Internship Report

CO_2 Utilisation and Power-to-X Possibility at Twence

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Acknowledgment

For the last three months from September – December 2017, I have done my internship in Twence. It was a great opportunity for me to have a working experience. Twence was a perfect platform to apply my knowledge in sustainable energy technology. I was assigned to a project of evaluating the possibility of carbon capture and utilisation as well as power-to-x technology. In this project I learned a lot of new insights especially on how an innovative company sets its strategy in a changing energy market condition. I also gain knowledge on combining engineering and business concept.

My sincere gratitude was addressed to:

1. The Almighty God, for all the health, capability, and perfect destiny to place me around very supportive people in this internship
2. Business Development and Strategy team of Twence for the countless discussions, remarks, time, and help during my internship, especially my supervisor Ido Sellis who has helped me arranging all the necessities in the company.
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J.K.P. Shaliha

Abstract

The fast development of renewable energy sources such as wind and solar in generating electricity has affected the electricity market, especially on shifting the price. This condition risks Twence in facing future energy market. On the other hand, Twence emits abundant amount of CO_2 that is valuable as a carbon source making sustainable product. Carbon Capture and Utilisation (CCU) and Power-to-X (PtX) concepts are promising for Twence forthcoming activities.

This study evaluated the possibility of realizing CCU-PtX technology at Twence. This report is divided into several chapters. In Chapter 1, a brief overview of Twence and the research set up are given. In Chapter 2, the possible CCU alternatives are identified and investigated. In Chapter 3, preliminary selection for choosing 3 most promising options are done by weighting score method. Chapter 4 describes the process simulation (using Aspen HYSYS v.8.8) of the base case scenarios to gain insights on the production/consumption volume in producing certain sustainable product. In Chapter 5, the economic study is carried out by comparing at the profitability indicators (Internal rate of return, net present value, and profitability index) of the preliminary-selected routes. A scaling possibility study of the most attractive business case is conducted in Chapter 6. Chapter 7 explains the potential risk and opportunities as well as the market overview of the final chosen and product. Finally, conclusion and recommendation for further study are drawn in Chapter 8. In a nutshell, at the reserved assumptions and limitations, the study concludes that the most attractive CCU-PtX alternative in Twence is formic acid production.

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Chapter 1. Introduction

The recent study combines the concept of Carbon Capture and Utilisation (CCU) and Power-to-X (PtX). The captured carbon in CCU refers to carbon dioxide (CO_2) as one component in flue gas effluent. Power in PtX in this project is attributed to renewable electricity generated from various kinds of waste while the “X” shows a wide range of final output that can be produced from utilizing the captured carbon and generated electricity.

1. 1. Company Overview

The recent study was carried out in Twence B. V from 5 September 2017 – 8 December 2017 under Business Development and Strategy team. Brief overview about company profile including the business activity as the main object of this study was explained in the following paragraphs.

1. 1. 1. Corporate

Twence B.V. is the largest waste processing company in Overijssel province. It was established in 2001 and was a former landfill back in 1986. The shareholders of Twence are municipalities who involve in setting the company’s main focus as well as energy supply to certain region. The municipalities basically want to incorporate social impact and returns within the regional economy. Until the end of 2016, the shareholders are Regio Twente, Vuilverwerkingsbedrijf Noord-Groningen and the municipalities of Almelo, Berkelland, Borne, Dinkelland, Enschede, Haaksbergen, Hellendoorn, Hengelo, Hof van Twente, Losser, Oldenzaal, Rijssen-Holten, Tubbergen, Twenterand and Wierden. Vuilverwerkingsbedrijf Noord-Groningen is a joint venture between the municipalities of De Marne, Eemsmond, Loppersum and Winsum.

1. 1. 2. Business activities

Aiming for circular economy, Twence processes an immense range of waste, such as recyclable waste, biomass, and non-reusable refuse-derived fuel. In its integrated waste processing facilities, the wastes are converted into renewable raw materials and energy. In the overall integrated process, Twence can recover ferrous and non-ferrous material as much as 14,000 tons and 4,000 tons respectively. The incineration process will produce 155,000 tons of bottom ash. The total steam production is 603 GWh while the generated electricity is 487 GWh. Most of the electricity is sold to the wholesale market through the public grid while the steam is delivered to Akzo Nobel (nearby chemical industry) and Ennaturlijk (Enschede district heating company). Due to the wide range of incoming waste stream, 54% of the energy produced is claimed to be coming from a non-fossil source.

In 2016, Twence successfully achieved turnover of € 107.8 million turnover from the sales of energy, and raw materials. It is equivalent with net profit of €12.1 million. The profit portion of Twente municipalities (€8 million) help the community in the region to do social and economic activities which are intended to upgrade the living quality. The current installed facilities are described in the following section.

a. Materials recycling facility

In 2016, Twence received 59,000 ton of the recyclable waste including commercial and industrial waste, construction and demolition debris, and oversized municipal solid waste. In the Materials Recycling Facility (MRF), these wastes are sorted. The waste wood will be sent to biomass incinerator as raw materials for producing green steam and electricity. The demolition waste and sand can be utilized for construction materials. Meanwhile, plastics, paper, ferrous, and non-ferrous materials will be sent out for reuse purposes.

b. Energy from Waste Plant

Currently, Twence has 3 lines of waste to energy plant (Afvalenergiecentrale, AEC) which incinerate 637,000 ton of non-recyclable refuse derived fuel into steam (592,000 MWh) and electricity (307,000 MWh). AEC line 1 (AEC-1) and line 2 (AEC-2) were built in 1997 while AEC line 3 (AEC-3) was just built on 2009. AEC-1 and AEC-2 has similar capacity while AEC-3 is two times bigger. The waste are burnt in the incinerator on a very high temperature of 850-1100^{o} C and the combustion heat is recovered by the boiler system attached to the incinerator, In the boiler, the water is converted into steam. Part of the steam goes to turbine and is converted into electricity. The waste combustion releases a huge amount of flue gas containing mainly N_2, CO_2, H_2O, excess O_2, and some traces of NO_x and SO_x. Due to the development of environmental regulation, during their lifetime, AEC-1 and AEC-2 have been attached to an additional flue gas treatment facility. Meanwhile AEC-3 installation is already equipped with flue gas treatment facility since the beginning. Being innovative, in 2014 Twence installs carbon capture facility in Line 3 which has CO_2 purity of more than 99%. The CO_2 is currently utilized to produce sodium bicarbonate (baking soda). The baking soda is used for own process in flue gas treatment.

c. Biomass Power Plant

The biomass power plant (biomassa-energiecentrale, BEC) was established on 2007. During 2016, it has combusted 185,000 tonnes of lower-quality wood and delivered 170,000 MWh of electricity. Part of the woods was obtained from the material recycling facility. In the coming years, Twence wants to build another biomass power plant that also produce steam instead of only electricity.

d. Bioconversion plant

Bioconversion plant consist of two major process which are anaerobic digestion and composting. The collected organic waste is first converted into biogas through anaerobic digestion by using specific bacteria. The solid fraction from the digester is then mixed with other organic waste and then be composted. The compost is sieved and contaminants were removed. Beside obtaining biogas from the anaerobic digestion, some biogas is also extracted from the existing landfill site. All these biogas is then converted into 11,000 MWh electricity and 11,000 MWh steam.

1. 2. Problem statement

The recent study was encouraged in Business Development and Strategy department in Twence due to an urge to overcome the following issues.

a. Disruption of renewable energy based electricity production resulting in decreasing electricity price

As mentioned in Section 1. 1, the main business activity of Twence is selling energy in terms of heat and electricity. However as can be noticed from Figure 1, the electricity price based on APX market shows significant shift towards a lower price in 2016 [1]. The average electricity price in 2014 and 2015 was around € 45/MWh while in 2016 it shifted to € 32/MWh. In the time being, Twence still has positive business case on electricity sales as the selling price is still higher than the production cost. However, the disruption of another renewable electricity producer such as solar and wind can bring down the electricity price further [2]. This risk urges Twence to look for another attractive business activity that can give an additional value to the generated electricity.

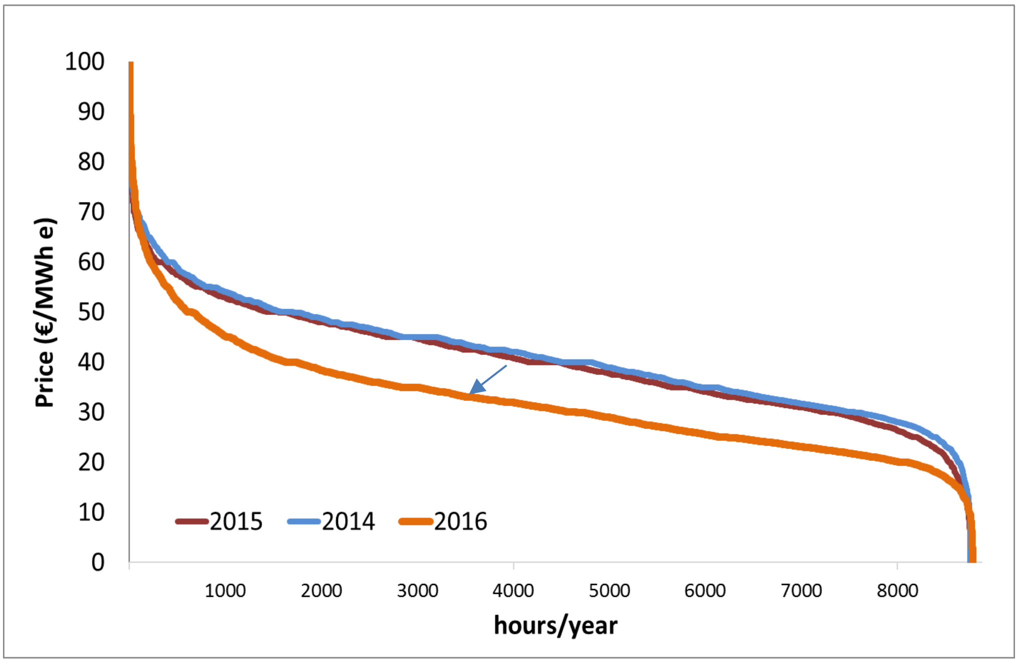

Figure 1. APX hourly price duration [1]

1. 2. 2. High volume of CO_2 emitted from the incinerator flue gas

Twence mainly process the incoming waste in its 4 lines of incinerators. The combustion product on any carbon-containing feedstock will have CO_2 in the flue gas. The emission of CO_2 in each line is listed in Table 1 with annual total production of 876.3 ktons.

Table 1. CO_2 emission volume in Twence [1]

Line	CO_2 emission (ktons/y)
AEC-1	165
AEC-2	175
AEC-3	319
BEC	213
Bioconversion	4.3

As a waste processing facility, Twence is legally allowed to emit CO_2 to the environment with no limitation. This is due to the fact that Twence main business activities already avoid the emission of 344,000 tonnes of CO_2 and consumption of 187 million m^3 of natural gas. However, CO_2 is a valuable carbon source beside biomass and is an important building block for various chemical and fuel production. Currently Twence captures part of the emitted CO_2 from AEC 3 and converts it into 8 ktons sodium bicarbonate/year. This renewable chemical production is estimated in annual reduction of CO_2 of 2-3 ktons/year [3].

1. 2. 3. Global demand and regional courage on a more sustainable product

The global awareness on circular economy has been emerging in the past decade. The mind set of seeing waste as a problem slightly shift to seeing waste a resource. Shortage on materials and fossil fuel was responsible for the need on reduce, reuse and recycle activity [4]. Since 2011 European Union has shown the commitment on reducing carbon dioxide emission. European Union encourages the application of carbon capture, storage, and utilisation by establishing related legislative and policy framework through its Framework Programme for Research and Innovation in Strategic Energy Technology Plan [5]. Moreover, European Commission offers a financial reward on its policy tools called The Horizon Prize for CO_2 Reuse. This programme is addressed for anyone who is able to come up with an idea to meet the challenge [6]. Business sectors are important actors for realizing the sustainable product. Their position in the whole value chain can affect other stakeholders to achieve the efficient and effective economic and environmental performances. Governments' instruments such as policy and regulation, bans, performance standards, and labelling scheme has been widely applied around the globe to address the sustainable product goal [7].

1. 3. Objectives

Based on the defined problems above, it can be understood that Twence needs to transform both generated electricity and captured CO_2 into a sustainable product. The primary objective of recent study is to evaluate the most suitable CCU and PtX routes.

The main objectives can be decomposed into:

i. What is the most suitable CO_2 utilisation routes to be coupled with existing Twence installation?
ii. How is the economic analysis on the selected route?

1. 4. Methodology

This feasibility study is carried out based on the following methodology as depicted in Figure 2.

