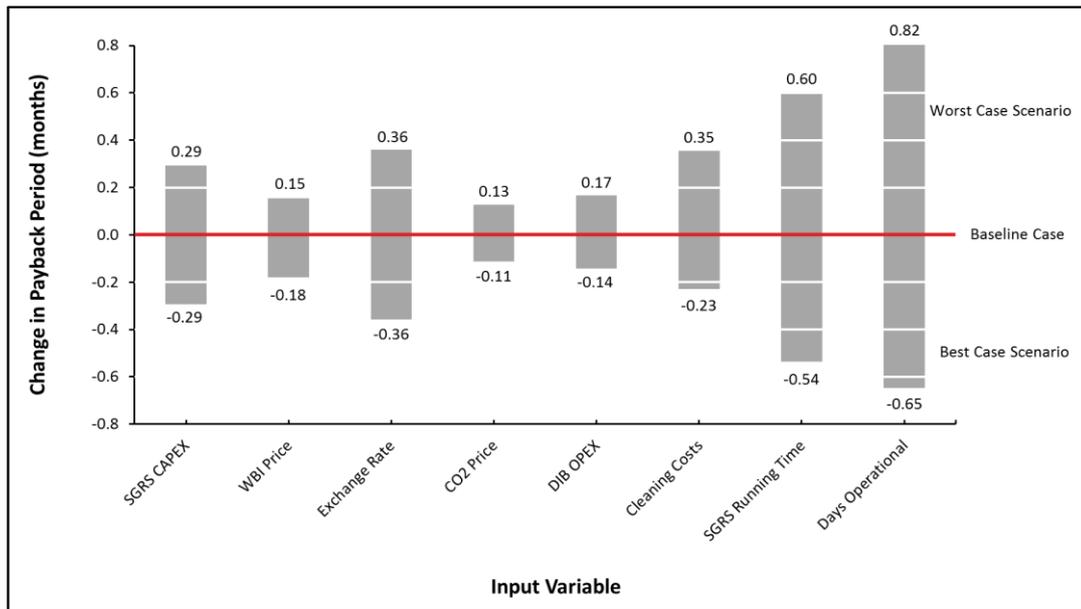
Extreme Change in Input Variables - Scenario 5 (500kg/h SGRS) - Expected change in project payback period when individual input variables are altered to possible extreme cases. The baseline case represents project payback period when baseline values for input variables are used, whilst data labels represent project payback period when input variables are altered to extreme cases.
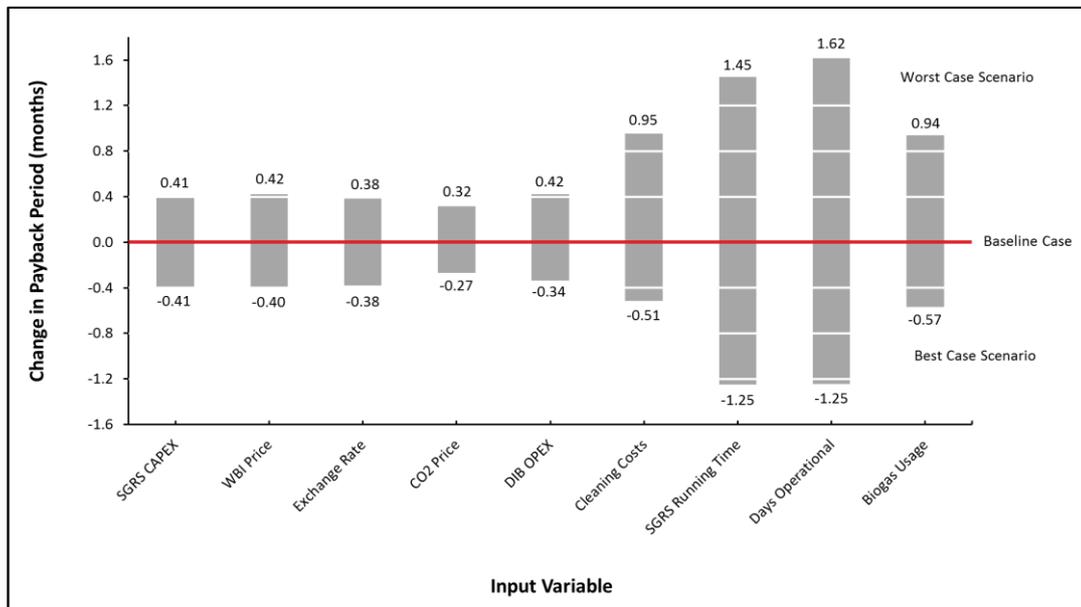
Appendix F - Focused Sensitivity Plots