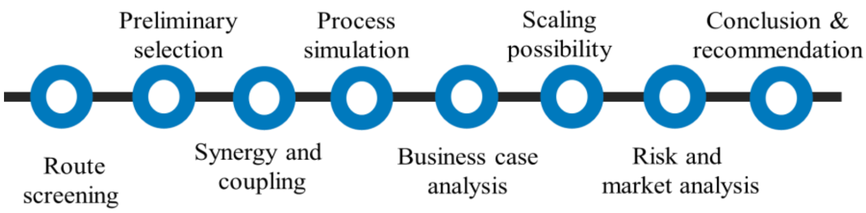

Figure 2. Timeline of the study

a. Possible route screening

The route screening is done mainly by literature review from various sources to have an extensive insight on the CCU project. It has to be noted that not all CCU options are aligned with PtX concept. However, due to enormous potential of CO_2 in Twence, it will be fruitful for the company if various CCU options are listed.

b. Preliminary route selection

The preliminary route selection is done by Weighted Scoring Method (WSM) in which all the possible CCU routes are prioritized based on several multidisciplinary criteria. The criteria are based on technology, economy, and applicability in Twence, including the alignment with PtX goal. The scoring of each criteria was done by literature review and discussion with Twence colleagues. In this step three routes were taken to be evaluated further.

c. Synergy with Twence resources

The base scenario parameters are adjusted by looking at Twence resources and limitation in the time being. The most important parameters are electricity consumption and CO_2 uptake.

d. Process simulation

The process simulation is done by Aspen HYSYS v.8.8 as a calculation tool for the mass and energy balance. Basic additional calculation was also performed in Microsoft Excel. Some assumptions were taken based on various references.

e. Profitability analysis

The capital investment, operational cost, and annual cash flow were firstly calculated to determine the economic performance. This performance was evaluated based on profitability criteria of internal rate of return (IRR), net present value (NPV), and profitability index (PI). Twence typical business case model was used to calculate the economic performance.

f. Scaling possibilities

After having the result of the base scenario performance, the most attractive route out of three chosen possibilities were analyse further to have either upscaling or downscaling based on situation and condition in Twence.

g. Risk and market overview

Risk and uncertainty is inevitable in doing any business activity. In this study, possible risk and opportunity were identified. The effect and brief recommendation on mitigation were also completed. Market overview of the chosen route was justified to see the current condition and outlook of the final selected product.

Chapter 2. Possible CCU Route Screening

2. 1. Material Application

In mineral application, CO_2 can be utilised basically for mineral carbonation, and curing agent. As curing agent, CO_2 is used to substitute water for curing modified cement [8]. This application is suitable for large project construction near the CO2 producers such as cement plant.

Mineral carbonation can be described simply as binding the CO_2 in various alkaline or alkaline-earth containing minerals to produce carbonates. The carbonation can be done in either direct or indirect route as presented in Figure 3. Direct route is suitable for minerals that are already rich in the alkaline or alkaline earth compound (Ca or Mg) while indirect carbonation requires an extraction step to activate the Ca/Mg compound. Common used minerals for carbonation processes are olivine, serpentine, and wollastonite [9]. The carbonates present in forms of calcium carbonate ($CaCO_3$) or magnesium carbonate ($MgCO_3$). The current challenges for mineral carbonation are the reaction rate and the reserves of the mentioned minerals [10].

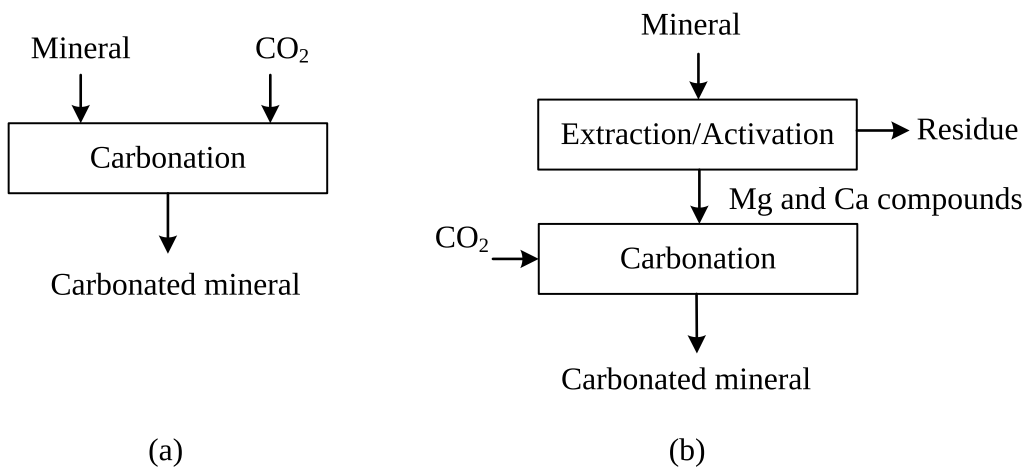

Figure 3. mineral carbonation (a) direct route (b) indirect route [10]

CO_2 also have the potential to help accelerating the weathering process of bottom ash that is produced in an incinerator plant such as Twence. Carbonation of bottom ash will have an effect on acid neutralization and trace metal leaching. It will also change the mineralogical composition of the bottom ash. The carbonation can advance the natural weathering from months to only few hours [11]. Beside bottom ash, metal slag also has the potential as a sustainable feedstock for mineral carbonation. The carbonated metal slag or bottom ash can be further processed for construction material purposes such as concrete, aggregates, or additive in shaped-end product [12].

Dutch Waste Management Association has a certain policy tool namely Green Deal which obligates all bottom ash producers to improve the quality of the bottom ash. In 2017, 50% of the bottom ash should meet the requirement for free use application while another half can be used in an isolated-constrained-monitored application. In 2020, all of the bottom ash should meet the free use application [13]. Thus, CO_2 utilisation in bottom ash would be seen as a must for Twence.

The current bottleneck for a viable mineral carbonation process on an industrial scale is the reaction rate of the carbonation reaction and reserves of certain minerals in natural rocks (olivine, serpentine, and wollastonite). Physical treatment such as size reduction and/or magnetic separation, and thermal treatment such as preheating are believed to help increase reaction rate [10].

Technology status of CCU in mineral application ranging from pilot to commercial scale. An overview of current status in various activities in some institutions is presented in Table 2.

Table 2. Technology status of CCU in mineral application [14]

Company	Status	Activity
Green Mineral	Pilot	Producing $MgCO_3$ from Olivine
Carbon 8 Aggregates	Commercial	Producing $CaCO_3$ from slag (residue)
Solidia	Commercial	Producing modified cement which bonds with CO_2 instead of water
Carbstone	In process to Commercial	Producing concrete-resembled material from slag

Carbon8Aggregates put investment of € 4.4 million for installing the plant with capacity of 110 ktons aggregates annually [15]. The cost estimation for Green Mineral product is ranging from € 46-59/ton [14]. Due to various construction materials, the estimated market size for CCU in material application is 80 million tons annually [10]. Carbon dioxide uptake in mineral application is for long term as it will not be released during the application of the final product.

2. 2. Food and Beverage Application

Carbon dioxide utilisation in food and beverage sector has been matured and has significant demand. In 2013, the market size was 11Mtonnes globally [16]. The gas is widely used to carbonate soft drinks as well as prevent fungi and bacteria in alcoholic beverages. As a food preservation, carbon dioxide presents in forms of dry ice. Furthermore, the dry ice has a wider application in process support such as sandblasting to remove paint, and chilling aluminium rivet [17].

Besides, supercritical CO_2 can be utilized for decaffeinating coffee and producing flavour and fragrances through distillation [18]. Carbon dioxide is at supercritical state at high pressure of 74 bar and 31°C. Before supercritical CO_2 becomes commercial in the market, methylene chloride or ethyl acetate was used to extract the caffeine in coffee beans. However, methylene chloride is harmful for human body and the ethyl acetate has high flammability and strong odour [19].

2. 3. Biological Use

For biological use, CO_2 is useful for algae cultivation and enhancing plant growth in green house.

a. Algae cultivation

In algae cultivation, CO_2 is bubbled through the ponds or bioreactors and is believed to increase the production rate. The production rate itself depends on what type of nutrient and cultivation scheme. Algae plantation has been mushrooming due to its growing market food and feed, pharmaceutical, and energy (biofuels) market [20]. Although it has a very high uptake potential, the economic potential for this CCU route is still uncertain since the algae transformation to biofuels and other applications are still in demonstration stage [21]. Compared to America and Asia, the market for algae in Europe is considerably smaller. With a productivity of around 200 tonnes algae/ha/year and CO_2 uptake of 1.8-2.0 tonnes CO_2/ton of algae produced, to supply high volume of CO_2, very huge algae plantation area is required [10], [21].

Algenol, an American company, invested USD 850 million on algae cultivation plant in Sonora desert which will utilize 6 million tons of CO_2 annually for producing 1 billion gallons of ethanol. The annual operating cost for running such algae plant is estimated to be USD 43,800 per hectare [22].

b. Green house

An advanced greenhouse planting system help The Netherland to be second largest food exporter in the world [23]. In greenhouses, temperature can be maintained at a certain warmth, that will support crops growth. Currently, around 70% of the Dutch greenhouses are heated by combined heat and power (CHP) system. The CO_2 from the fuel combustion can be supplied to the greenhouses and it fulfils 60% of the overall CO_2 needed. However, the heat can also be supplied from solar panel and geothermal system. In these systems, the greenhouses may need external sources of CO_2. Carbon dioxide level in greenhouses is set at a higher level (600-1000ppm) compared to atmospheric CO_2 level (400 ppm). It represents the demand of around 100 – 300 kg CO_2 per hectare per hour. The current CO_2 uptake in Dutch greenhouse sector is 500 ktons per year as can be seen from Figure 4 [24].

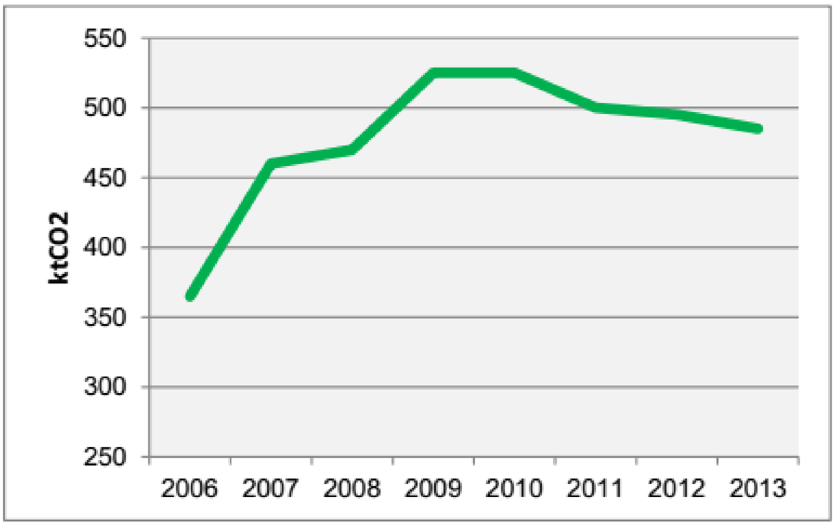

Figure 4. External CO_2 consumption in the Dutch horticultural sectors [24]

2. 4. Process Support

Process support refers to various application, where the CO_2 is supplied without any conversion. Some of the existing applications are welding, pneumatics applications, metal working, semiconductor cleaning, waste water treatment, urea yield booster, and enhanced oil recovery. In welding process, CO_2 is used to shield the arc at the welding wire tip. It prevents the oxidation of the metal [22]. Usually the CO_2 is used together with either argon or helium as the shielding gas [25].

a. Semiconductor cleaning

The increasing application of semiconductor material like in solar panel demands an enhancement in its cleaning technology. The semiconductor material cleaning can be done by wet cleaning and chemical methods. Unfortunately, these methods are associated with surface damage issue, by products generation and low cleaning effectiveness. Using CO_2 gas cluster cleaning is confirmed to have overcome the mentioned issues [26].

b. Urea yield booster

Urea has global market size of 100 million tons per year and it needs around 7 tons CO_2/ton of urea [10]. There is no wonder why urea production is among the biggest consumers of CO_2. Urea is produced by Stamicarbon process which has two steps including Reaction (1) and (2) [17]. In the first step ammonia is reacted with the carbon dioxide to form carbamate. The carbamate is then decomposed into urea and water. The first step is exothermic while the latter is endothermic. Urea production is conducted at 185-190^{o}C and at pressure of 180-200 atm [27].

$$2\,NH_3 + CO_2 \leftrightarrow\; H_2N - COONH_4 \tag{1}$$

$$H_2N - COONH_4 \;\leftrightarrow (NH_2)_2CO + H_2O \tag{2}$$

The CO_2 used in the first step was from a captive source of ammonia production through Haber-Bosch process. However, there is not enough captive CO_2 to convert all the ammonia to carbamate. By adding additional sources of CO_2, the yield of urea can be boosted [21]. This idea has been practised in industry since early 2000. However, as the market of urea has been saturated, and it has a volatile price and demand, the CCU option for this application is no longer attractive [22].

c. Enhanced hydrocarbon recovery

The application of CO_2 to recover hydrocarbon starts on Enhanced Oil Recovery (EOR) which has been known since 1980s. In this mature process, CO_2 is injected into a depleted crude oil reservoir. As the gas diluted within the oil, the viscosity of the fluid decrease and facilitate to flow upwards. The CO_2 uptake for EOR application was around 50 million tons per year. Most of the CO_2 was originated from the reservoir itself, thus the CO_2 cost is less than USD 20/ton.