Focused Sensitivity Analysis - Scenario 2 (285kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±1% when based on extreme case results. The baseline case represents project payback period when baseline values for input variables are used.
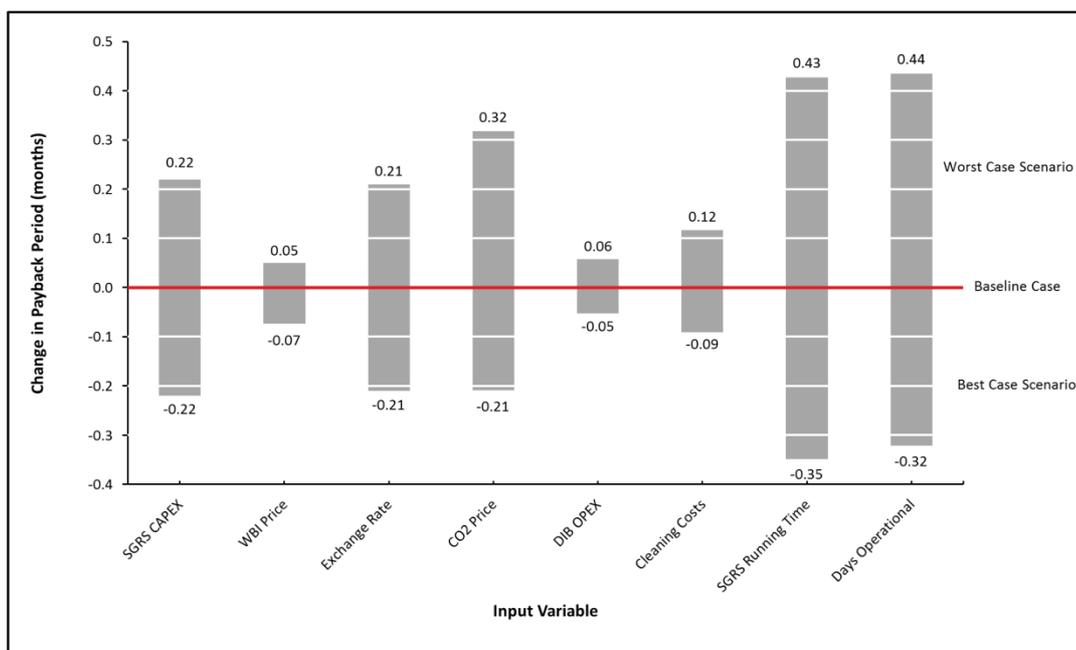

Focused Sensitivity Analysis - Scenario 3 (285kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±1% when based on extreme case results. The baseline case represents project payback period when baseline values for input variables are used.
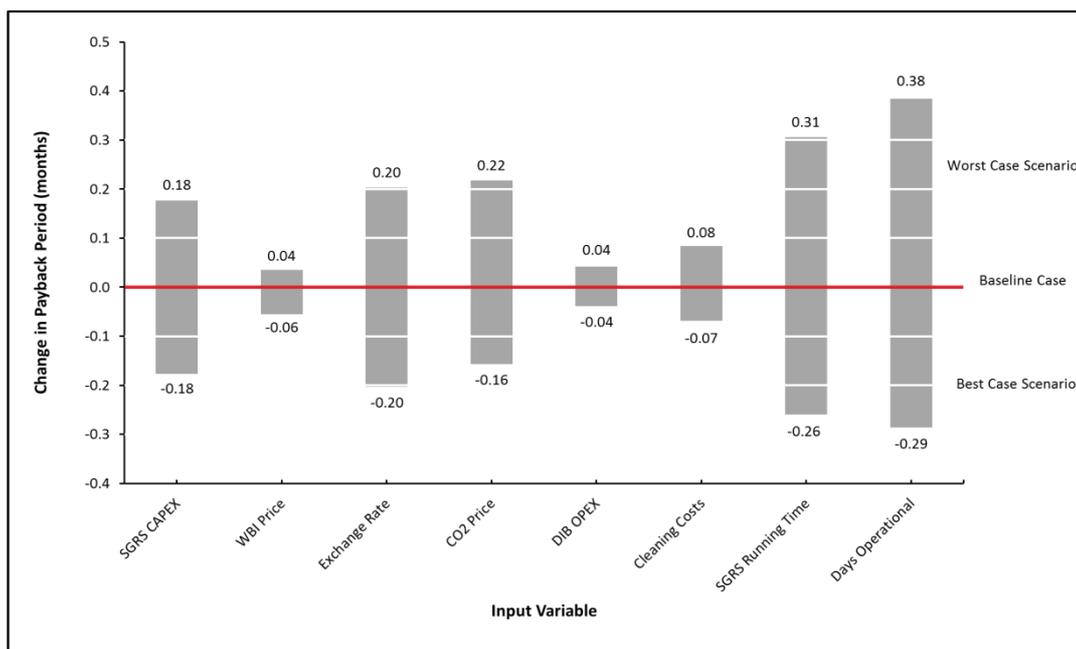
Focused Sensitivity Analysis - Scenario 4 (285kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±1% when based on extreme case results. The baseline case represents project payback period when baseline values for input variables are used.