Analogous to EOR system are Enhanced Gas Recovery (EGR), Enhanced Coal Bed Methane (ECBM), and Enhanced Geothermal System (EGS). EGR process differs from EOR as the mixing of the methane and CO_2 is minimal. The EGR is not considered attractive as it has low economical profit and is still immature. A EGR pilot experiment in the Netherland even has been discontinued. In ECBM, carbon dioxide is adsorbed by the coal and makes the methane released and easily be recovered at the surface. Until 2011, the technology status of ECBM was still on a pilot stage. CO_2 is utilized in ECBM in its supercritical state. The CO_2 can be used either as the heat exchanging fluid media or as the working fluid in its overall power cycle. The CO_2 uptake in this application is estimated to be 24 tons CO_2/MW. All of EOR, EGR, ECBM, and EGS has long term CO_2 uptake potential [22].

2. 5. Chemical and Fuels

CO_2 is a promising carbon source to form any hydrocarbon compounds and its derivatives such as alcohol, carboxylate, polymers and others. In each group, there are various chemical compound depends on the amount of carbon in each formula. The C1 compound in each hydrocarbon, alcohol, and carboxylate group are explained. The C1 from hydrocarbon group is methane, while from alcohol and carboxylate group is methanol and formic acid. In addition, the potential of producing polymer precursor is also investigated.

a. Methanol

In the conventional natural gas route, methanol is produced by three main steps, natural gas reforming to produce synthetic gas (syngas), methanol catalytic synthesis, and distillation [28]. Beside natural gas reforming, coal gasification is also widely known to produce the syngas. Renewable methanol can be produced by various options such as biomass gasification to produce syngas or through CCU and electrolysis of water using renewable electricity. Water electrolysis produces hydrogen which can be reacted with the captured CO_2 on the methanol reactor. Distillation is also needed to obtain methanol at a certain purity [21].

The CO_2 uptake potential of methanol is not permanent as the CO_2 is released to the atmosphere as the methanol burnt [14]. It needs around 1.4 tonnes of CO_2/ton of methanol and energy consumption of 45 MJ/kg methanol [29].

Commercial renewable methanol plant which incorporates the CCU has been built in George Olah, Iceland by Carbon Recycling International. It has capacity of 5000 tonnes methanol per year with investment of around € 15 million [21]. The operational cost for producing renewable methanol depends on the sources and is higher than the fossil-based methanol [29].

Methanol has considerable market size of 40 million tons annually [10]. This alcohol is an important chemical building blocks to produce other chemicals such as formaldehyde, MTBE, carboxylate, DME, and others. Methanol also has potential to be blended with gasoline [30].

b. Formic Acid

Formic acid was synthesized currently through two pathways including methyl formate hydrolysis and preparation of free formic acid from formates [31]. Most of the productions are done by the first method (81%). In methyl formate hydrolysis, methanol is firstly carbonylated with carbon monoxide to form in methyl formate. The methyl formate is then hydrolysed to formic acid and methanol. The chemical reactions are presented in Reaction (3) and (4).

$$CH_3OH + CO \rightarrow HCOOCH_3 \tag{3}$$

$$HCOOCH_3 + H_2O \rightarrow CH_3OH + HCOOH \tag{4}$$

Formic acid can be produced from formates if the formate production happens as a by-product or in other economically process. The formates such as sodium formate or calcium formate is reacted with strong acid such as nitric acid or sulfuric acid to yield formic acid and respective salt. The production of salt is unavoidable and becomes the major disadvantage of this pathway. The reaction example involving natrium formate with sulphuric acid is presented in Reaction (5)

$$2\,HCOONa + H_2SO_4 \rightarrow 2\,HCOOH + Na_2SO_4 \tag{5}$$

Renewable production of formic acid from CO_2 utilisation can be done in either thermochemical conversion or electrochemical reduction. In thermochemical route, the main feedstocks are the CO_2 and H_2 which is produced by water electrolysis using renewable electricity. After being captured, purified, and compressed, CO_2, together with H_2, and amine are reacted in a catalytic reactor resulting in FA-amine adduct. After going through catalyst and solvent recovery, FA-amine adduct is separated in distillation column [32].

In electrochemical reduction route, water and CO_2 are fed into the reduction cells. Electricity is supplied to reduce the reactants and produce formic acid [33]. The electrochemical reactor scheme is presented in Figure 5. Although having a more mature technology, thermochemical route has higher production cost compared to direct electrochemical reduction.

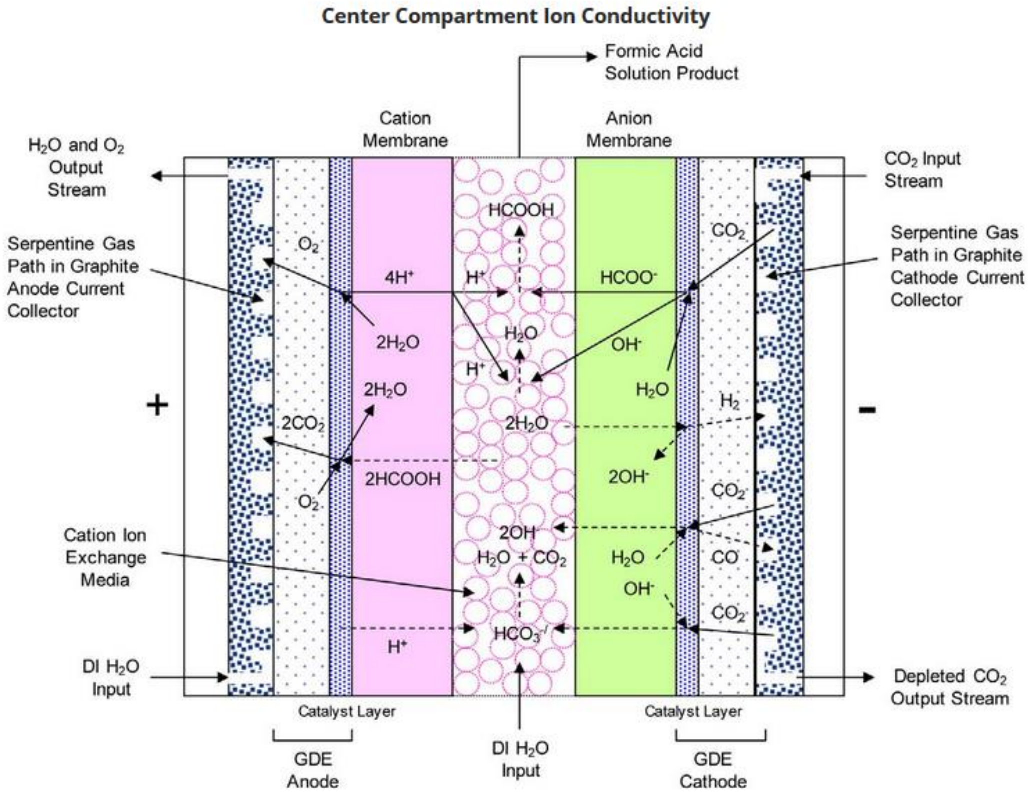

Figure 5. Electrochemical cell of CO_2 - to formic acid [34]

A feasibility study of CO_2 utilisation to produce formic acid via thermochemical route found a CAPEX of € 16 million to build 12 ktons formic acid per year [32]. While COVAL estimates an investment of around € 4 million to install electroreduction plant of CO_2 to formic acid with capacity of 3 ktons/year [33]. The production cost for producing renewable methanol through electroreduction is USD 250-300 per ton formic acid [33]. Meanwhile, the thermochemical pathway, the cost is € 1524/ton formic acid [32]. Compared to methanol, the market size of formic acid is much smaller It is 400 ktons per year [10]. Current players of renewable formic acid producers are DNV GL and Mantra Venture group. In 2007, DNV (2007) built a small-scale demonstration plant which has the production capacity of 350 kg formic acid annually. Mantra Venture Group finished works on a pilot plant, which is able to produce 35 tons of formic acid per year. Both companies apply direct electrochemical reduction [32].

c. Methane

Methane, the main component in natural gas is one of the major chemical building blocks. The renewable production of methane can directly reduce the consumption of natural gas and consecutively CO_2 emission. CCU application to produce methane can be done through thermochemical catalytic conversion, biological technology, or electrochemical reduction.

The catalytic conversion of methane is highly exothermic. The typical operated temperature is 200°C – 500°C at pressure between 1 to 100 bar. Presence of catalyst such as Ni, Ru, Rh, and Co can support the reaction. The conversion can be done in either fixed bed, fluidized bed, three-phase, or structured reactor [35].

Biological methanation comprises methanogenic microorganisms as biocatalyst. The process mainly occurs in three stages: hydrolysis of organic substrate into monomers, conversion of the monomers to acetate, carbon dioxide, and hydrogen, and lastly the aceticlastic methanogenesis and hydrogenotrophic methanogenesis. The process happens in mild condition with temperature of 20ºC – 70ºC and 1 – 10 bar. Biological methanation involves digester to convert the biomass into methane and CO_2, and a methanation reactor to convert the CO_2 with hydrogen. The digestion and methanation can be done in the same or separate unit operation [35].

The electrochemical reduction refers to reduction of CO_2 and water directly to methane. Water is supplied from anode while the CO_2 is fed from the cathode. The selectivity and conversion of this process highly depends on the used electrode and electrolyte, as well as the given potential. Unsuitable process condition can lead to the major production of impurities. Yet, the appearance of impurities is inevitable [36].

The current projects of renewable methane production are a thermochemical conversion plant by Etogas and microbiological methane synthesis by Audi and Viesmann Group [14]. The required investment of methane production relies on the electrolyser price and the methanation reactor. Current electrolyser has price range of 1000-2000 EUR/kW while the methanation reactor needs investment of around 1000 EUR/kW SNG [37].

d. Polymer

CO_2 utilisation in polymer industry is potential to replace part of fossil-based precursor. CO_2 is firstly utilized to form polyol by reacting it with epoxide with support of certain catalyst (i.e.DMC catalyst). Polyols are precursors to other chemicals such as polyurethane if it is reacted with isocyanate. The reaction steps are presented in Reaction (6) and (7) [38]. Beside CCU, renewable polyol can also be produced from vegetable oils [39].

$$CO_2 + Epoxide \xrightarrow{DMC\ Catalyst} Polyol \tag{6}$$

$$Polyol + Isocyanate \rightarrow Polyurethane \tag{7}$$

The market size for polyols is 2.8 million tons per annum [38] and the polyurethane is 14.2 million tons per year [40]. Polyurethane is used to manufacture foam, mattresses, furniture, shoe soles, and others. Polyurethane production CO_2 uptake is 1,7 kg CO_2/kg polyurethane. Bayer and Covestro has built a CO_2-based polyol in Dormagen, Germany with capacity of 5000 tonnes by investment of € 15 million [38]. In addition, a pilot plant has also been installed in surface water treatment plant Enschede [41].

2. 6. Protein Production

Renewable protein production aims to close the carbon and nitrogen loop. The production scheme overview is depicted in Figure 6. This process overlaps with waste treatment process to obtain the ammonium and CO_2. The ammonium and CO_2 are then reacted with hydrogen generated by electrolysis in a biological reactor. The solid part of the reaction product is dried and refined. Finally, the protein and prebiotics are obtained [42].

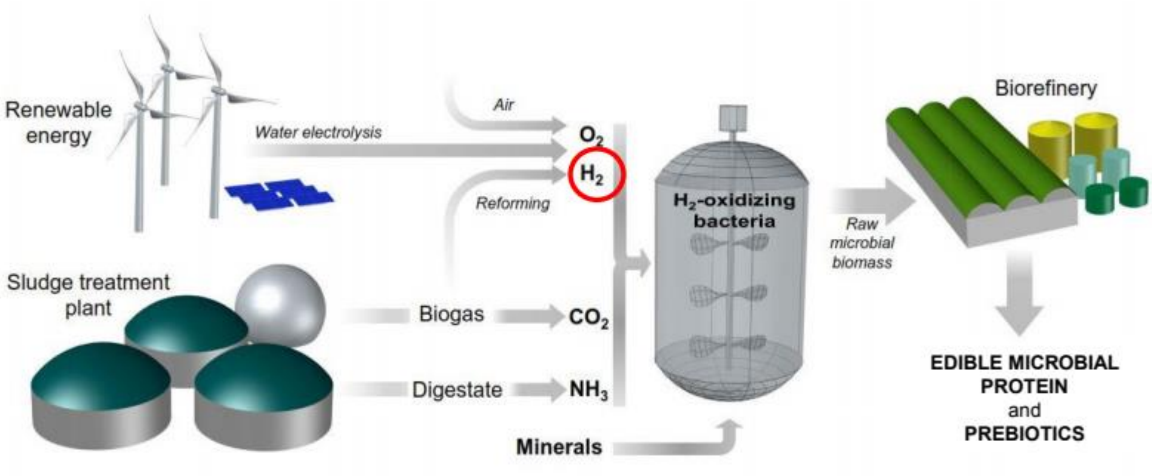

Figure 6. Power to protein scheme

Avecom, as a leading company in such renewable protein production still estimates the investment needed while the operating cost has been estimated to be around 1,1 EUR per kg protein produced. Energy requirement for this process is 452 MJ/kg protein, much lower than the conventional route that takes 4000 MJ/kg protein. Currently, pilot plant has been built in Enschede. The long-term application for this protein is on food, livestock feed, and various industries such as paper processing, leather production, and foam stabilizers [42].

Chapter 3. Preliminary Selection

The preliminary selection of the possible routes is done by the weighted scoring method (WSM). This decision-making method have widely been used for evaluation and selection of several possibility [43]. The straight quantification can indicate which alternative should be prioritized. As the method is very subjective, multidisciplinary analysis from various perspective is needed. In this study, the input was taken by discussion and literature review.

3. 1. Weighted Scoring Method

Supposed there are i CCU routes alternatives with j deterministic criteria. Each alternative is given score on each criterion. The score shows the performance of each alternative on each criterion. All the individual score is multiplied by each criterion weight. And the product is sum up to obtain the final score. The illustration of the weighted scoring method is shown on Table WSM and where the final score is calculated by Eq. (1).

Table 3. Illustration of weighted scoring method on each alternative and criterion

Alternatives	Criterion 1	Criterion 2	..	Criterion j	Final score
	W1	W2	..	Wj	
A1	S11	S12	..	A1j	F1
A2	..	..	..	A2j	F2
..	..	..		..	…
Ai	Si1	Si2	..	Aij	Fi

$$Fi = \sum_{i=1;j=1}^{i=9;j=6} Wj\, Sij \qquad Eq. (1)$$

3. 2. Deterministic Criteria

The chosen criteria are technological status, market and economy, and applicability at Twence. The weight of each criterion is assumed to be similar, 30% for the technological status, 30% for the market and economy, and the highest weight of 40% is for the applicability in Twence. The technological status is based on the technology readiness level (TRL). The market-and-economy criterion is decomposed to sub criteria of market and economy. Market sub-criterion reflects the market size, market acceptance, or any competitors on sustainable production. Economy sub-criterion indicates the capital and operational expenditures and revenue. Applicability in Twence criterion is divided into several sub-criteria: feedstock and energy, added value to CO_2, and added value to electricity. Feedstock and energy sub-criterion represents the ease and availability of the two factors. The added value of CO_2 is chosen to see whether the final product implements any conversion that gives added value to the CO_2 or it is only CO_2 that is supplied to the customer. The added value of electricity is determined the implementation of PtX concept in each possible CCU routes. As mentioned in Chapter 1, this study combines the concept of CCU and PtX to overcome the previously defined problems in Section 1. 2.

3. 3. Scoring

The scoring parameters for each criterion is presented in Table 4. The score is set as 1, 2, and 3 for most criteria except the added value given to CO_2 and electricity.

Table 4. Scoring parameter

(Sub) Criterion	Scoring Parameters
TRL	3: The selected route already or nearly has a commercial scale plant 2: The selected route already or nearly has demonstration scale plant 1: The selected route is still on lab-scale
Market	3: The selected route has maximum one barrier on either market size, market acceptance, and the presence of competitors on sustainable production 2: The selected route has maximum two barriers on either market size, market acceptance, and the presence of competitors on sustainable production 1: The selected route has barriers on all market size, market acceptance, and the presence of competitors on sustainable production
Economy	3: The selected route has low capital and operational expenditures and high revenue 2: The selected route has either high capital investment, operational expenditures, or low revenue 1: The selected route has high capital investment, high operational cost, and low revenue
Feedstock and energy	3: The selected route feedstock and energy is easily found and available for Twence 2: The selected route has limitation on an available and affordable feedstock and energy for Twence 1: The selected route feedstock and energy is hardly available and affordable and
CO_2	3: The selected route converts CO_2 into new product 1: The selected route supplies CO_2 is in bulk
electricity	3: The selected route implements Power to X concept which requires significant demand for electricity 1: The selected route does not implement Power to X concept

a. Material application

For materials application, the TRL is set to 3 as company like Carbon8Aggregates and Solidia has successfully built commercial plant [14]. The market criterion is set to 3 as there are no opposition towards sustainable materials construction and the market size is high. The application is also encouraged by government and regional institutions. The economy criterion is set to 3 as the capital and operational cost as well as the revenue are comparable to the conventional material production. Further, the producers can have incentives from relevant government. The feedstock-and-energy criterion is set to 2 as most of the carbonates production relies on the reserves on natural rocks like olivine, serpentine, and wollastonite. However, for application in bottom ash and metal slag, the feedstock reserves are not considered as problems. The added value of CO_2 of materials application is set to 2 as for Twence the possible materials application is for accelerating the weathering process and later on the bottom ash is sold as free-use construction material. The material application route does not use implement PtX concept and does not use significant amount of electricity. Yet the electricity is still needed for operational purpose such as moving belt conveyor.

b. Food and beverage application

The food and beverage application has mostly mature uses of CO_2, thus the TRL criterion is set to 3. The market size for this route is high, however it faces acceptance problem as the CO_2 source in Twence is from waste. Although the purity is sufficient for food grade application, there is still scepticism in using waste-based CO_2 for food and beverage use. Hence the score for market criterion is set to 2. The economy criterion is set to 3 as the costs and revenue is considerable with the conventional CO_2 processing in this sector. The feedstock and energy criterion is set to 3 as there is no certain feedstock needed for preparing the CO_2. Most of the food and beverage routes application supply the CO_2 in bulk, so the added value CO_2 criterion score is set to 1. Unfortunately, food and beverage does not implement PtX concept, so the added value electricity score is defined as 1.

c. Biological use

In biological use, the CO_2 has been extensively used to enhance the growth of the crops in algae plantation and greenhouse. Thus, the TRL score is set to 3. There is no opposition regarding the use of CO_2 to help crops growth, and market size is large, thus the market criterion is set to 3. Algae production is land-intensive that may require a lot of investment, however the other economic parameters are considerable, thus the economic criterion is set to 2. Algae cultivation and greenhouse application does not need any complicated feedstock and needs no large amount of energy, so the feedstock-and-energy criterion is set to 3. The added value of CO_2 criterion is set to 1 as Twence claims that the company will not build algae plantation in the time being and will only supply CO_2 as bulk. Algae cultivation and green house application does not implement PtX concept, so the added value electricity score is set to 1.

d. Process support

As a process support, CO_2 has been used since early 20th century [22]. Nearly all application needs CO_2 to be supplied as bulk. Thus, the TRL is set to 3 while the added value of CO_2 is set to 1. The market is growing from some applications, yet there are a lot of competitors that can supply sustainable CO_2. So, the market criterion is set to 2. Huge market in CO_2 application as process support drives a high revenue on this sector, meanwhile the CO_2 production cost can still be covered with the CO_2 market price. Hence, the economy of this application is set to 3. In this application sector, feedstock and energy criterion is valued to 3 as there is no specific feedstock and energy is necessary, only for capturing, conditioning, and transporting the CO_2. Added value of electricity is scored to 1 as the PtX concept is not realized.

e. Fuel and chemical production

As there are a lot of promising application of CO_2 in fuel and chemicals, more detail selection in each functional group is brought. As described in previous chapter, all fuels and chemical production in CCU requires electricity for conducting the electrochemical reaction. So, the added value electricity for polymer, carboxylate (formic acid), alcohol (methanol), and gas (methane) production is scored to 3. Commercial plant has been built for CCU application in producing polymer, methanol, and methane, thus the TRL criterion for these three products is 3. Formic acid production is set to 2 as the current status is still on demonstration plant [32]. For all fuel and chemical production, there is market barrier on other sustainable CO_2 producers (i.e. captured CO_2 from power plant). Polymer, especially polyol has a limited market size and the demand growth is bounded on chemical industry (fuel is not relevant). Hence, the market criterion value for polymer production is set to 2, while for other 3 products, the score is 3. Looking at the economy criterion all the process needs electro reduction cell that requires huge investments. However formic acid, polymer, and methanol has high market price that may cover the huge investment. On the other hand, following the natural gas price, methane production is subjected to low market price. Because of the mentioned reasons, the economic criterion for polymers, formic acid, and methanol is set to 2, while for methane the score is set to 1. In polymer production, epoxide is needed as feedstock for synthesizing the polyols. Besides, isocyanate is also needed for producing the polyurethane. Because both epoxide and isocyanate are fine chemicals which are not available currently at Twence, the feedstock criterion is set to 1 for polymer production. The major feedstocks for methanol, formic acid, and methane production are only water and CO_2. So, the value for feedstock criterion for the three options is set to 3. As there is an added value for each fuel and chemical production, the added value of CO_2 is set to 3. Because the PtX concept is realized in all fuel and chemical production the score for added value of electricity is also set to 3.

f. Protein production

In protein production, the TRL criterion is set to 2 because a demonstration plant has been installed in Enschede [41]. Facing barrier in terms of CO_2 production competitors, and possible market opposition, the market criterion is set to 2. The requirement of electrolyser to produce hydrogen makes the investment huge, meanwhile the revenue is estimated to be low because the protein demand still can be fulfilled from another natural resource (animal and plant). Therefore, the economic criterion is set to 1. The feedstock needed for producing protein is CO_2, water, and wastewater sludge. Twence has to look for a sustainable supply of wastewater sludge to be able to conduct this production. The feedstock criterion is set to 2. As the final product is not CO_2 and PtX concept is implemented, then the score of these two criteria are set to 3.

3. 4. Final Score

The summary of alternative scoring on each criterion as well as the final score is presented in Table 5. It can be noticed that methanol and methane seem to be the most promising alternative for CCU and PtX application in Twence. Equal final score is found on both material application and formic acid production. Referring to the obligation of Dutch Waste Management Association that bottom ash should be processed into free use application in 2020 [13], and this processing requires CO_2 consumption to enhance the weathering step, then the material application especially in bottom ash processing is not evaluated further. It is more interesting to bring the possibility of formic acid into comparison with methane and methanol production as implementation of CCU and PtX in Twence.

Table 5. Scoring summary

Routes	TRL	Market and Economy		Applicability			Final Score
		Market	Economy	Feedstock & Energy	Added Value CO_2	Added Value Electricity	
	30%	15%	15%	10%	15%	15%	
Materials	3	3	3	2	3	1	2,55
Food and Beverage	3	2	3	3	1	1	2,35
Biological Support	3	3	2	3	1	1	2,35
Process support	3	2	3	3	1	1	2,35
Polymers	3	2	2	1	3	3	2,40
Formic Acid	2	3	2	3	3	3	**2,55**
Methanol	3	3	2	3	3	3	**2,85**
Methane	3	3	1	3	3	3	**2,70**
Protein	2	2	1	2	3	3	2,10

Chapter 4. Process Simulation

Process simulation is done to have a deeper overview of volume production, energy and utilities requirement. It is also helpful in determining the relevant operation unit prices. However, this study does not cover the sizing of each unit operation. Process diagram and operating condition on each chosen possible route were adapted from various literature. The mass balance calculation and part price estimation were done by Aspen HYSYS v.8.8. Complete mass balance is provided in Appendix A.

4. 1. Base Scenario Justification

Annually Twence produces 0.9 million tonnes of CO_2. Twence aims to make use around 10% of the available CO_2. However, the CO_2 uptake requires different electricity consumption on each selected alternative. The base case scenario was justified by firstly seeing the stoichiometric calculation on each alternative and identify the key factor of electricity consumption. After that, the electricity consumption is estimated by evaluating the current efficiency status on each route.

4. 1. 1. Methane Production

Methane (CH_4) synthesis in this study follows the major reaction on Reaction (8)

$$4\,H_2 + CO_2 \rightarrow CH_4 + 2\,H_2O \qquad (8)$$

Where the hydrogen is produced by Reaction (9)

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \qquad (9)$$

From the stoichiometric calculation it is known that every 1 ton of CO_2 needs 0.18 ton of H_2 that is produced by electrolysis of water. If the H_2 energy content is assumed to be 0.0394 MWh/kg-H_2 and the current electrolyser efficiency is assumed to be 70%, it means that the electrolyser requires 10.1 MW electricity for every 1 ton/h of CO_2 - processed.