Focused Sensitivity Analysis - Scenario 5 (285kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±1% when based on extreme case results. The baseline case represents project payback period when baseline values for input variables are used.
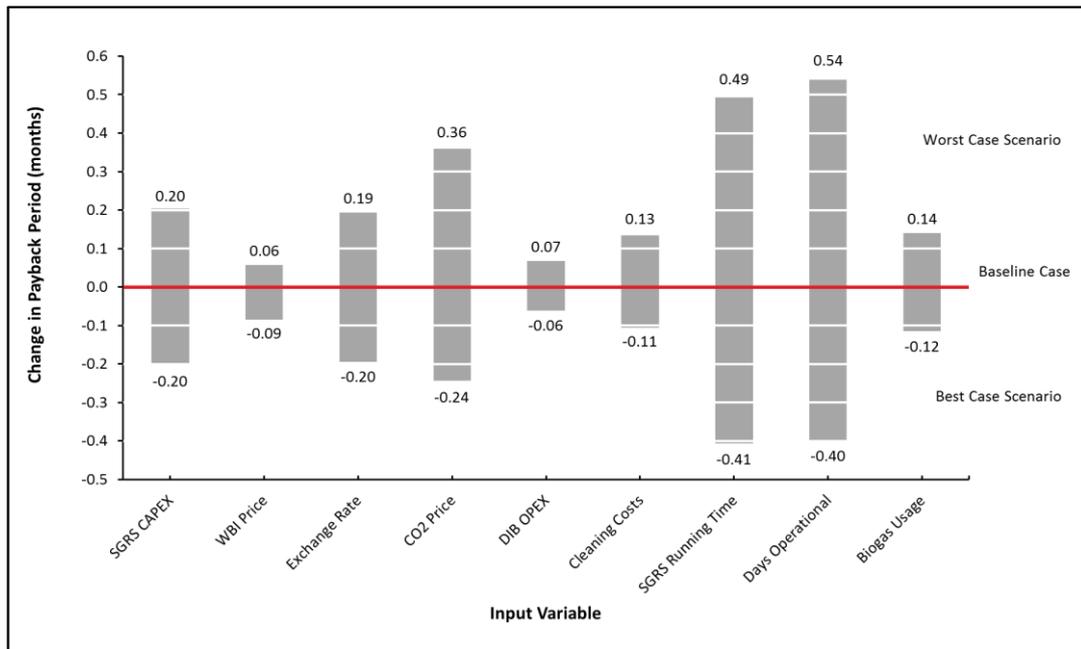
Focused Sensitivity Analysis - Scenario 3 (500kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±1% when based on extreme case results. The baseline case represents project payback period when baseline values for input variables are used.

Focused Sensitivity Analysis - Scenario 4 (500kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±1% when based on extreme case results. The baseline case represents project payback period when baseline values for input variables are used.

Focused Sensitivity Analysis - Scenario 5 (500kg/h SGRS) - Expected change in project payback period when altering individual input variables by ±1% when based on extreme case results. The baseline case represents project payback period when baseline values for input variables are used.

Appendix G - Alternative Power Generation vs Increased Biogas Usage Calculations

Values:

Power generation efficiency $(n_p) = 0.35$ (Energy.gov 2016)

Energy available in biogas $(E_b) = 6.8 \frac{kWh}{m^3}$ (The Biogas 2009)

Biogas density $(\rho_b) = 1.11 \frac{kg}{m^3}$ (The Biogas 2009)

Electricity price $(P_e) = \$0.24/kWh$

Natural gas price $(P_n) = \$0.26/kg$

Analysis:

Money saved per kg of biogas used for power generation:

$$S_p = \frac{E_b n_p P_e}{\rho_b} = \frac{(6.8)(0.35)(0.24)}{1.11} = \$0.515 \text{ per kg of biogas}$$

Cost savings of power generation compared to replacing natural gas with biogas:

$$\% \text{ Increase} = \left(\frac{S_p - P_n}{S_p}\right) \times 100 = \left(\frac{(0.515 - 0.26)}{0.515}\right) \times 100 = 49.5\%$$