4. 1. 2. Methanol Production

Methanol production (CH_3OH) is based on Reaction (10)

$$3\,H_2 + \;CO_2 \rightarrow CH_3OH + \;H_2O \qquad (10)$$

The hydrogen is also produced by electrolysis as expressed previously in Reaction (9)

Stoichiometrically, every 1 ton of CO_2 demands 0.136 ton of H_2. Along with the same assumptions of hydrogen energy content and electrolyser efficiency in Section 4. 1. 1. methanol production needs 7,7 MW electricity to convert 1 ton/h CO_2.

4. 1. 3. Formic Acid Production

In this study, formic acid (HCOOH) production happens in a single module with the feedstock of CO_2 and H_2O directly through Reaction (11) [33] [34].

$$H_2O + CO_2 \rightarrow HCOOH + \frac{1}{2}O_2 \tag{11}$$

As can be calculated, every 1 ton/h CO_2 processed, 1,05 ton of formic acid is produced. If formic acid has energy content of 5.4 MJ/kg and the current CO_2-to-formic acid electroreduction module efficiency is 50% [33], then the electricity consumption is 3.14 MW.

4. 1. 4. Justification Result

To justify the base scenario, it is assumed that electricity consumption in electro reduction process is the major electricity requirement. Twence currently has the electricity generation capacity of 60 MW. From Figure 7, it can be seen that methane production has the highest power consumption, so it becomes the limiting case. Due to the available electricity generation capacity, the CO_2 uptake for base case scenario is taken to be 50 ktons/year. This uptake is less than Twence goal. However, the available maximum electricity production should be prioritized. The operation hour is assumed to be 7884 hours year, corresponds to Twence availability history of 90% for most of the lifetime. The summary of base case scenario assumption is written in Table 6.

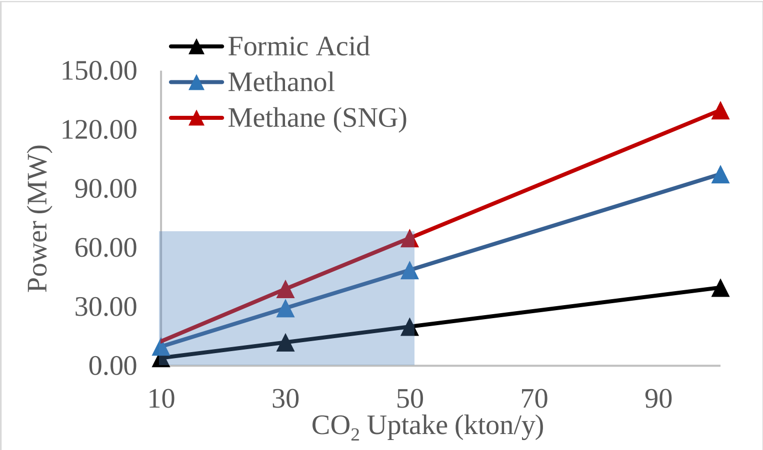

Figure 7. Energy consumption on various CO_2 uptake

Table 6. Assumption on base case scenario

Parameters	Value
Operation hours	7884 hours/year
Limiting electricity consumption	60 MW
CO_2 uptake	50 ktons/year

4. 2. Process Description and Simulation Result

4. 2. 1. Methane Production

Methane production is conducted in two stage processes namely electrolysis and methane synthesis. The operation condition is adapted from a report by DNV-GL [44]. The process flow diagram of methane production is depicted in Figure 8. Water enters the electrolyser ERC with flowrate of 10.4 ton/h. The water consists of make-up water in Stream 12 and the circulated water from the flash tank T1 in Stream 9. The electrolysis produces 9.2 ton/h of pure oxygen and 1.2 ton/h hydrogen. The hydrogen in Stream 14 is compressed to 9 bars to meet the requirement for methane synthesis operation condition. The Compressor C1 represents a two stages compression with intercooler in between with pressure ratio of 3. Fresh captured CO_2 in Stream 1 with flowrate of 6.3 ton/h is also compressed to 9 bar in Compressor C2. Similar to Compressor C1, Compressor C2 is also a multi-stage compression with intercooler in between. The mixture of CO_2-H_2 enters catalytic Reactor R1 with inlet temperature of 85^{o}C. The reaction occurs in with the help of Nickel-based catalyst. Methane synthesis reaction is highly exothermic [35], thus the heat is recovered to produce steam through coupled boiler system. The reaction has conversion of 95% and has by-product of CO, however the CO is produced in a negligible amount (0.5%-mole). The reactor outlet temperature in Stream 4 is still very high (377^{o}C). Some of the heat is utilized in the Economizer H1 to preheat boiler feed water, so the temperature is reduced to 275^{o}C. The stream pressure is then reduced by Valve V1 before it enters Cooler H2 to bring down the temperature to 40^{o}C so that the water in the Stream 7 is condensed. Liquid and vapour phase are separated in Flash Tank T1. The liquid phase, which consists of water is circulated to the electrolyser while vapour phase goes to Gas-Dryer Unit T2. Water content in Stream 8 is adsorbed and collected separately. The final product is found at Stream 10 which has mass flowrate of 2.5 ton/h SNG, corresponds to 7.7 Nm^3/h and energy content of 24.4 MW. The composition in Stream 10 is 95%-mole CH_4 and impurities of CO_2 and CO equal to 4.8%-mole and 0.15% respectively. This specification meets the standard to inject the methane to the natural gas grid [44].

As mentioned before, the reaction heat is recovered by steam production in Stream 18. The steam is produced on 4 bar and 170^{o}C with mass flow of 6.2 ton/h, corresponds to energy flow of 4.8 MW.

The electricity consumption of the whole system is 67 MW, consists of 65 MW for electrolyser and 2 MW for the compressors. The cooling system needs make-up cooling water of 33 ton/h while the water needed for overall process is 11.8 ton/h.

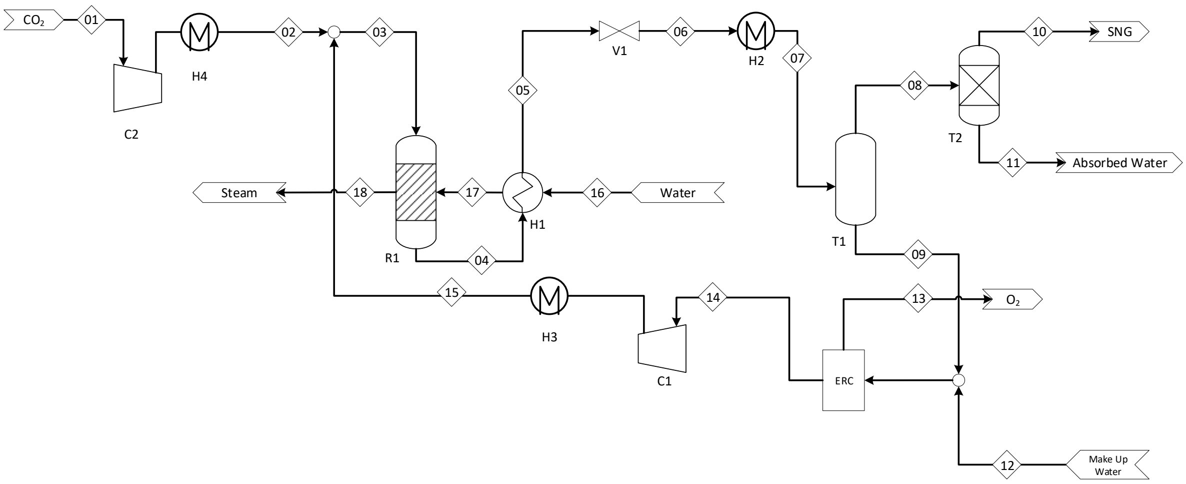

Figure 8. Process flow diagram of methane production

4. 2. 2. Methanol Production

Methanol production has three major stages which are hydrogen production through electrolysis, methanol synthesis, and product purification through distillation. The process flow diagram of methanol production is presented in Figure 9. The following operation condition is adapted from renewable methanol production in Iceland [29]. Water enters the electrolyser in Stream 18 with flowrate of 8.1 ton/h to yield 7.2 ton/h of pure oxygen in Stream 19 and 0.9 ton/h hydrogen in Stream 20. The hydrogen is then compressed to 51 bar in multi stage compression represented by Compressor C3. The compression steps have pressure ratio of 1.9 – 3. To achieve higher compression efficiency, intercoolers are installed between any compression stage. However, there is a pressure loss of 5 psi on each heat exchanger. Hydrogen leaves the compression system on 125^{o}C in Stream 21. On the other hand, fresh captured CO_2 is also fed to compression system to raise its pressure to 51 bar. Multi stage compression system equipped with intercooler is installed. The fresh CO_2 and H_2 stream is mixed with the unconverted feedstock in Stream 10. The total CO_2/H_2 mixture enters the system is 48.5 ton/h with CO_2 composition of 82%-mass. The reaction occurs in Cu/ZnO catalytic reactor. The conversion of CO_2 is 16%. Thus, there are still a lot of unreacted CO_2 that needs to be circulated. The outlet reactor temperature is 285^{o}C and is cooled down by heating inlet reactor stream in Heat Exchanger H1, thus the temperature could be reduced to 112^{o}C. This cooling system may be happened in stages. The product in Stream 6 still consists of methanol, water, and unreacted feed. To be able to separate the liquid and gas phase in Flash Tank V1, the temperature needs to be reduced by Cooler H2 to 70^{o}C. The unreacted gas is cooled down further and re-compressed in Cooler H3 and Compressor C2 respectively, hence Stream 10 will have the pressure 51 bar and 46^{o}C. The liquid phase from Flash Tank V1 is flashed by Valve V1 before enters Distillation Column T1. The distillation is conducted at 1.4 bar to purify the 64%-mass methanol to 95%-mass methanol as the common concentration for methanol. The reboiler duty of the distillation is 3 MW, thus this much of steam has to be supplied to conduct the distillation process. Water as the bottom product in Stream 15 is cooled down by Cooler H5 before it is circulated back to the electrolyser system. Meanwhile, methanol 95%-mass as the top product of distillation is then cooled down to 25^{o}C before it enters the storage tank. This system can produce 4.9 ton/h methanol which contains energy of 28 MW.

The electricity consumption of the whole methanol production system is 52 MW, which 49 MW of it, is used for hydrogen production. The cooling system needs make-up cooling water of 61 ton/h while the water needed for overall process is 5.7 ton/h.

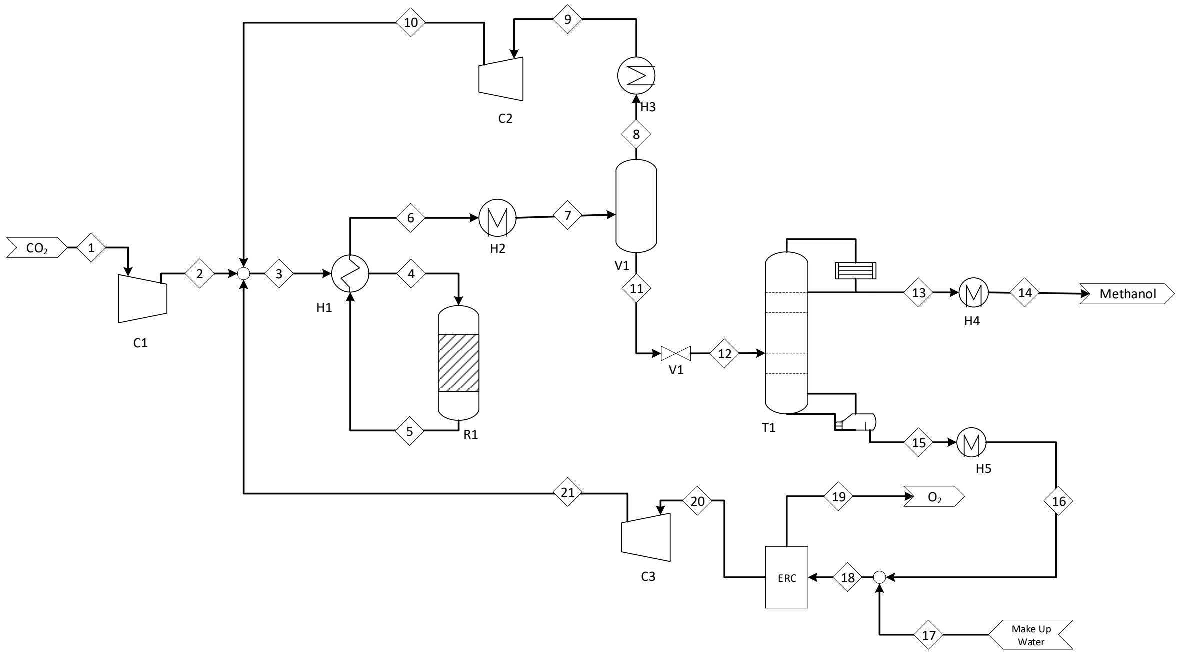

Figure 9. Process flow diagram of methanol production

4. 2. 3. Formic Acid Production

Unlike the other two processes, electroreduction in formic acid production performs to directly react water and CO_2 to yield formic acid and oxygen in a single reactor (may consist of several modules). The process flow diagram of formic acid production is shown in Figure 10. To meet the market concentration, the formic acid-water mixture is purified in distillation column. The operation condition is adapted from [33, 45].

Fresh CO_2 in Stream 1 and make-up water in Stream 18 as much as 6.3 ton/h and 3.8 ton/h respectively are fed into the Electroreduction Cell ERC. The reaction is assumed to have 15% conversion, thus unconverted CO_2 is circulated in Stream 4 and 5 while the formic acid and unconverted water leaves the reactor at Stream 7 with mass flowrate of 26.8 ton/h. The by-product oxygen with mass flowrate of 2.3 ton/h leaves the reactor at Stream 3 and goes to the storage tank or further processing. Part of the formic acid/water flow is circulated back to the reactor to enhance the reaction performance on Stream 8. The concentration of Stream 7, 8, and 10 are the same which contains 45%-mass formic acid. As the formic acid is corrosive, special stainless steel is needed prevent the pipe corrosion. Also, the concentration before entering the distillation column cannot be higher, otherwise the investment cost of the relevant unit operation and piping become higher. On the other hand, if the concentration is lower, more energy is needed to purify the final product. Formic acid has higher boiling point than water, hence formic acid becomes the bottom product and water becomes the distillate. This chemical property also indicates that the reboiler duty to boil up the formic acid/water mixture is very high. To reduce the consumption of steam, distillation inlet in Stream 10 is preheated to 61°C in Heat Exchanger H1 by using the hot bottom product in Stream 12. The distillation happens at 4 bar as suggested by a study in [46]. The final product formic acid which has concentration of 85%-mass is further cooled down by Cooler H2 before it goes to the storage tank in Stream 14. Stream 14 has flowrate of 7.6 ton/h with energy content of 9.7 MW. Water at Stream 15 is cooled down by Cooler H3 before it is circulated back to the electroreduction cell.

The formic acid production system uses 20.25 MW electricity for the electroreduction process and 20 MW steam in its distillation. Huge amount of make-up cooling water of 119 ton/h is needed to support the cooling process. Another 4 ton/h consumption of process water is needed to conduct the overall process.

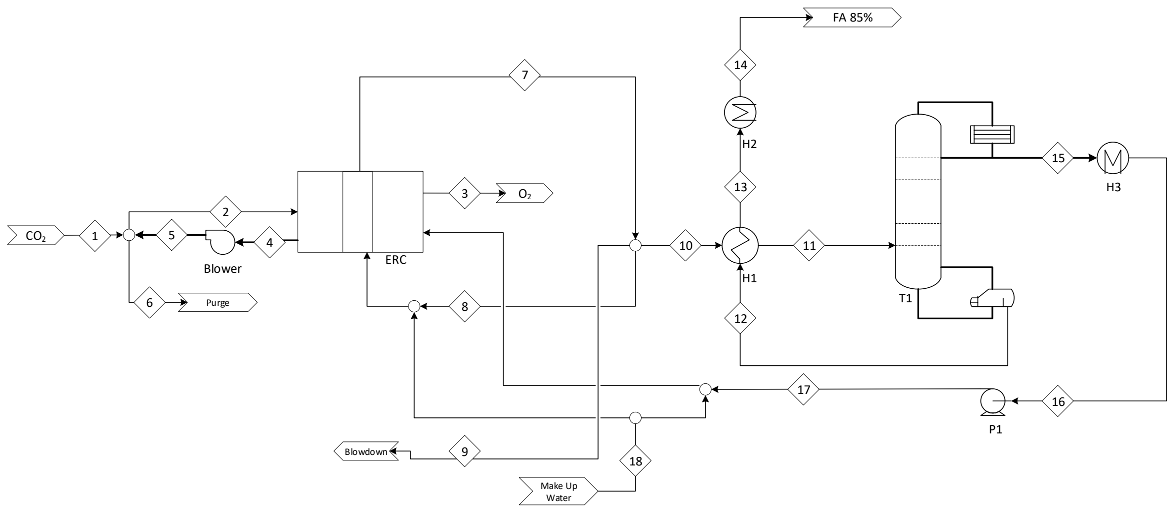

Figure 10. Process flowsheet diagram of formic acid production

4. 3. By-product Utilisation

The three alternatives produce notable amount of oxygen. Methane production has 9.2 ton/h oxygen by-product while methanol and formic acid produces 7.2 ton/h and 2.3 ton/h respectively. The more oxygen produced indicates the more water is electrolysed in each system. There are two possible options for Twence to make use of the oxygen by product: selling it or using it in the current installation

a. Option 1: Selling the oxygen

Oxygen is a valuable material. The industrial market price is around 100 EUR/ton. The price is slightly higher if it is prepared for medical use. However, is only feasible to be transported in gas form, as it has cryogenic temperature to meet its liquid phase. Oxygen liquefaction is energy and cost intensive for this scale of production. Liquid oxygen is usually produced in air separation unit in a large-scale plant. To reduce the volume, oxygen is usually compressed to 180 bars for bulk transportation by truck. The high pressure demonstrates an increase in capital investment.

b. Option 2: Using oxygen in current installation

In current installation, waste and wood are combusted by using air in the incinerators. However, it is only oxygen that is needed to burn the materials, and 80% of air consists of nitrogen, thus the flue gas volume in the incinerator outlet becomes very high. If part of the air is substituted with oxygen, then the volume of the flue gas can be reduced. The flue gas treatment can be done in an easier way and requires less chemicals. It is also easier if the CO_2 out of the flue gas want to be captured

This kind of utilisation is suitable for AEC-1 and AEC-2 where the flue gas treatment installation has come to the end of lifetime and needs replacement soon. If the flue gas volumetric flow is reduced, then less investment is needed for the new installation.

Chapter 5. Profitability Analysis

From the preliminary selection, methane, methanol, and formic production seem to be attractive alternatives of CCU and PtX in Twence. To evaluate the feasibility from economic perspective, profitability analysis on each case was performed. It was also mentioned in previous chapter that there is a possibility to sell the oxygen as valuable by-product. Importing this new variable to the previous selected alternative, there are now 6 scenarios of whose economic performance needs to be investigated as listed in Table 7.

Table 7. Scenarios of CCU – PtX project

Scenario	Main Product	Sales of Oxygen
1	Methane	Yes
2	Methane	No
3	Methanol	Yes
4	Methanol	No
5	Formic Acid	Yes
6	Formic Acid	No

The assessed profitability indicators were Internal Rate of Return (IRR), Net Present Value (NPV), and Profitability Index (PI). Internal rate of return indicates the discount factor when the NPV equals to zero. An attractive business case should have IRR greater than the discount factor (compound interest). As value of money changes over time, the net present value explains how much profit at the end of the plant's lifetime equals to the present worth. Profitability index is the ratio between NPV and the capital investment. The capital investment and annual cash flow should be determined first before these profitability indicators can be calculated. Calculation sheet of the annual cashflow and profitability indicator is available on Appendix B.

5. 1. Capital Investment

The capital investment (or capital expenditure, CAPEX) is defined as an amount of money that is invested for long-term asset which is necessary for future business activity. This study estimated the CAPEX based on three major cost items: purchased equipment cost, physical plant cost, and final fixed capital. The contributing details on cost items were listed in Table 8. The purchased equipment cost describes the cost needed to buy the equipment at a certain specification. The physical plant cost is defined as the additional cost that is necessary for the completion of the purchased equipment. Final fixed capital is the cost required for the realization of the overall project.

Each purchased equipment cost is subjected to the cost items factor in Table 8, unless defined separately. Thus, it is important to look on the price coverage on any equipment cost data. Sometimes, the available price data were subjected to a different capacity and year of installation. Capacity and year correction follows Eq. (2) and Eq. (3).

$$P_A = P_B \left(\frac{Capacity_A}{Capacity_B}\right)^x \qquad Eq.(2)$$

Where P_A is the equipment price at capacity A and P_B is the equipment price at capacity B, while x is a factor that is specific to the equipment and usually ranges from 0.5 to 0.7. The year correction price depends on the Chemical Engineering Plant Cost Index (CEPCI).

$$P_M = P_N \frac{CEPCI_M}{CEPCI_N} \qquad Eq\ (3)$$

Where P_M is the equipment price at year M and P_N is the equipment price at year N. The CEPCI for this business case was set on 558. The CEPCI data were collected from [47].

Table 8. Cost item factors

Cost Item	Factor
Physical Plant cost (PPC)	
f_1: Piping, instrumentation, and electrical devices	26%
f_2: Installation	20%
f_3: Civil work and site development	15%
f_4: Storage	10%
Final fixed capital (FFC)	
f_5: Design and Engineering	30%
f_6: Contractor's fee	5%
f_7: Contingency and unforeseen	10%

The physical plant cost items factors were obtained from a feasibility study of fuel production through CCU and PtX [30] while the final fixed capital cost items factors were taken from Twence typical assumption [48]. This study collected the equipment cost from various references such as Aspen HYSYS v.8.8 Economic Analyzer, books, reports, and catalogues

Eq. (4) shows the calculation of physical plant cost (PPC) from the purchased equipment cost (PEC), while Eq. (5) is for the calculation of final fixed capital. The variable f_n defines the corresponding cost item factor as described in Table 8.

$$PPC = PEC\ (1 + f_1 + f_2 + f_3 + f_4) \qquad Eq.(4)$$

$$FFC = PPC\ (1 + f_5 + f_6 + f_7) \qquad Eq.(5)$$

As mentioned in Table 7, there are scenarios that involves sales of oxygen and some do not. The major difference in the CAPEX between the two cases is installation of compressors. The details of CAPEX on each scenario is presented in Table 9 - Table 14. The CAPEX was calculated based on the major equipment cost. All scenarios need to purchase heat exchangers, compressors, and cooling tower. Methanol and methane synthesis needs electrolyser to produce hydrogen and certain reactor each. Formic acid electroreduction cell is already able to produce hydrogen and synthesize formic acid in the same module. Methanol and formic acid need to install distillation column to achieve a particular purity, so it can meet market commercial specification.

It can be seen that compression of oxygen needs an additional € 7-11 million. Methanol production has the lowest capital investment among three alternatives while methane production corresponds to the highest fund. It can be seen that electrolyser is responsible for more than 50% of the total investment in the most cases. Thus, it makes sense that methane has the highest investment as it needs more hydrogen per amount of CO_2 converted to produce methane, compared to methanol and formic acid.

Table 9. CAPEX of Scenario 1 (Methane production with sales of oxygen)

Component	Price (M Euro)	Coverage, Year	Reference
Electrolyser	65.1	Final Fixed Capital, 2017	[37]
Reactor	33.5	Purchase Equipment (FFC =150% PEC)	[37]
Heat Exchanger	0.13	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Compressor	9.9	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Cooling Tower	0.41	Purchased Equipment, 2017	[49]
Final Fixed Capital (Million €)			140.9

Table 10. CAPEX of Scenario 2 (Methane production without sales of oxygen)

Component	Price (M Euro)	Coverage, Year	Reference
Electrolyser	65.1	Final Fixed Capital, 2017	[37]
Reactor	33.5	Purchase Equipment (FFC =150% PEC)	[37]
Heat Exchanger	0.13	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Compressor	5.4	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Cooling Tower	0.41	Purchased Equipment, 2017	[49]
Final Fixed Capital (Million €)			129.8

Table 11. CAPEX of Scenario 3 (Methanol production with sales of oxygen)

Component	Price (M Euro)	Coverage, Year	Reference
Electrolyser	48.8	Final Fixed Capital, 2017	[37]
Reactor	5.4	Final Fixed Capital, 2017	[50] [51]
Heat Exchanger	0.3	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Compressor	12.9	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Distillation	0.15	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Cooling Tower	0.19	Purchased Equipment, 2017	[49]
Final Fixed Capital (Million €)			87.2

Table 12. CAPEX of Scenario 4 (Methanol production without sales of oxygen)

Component	Price (M Euro)	Coverage, Year	Reference
Electrolyser	48.8	Final Fixed Capital, 2017	[37]
Reactor	5.4	Final Fixed Capital, 2017	[50] [51]
Heat Exchanger	0.3	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Compressor	8.4	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Distillation	0.15	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Cooling Tower	0.19	Purchased Equipment, 2017	[49]
Final Fixed Capital (Million €)			76.3

Table 13. CAPEX of Scenario 5 (Formic acid production with sales of oxygen)

Component	Price (M Euro)	Coverage, Year	Reference
Electroreduction Cell	36.4	Purchased Equipment, 2017	[33]
Heat Exchanger	0.04	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Compressor	4.66	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Distillation	2.03	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Cooling Tower	0.13	Purchased Equipment, 2017	[49]
Final Fixed Capital (Million €)			107.0

Table 14. CAPEX of Scenario 6 (Formic acid production without sales of oxygen)

Component	Price (M Euro)	Coverage, Year	Reference
Electroreduction Cell	36.4	Purchased Equipment, 2017	[33]
Heat Exchanger	0.04	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Compressor	1.44	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Distillation	2.03	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Cooling Tower	0.13	Purchased Equipment, 2017	[49]
Final Fixed Capital (Million €)			99.1

5. 2. Annual Cashflow

Annual cashflow is defined as the difference between the revenue and operational cost on annual basis. The cashflow should be positive which means that there is a yearly profit to pay the investment back and gain profit from the business activity. The revenue from this project comes from the sales of the main product, and the by-product if necessary. Because the final product has possibility to be claimed as renewable fuel or chemical, Twence has the potential to receive incentive from the government.

Methanol, methane, and formic acid price is assumed to be 350 €/$ton_{Metahnol}$ [52], 30 €/$MWh_{Methane}$, and 550 €/$ton_{Formic\ Acid}$ [53] respectively. It is possible to have a renewable product certificate values 80 €/MWh [1]. If the scenario involves sales of oxygen, then the oxygen is priced at 100 €/$ton_{O2.}$ On methane production, steam at considerable amount is generated. The steam is priced at 4 €/MWh [1]. By multiplying the production volume and each cost function, the revenue for each case can be obtained.

The operational cost is associated to the practical expense of the production activity. The calculation is constructed from several indicators as shown in Table 15. Twence is currently sell the electricity on the market at around 35 €/Mwhe [1] . However, Twence is administratively objected to a distribution tax as they use national existing grid. Thus, Twence should allocate a higher price for electricity. The CO_2 cost is necessary to keep the CO_2 capture plant run. Transportation cost, water cost, and operators salary are based on Twence's typical figures. Maintenance and auxiliary cost is set on 3% and 5% of the CAPEX for methane/methanol production and formic acid production respectively. As formic acid is corrosive, hence it is assumed to have a higher protion of maintenance. Steam cost is not included as the steam can be provided by own boiler. Unlike electricity, the steam is not subjected to any taxes. The steam requirement from any scenario still meet the steam specification produced at Twence. Thus, it is not necessary to change Twence installation, neither buy the steam from other provider. For Twence's convenience, the annual cash flow and the other profitability analysis are calculated on Twence standardized business case model. However, this business case model complies to cashflow before taxes (except electricity).

Table 15. Revenue and operational cost items

Parameters	Cost Function
Revenue	
Formic acid	550 €/ton Formic Acid 85%
Methanol	350 €/ton Methanol
Methane	30 €/MWh Methane
Oxygen	100 €/ton O_2
Steam (on methane production)	4 €/MWh
Incentives	80 €/MWh
Operational cost	
Electricity	47 €/MWh
CO_2 capture	30 €/ton CO_2
Transportation liquid product	10 €/ton Formic Acid 85%
Transportation O_2	20 €/ton O_2
Water	1.5 €/ton water
Operators	55,000 €/FTE
Maintenance and Aux	5% of CAPEX

The annual cashflow of each scenario is depicted on Figure 11. Formic acid production has the potential to generate the highest income for the company. Sales of oxygen seems to give insignificant difference due to the low volume of oxygen produced. In methanol production, sales of oxygen can increase the income nearly twice. Methane production at the assumed prices performs negative cashflow. However, the study also revealed that the methane business case is very volatile to any price shifts. For example, if Twence can manage the electricity taxes so the company does not need to pay the distribution tax, then the cashflow is already positive for both scenarios.

Anyhow, the positive cashflow does not straightforwardly guarantee the attractiveness of a business case. A deeper look on IRR, NPV, and PI is necessary.

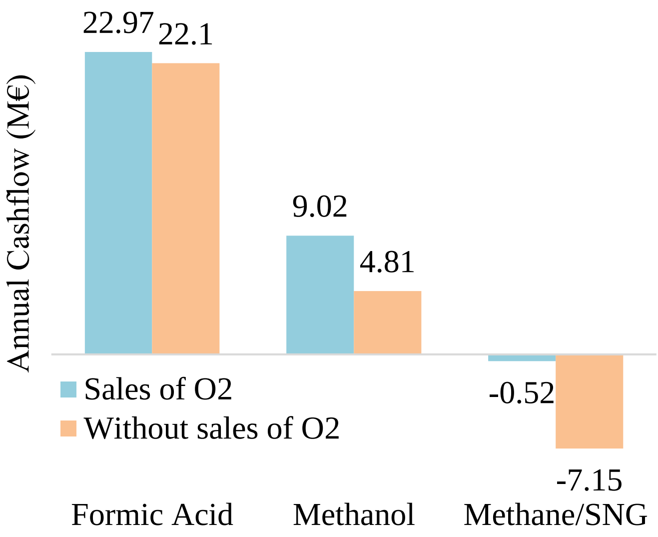

Figure 11. Cashflow of each scenario

5. 3. Net Present Value and Internal Rate of Return

The determination of business case attractiveness is done by profitability analysis by evaluating the internal rate of return (IRR), net present value (NPV), and profitability index (PI). The business case model is assumed to have discount factor of 9.5% and plant lifetime of 20 years (common lifetime for chemical plant). The IRR and NPV for the six scenario is presented in Table 16.

Table 16. IRR and NPV of each scenario

Scenario	Main Product	Sales of Oxygen	IRR	NPV (M€)
1	Methane	Yes	-	-146.27
2	Methane	No	-	-190.42
3	Methanol	Yes	10.11%	4.00
4	Methanol	No	4.15%	-27.69
5	Formic Acid	Yes	23.0%	125.10
6	Formic Acid	No	23.8%	124.17

The IRR of the methane production project cannot be calculated as the cashflow is negative, thus the NPV must be negative. Meanwhile, the IRR calculates the discount rate when the NPV equals to zero. This condition will not be performed for a negative cashflow case. From this IRR and NPV evaluation, methane production scenarios seem to be not attractive at the current assumed cost parameters. Recalling the cashflow of methanol production, the sales oxygen can double the annual income. The IRR for Scenario 3 and 4 are 10.11% and 4.15% respectively. As the IRR for Scenario 4 is less than 9.5%, then the NPV shows negative value. The negative value indicates that the final profit at year 20 is still considered as a loss with the present money value.

In short, Twence could not expect a profit from the methanol production without selling the by-product oxygen. Formic acid production scenarios seem to give attractive IRR and NPV. The IRR for Scenario 5 and 6 are 23% and 23.8% with the corresponding NPV € 125.1 million and € 124.17 million respectively.

According to the IRR, Scenario 5 is the most promising alternative, yet the NPV difference with Scenario 6 is only € 1 million. The CAPEX difference between the two cases is roughly € 8 million. Hence, the economic performance analysis will be continued to the profitability index (PI). The PI will compare the value created (NPV) with resource consumed (Capital Investment). Alternative with higher PI is preferred. As depicted in Figure 12, the profitability index of Scenario 6 is more attractive than Scenario 5. Also, compared to Scenario 4, the profitability index of formic acid production alternatives is still higher ($PI_{scenario4}$ = 0.05). The other alternatives (Scenario 1, 2, and 3) have PI less than zero as the NPV is negative.

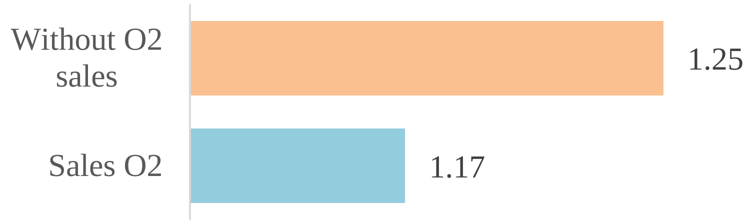

Figure 12. Profitability index of formic acid production alternatives

All in all, based on the IRR, NPV, and PI as profitability indicators, at current assumptions, formic acid production without the sales of oxygen is the most attractive project

Chapter 6. Scaling Possibility

Scaling analysis refers to any potential of upscaling/downscaling the base case scenario assumptions to make the project is likely more feasible in the near time. From the economic evaluation in Chapter 5, the preferred alternative is formic acid production without the sales of oxygen. Thus, the scaling possibility of this alternative will be analysed in this chapter.

6. 1. Downscaling Consideration

The summary of assumptions and findings for the selected alternative is shown in Table 17.

Table 17. Result of base case formic acid production study without the sales of oxygen

Parameters	Value
Assumptions	
CO_2 uptake	50 ktons/year
Operation hours	7884 hours/year
Findings	
Formic acid production	59.9 ktons Formic acid/year
Electricity consumption	20.25 MW
Steam consumption	20 MW
CAPEX	€ 99 million
Annual cash flow	€ 22 million
IRR	23.8%
NPV	€ 124 million

From operational perspective, the selected alternative still consumes a high portion of energy, 20.25 MW electricity and 20 MW steam. With current energy demand from shareholders for the respective regions, Twence has the possibility to be a net energy consumer instead of using their own generated energy. From financial perspective, a new investment of € 99 million is considered high. As 31 December 2016, Twence has tangible fixed assets of € 237 million. This new project CAPEX values almost half of the current total installations. Therefore, the project will be scaled down.

Instead of processing 50 ktons CO_2/year, the revised assumptions will be 15 ktons CO_2/year. The revision is taken from a discussion within the Business Development and Strategy team by considering the energy consumption (especially electricity) and the invested CAPEX. Twence aims to see a project with a CAPEX volume of around € 30 million- €50 million, half of the current estimation. However, due to the cost and capacity relations as mentioned in Eq. (2), the capacity cannot merely be downscaled half of the base case, but around one-third. By a rough estimate, the energy consumption would be one-third of the base case scenario, accounted for 6 MW of electricity and 6 MW of steam. These volume is considered as technically feasible.

6. 2. Downscaling Result

The downscaling analysis is started with the process simulation to have the insight of the production volume and the energy consumed. The parameters are important to further investigate the economic performance. The simulation was carried out in Aspen HYSYS v.8.8. The difference on mass balance and energy consumption for the two base scenarios is presented on Table 18.

Table 18. Base case scenario and downscaling result

Parameters	50 ktons/year CO_2	15 ktons/year CO_2
Formic acid production	60 ktons FA/year	18 ktons FA/year
Oxygen production	16 ktons O2/year	5.4 ktons/year
Electricity consumption	20.25 MW	6.05 MW
Steam consumption	20 MW	7 MW
Water consumption	123 tons water/hour	38 tons water/year

After having the figures of the mass balance and energy consumption, the economic performance analysis can be performed. The CAPEX estimation is presented in Table 19. It can be seen that the CAPEX for the downscaled scenario is € 43.52 million. This CAPEX is within Twence's range.

Table 19. CAPEX of downscaled formic acid production without the sales of oxygen

Component	Price (M Euro)	Coverage, Year	Reference
Electroreduction Cell	14.4	Purchased Equipment, 2017	[33]
Heat Exchanger	0.0362	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Compressor	1.23	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Distillation	1.902	Purchased Equipment, 2013	Aspen HYSYS v.8.8
Cooling Tower	0.06	Purchased Equipment, 2017	[49]
Final Fixed Capital (million €)			43.52

The annual cashflow comparison between the base scenario and downscaled scenario of formic acid production without the sales of oxygen is presented in Table 20. The annual cashflow reduces more than one-third of the base case scenario's. This finding is due to the operators' salary and the maintenance cost. Number of operators is based on the number of installed equipment. Neglecting any redundant, there is no difference in the number of installed equipment between these two cases, only the capacity that is reduced. Next, maintenance cost is a function of CAPEX. As the capex in the downscaled scenario is half, instead of one-third, of the base case scenario, it contributes as a significant cost items. A further detail on maintenance planning and expense should be investigated. Except these two parameters, the expenses are nearly one-third of the base case scenario.

Table 20. Annual cashflow of the base case and downscaled scenario comparison

Parameters	Annual Savings (€)	
	50 ktons CO_2/year	**15 ktons CO_2/year**
Revenue		
Revenue Formic Acid 85%	32,965,299.68	10,081,665.00
Revenue Incentives	6,117,984.00	1,879,545.60
Operational Cost		
Electricity Cost	-7,503,597.00	-2,241,815.40
CO_2 Cost	-1,500,000.00	-450,000.00
Cooling Water	-1,404,928.80	-319,302.00
Process Water	-63,072.00	-17,344.80
Product Transportation Cost	-599,369.09	-183,303.00
Operators	-962,500.00	-962,500.00
Maintenance	- 4,956,825	-2,175,887.95
Savings		
Annual cashflow	22,092,991	5,611,057

The comparison of the profitability indicators can be found in Figure 13 and Figure 14. By processing 18 ktons/year CO_2 into formic acid, Twence is estimated to achieve NPV of €13.2 million for the 20 years plant lifetime. Compared to the base case scenario, the NPV is hardly decreasing. However, the positive NPV corresponds to the IRR of 13.3%, higher than the discounted factor of 9.5%. Theoretically, this IRR should be attractive enough for realizing such chemical plant project. Arriving to the profitability index, the PI for the downscaled scenario shows a value less than unity, while in the base case scenario, the ratio of NPV and CAPEX is higher than unity.

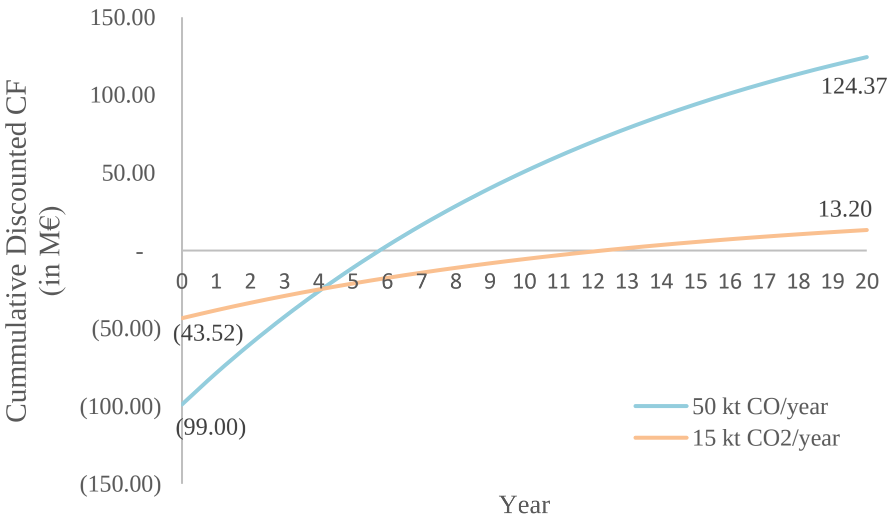

Figure 13. Project cashflow of the base case and downscaled scenario

In conclusion, downscaling to one-third of the base case scenario still has an attractive business case, although the profitability indicators show significant reduction from the base case.

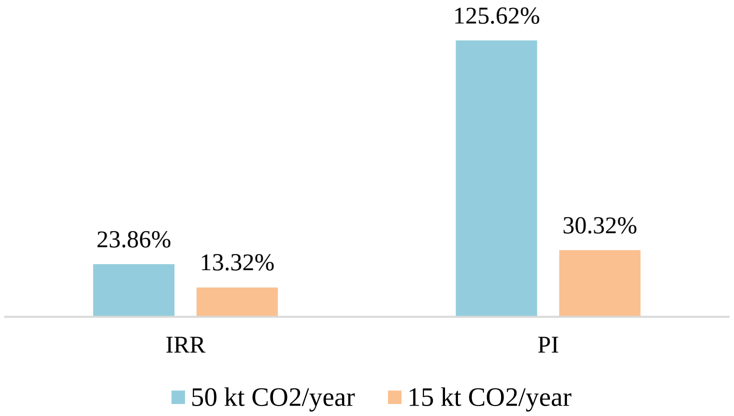

Figure 14. IRR and PI of the base case and downscaled scenario

Concluding the explanation, downscaling to one-third of the base case scenario still has an attractive business case, although the profitability indicators show significant reduction from the base case.

Chapter 7. Risk, Opportunities, and Market Overview

7. 1. Risk and Opportunities

Risk and uncertainties are unavoidable in doing any business activity. The risk can come from various perspectives, involving wide range of stakeholders. In this chapter, risk in operational, financial, market and legal pint of view will be briefly identified. The related opportunities to CCU-PtX realisation to produce formic acid.

7. 1. 1. Operational Risk

Operational risk is correlated with any technical and managerial issue that might cause problem in the business operation. Some identified operational risks are delay in construction stage, failure in production, delay and capacity issue in logistic and supply chain, and the reliability of internal corporate activities.

Delay in construction and commissioning stage can happen due to misscheduling on procurement, installation, and commissioning, or the mismatch installed unit operation and the detailed construction design. The effect of such risk is the later starting period for production and the time frame of the whole project might be shifted. If there is any strict payment schedule and the unforeseen cost could not cover the payment, the overall NPV might be reduced due to penalty. This risk can be prevented by providing a spare period to anticipate the delay and if possible have a more flexible billing schedule especially if the investment has significant share of debt.

Technical failure in operation examples in such chemical plant is explosion due to overpressure in piping or reactor, gas and chemical release, surging and tripping compressor, and corrosion. Overpressure might be happened due to accumulation of any fluid in a pipe section or reactor, sudden increase of temperature, mismatch valve opening, or the occurrence of hotspot due to inhomogeneous heat distribution. Overpressure shall be prevented by installation of layered pressure release system, good maintenance and reliable pressure indicator and monitor. Gas and chemical release might be happened due to the opened pressure relief system, piping or reactor leakage, or explosion. Chemical release can be prevented by installing reliable gas detector and to minimize the further possibility of fire and explosion, suitable spaces between unit operation and building should be assessed and realized. Compressor problem is a common issue in a chemical or power plant. Good maintenance of the compressor, reasonable gas flowrate in the compressor, and preventing any liquid phase occurred in the reactor should be theoretically enough to prevent the compressor issues. Corrosion is a risk that is likely to happen in formic acid production. Corrosion can cause the leakage in pipe or reactor, and further induces the chemical leakage and sudden pressure drop. Corrosion can be prevented by using suitable material and the sacrificed layer.

Delay and capacity issue in logistic and supply chain are related to the guarantee of electricity and CO_2 supply, final product transportation, cross-border shipment, and insufficient storage capacity. If either electricity and CO_2 cannot be supplied proportionally, there will be a decrease in the final product (methane, methanol, or formic acid) production rate. If the feedstock and energy required are not available for a significant period, the plant should be shut down, and it takes some hours to days to start up the plant until it operates normally. To prevent this issue, CO_2 should be buffered in a certain capacity, while the electricity supply can be guaranteed by installing back-up turbine or being on-grid to the regional or national electricity network. Final product transportation issue is related to the delivery and shipment of the product to customers. Appropriate scheduling and complete documentation should be prepared especially if the shipment involves a cross-border transportation. Storage capacity is associated with the previous shipment issue and the mismatch of demand and supply. Chemical plant production rate is not very flexible, thus purchase agreement should be determined in terms of months or years. Lastly, reliability risk on internal corporate management incorporate especially human resource management and research and development activity. The human resource should ensure that the company recruits a competence employee and provide adequate workshop and training. Research and development activity is very important for innovative company like Twence, otherwise it cannot follow the fast-changing-and-growing renewable energy market. Research and development fund and cooperation with other institutions should be prepared and expanded.

7. 1. 2. Financial Risk

Financial risk is associated with income and cost. A sensitivity analysis on several financial parameters is conducted for the case of formic acid production with CO_2 uptake of 15 ktons/year. The chosen parameters are plant lifetime, maintenance cost, CO_2 cost, electricity price, incentive, production rate, formic acid price, and the capital investment. The sensitivity of the changing parameter to the internal rate of return can be seen on Figure 15.

The basic scenario plant lifetime is 20 years. If the plant lifetime happens to be shorter than expected, the IRR would be decreased from 13.3% to 10.9% (NPV= € 3.6 million). On the other hand, if the plant lifetime can be extended to 26 years, the IRR would increase to 14.2% (NPV= € 19.5 million). The base assumption of annual maintenance cost is 5% of the CAPEX. If the maintenance cost is realized to 3.5%, the IRR raises to 15.1% (NPV= € 19.8 million) while if more maintenance is needed and the maintenance cost becomes 6.5% of the CAPEX, then the IRR would drop to 11.5% (NPV: € 6.6 million). Carbon dioxide cost depends on the capture process including the used solvent and energy. If the solvent price and related energy dropped and makes the CO_2 cost to € 21/ton CO_2, then the IRR slightly increases to 13.7% (NPV: € 14.6 million). Opposed to that, if the CO_2 cost increase to € 39/ton CO_2, the IRR decreases to 12.9% (NPV: € 11.8 million). Currently, Twence sells the electricity to its customer at average price of € 33/MWh, however due to the taxes, the electricity cost that is subjected to this project is € 47/MWh. If the taxes can be cut and this CCU and PtX project can have the electricity € 33/MWh, the IRR of the project can increase to 15.2% (NPV= €20 million). From the APX electricity price profile in Figure 1 it can be seen that in 2016, the average electricity price shifts to a lower price. However, if on the year the formic acid plant starts to produce and the electricity price increases back to around € 42/MWh, and taxes are still subjected to the cost, the electricity cost might increase to € 61/MWh. It will reduce the IRR to 11.4% (NPV €6.4 million). In the business case analysis, one of the revenue source is the incentives from relevant government. The base case assumption is € 80/MWh energy flow. If the realization of the incentive varies between €56/MWh to €104/MWh, the IRR will be on range of 11.7% (NPV= €7.5 million) to 14.9% (NPV= € 18.9 million). In base case scenario, the formic acid plant has availability of 90% that represents the production of 18 ktons of formic acid annually. If operational problem occurs and the formic acid production drops to 13 ktons/year, the IRR will also drop to 3.5 % (NPV= €-17 million). But, if the plant operation is done well until it reaches availability nearly 100%, the formic acid production can increase to 20 ktons/year and will bounce the IRR to 15.7% (NPV= € 22 million). Current formic acid price ranges from € 500 - € 600/tonnes [53]. The assumed formic acid price is € 550 /tons. If all the attained customers only want to buy the formic acid at € 500/ton, then the IRR would decrease to 10.7% (NPV= 3.9 million). However, if Twence can sell the formic acid at the highest market price, the IRR increases to 15.8% (NPV= 22.4 million). Lastly, if Twence can obtain subsidy from any relevant institutions or the electroreduction cell decreases which results in decreasing CAPEX to 70% of the base case, the IRR bounces to 22% (NPV= 33 million). Meanwhile, if there is any significant divergence on current assumption that makes the CAPEC to be 130% of the base case, the IRR would drop to 7.9 % (NPV= € 6.5 million). From Figure 15 it can be seen that CAPEX, formic acid price, and formic acid production rate are the most sensitive to IRR (and NPV correspondingly). Meanwhile, due to the low uptake of CO_2, variety on CO_2 cost is the least sensitive to IRR (and NPV).

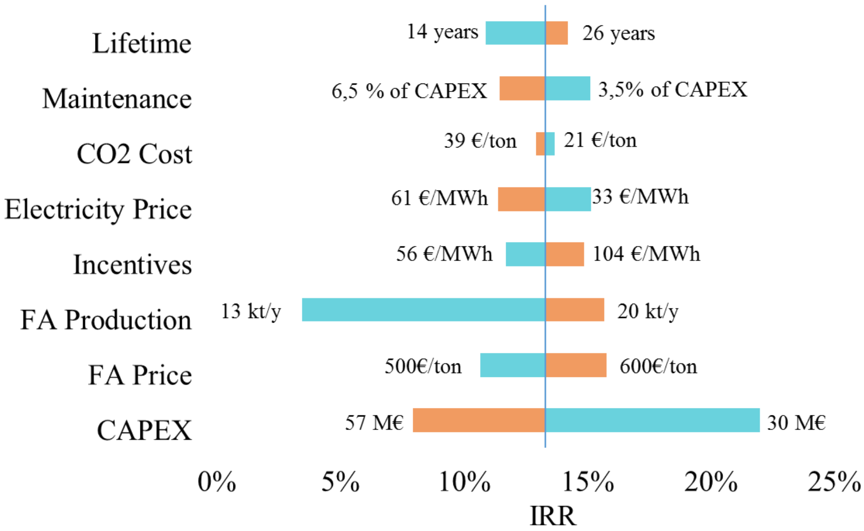

Figure 15. IRR Sensitivity to varying parameters value

7. 1. 3. Market and Legal Risk

Market and legal risk includes the seasonality demand of the product, shift in product specification, regulation development, competition in a bigger market, and global economic condition.

Seasonality refers to demand volume variation based on season. Energy consumption in winter may differ with the consumption in summer. Thus, the storage capacity should be sufficient to depot the product until the delivery time. The storage system should guarantee that the product quality does not decline. A technology development may induce an enhancement product quality. Mixture of water-formic acid is azeotropic. To have a more than 90% purity, it needs special purification system such as azeotropic distillation or extraction [31]. However, it may increase the operational cost, and so is the market price. Once a new purification system is established with a more affordable cost, and the market price for the pure formic acid decreases, customers may shift their specification preference. If any formic acid producer cannot cope up with the new technology installation, their existing customer may not extend the purchasing contract.

Regulation development relates to any policies especially in regards to CO_2 emission. The learning process of regulation can have both risk and opportunities to the development of CCU-PtX realisation. The government and related institutions may settle new CO_2 emission standards and policies for fossil-based power producers. The supporting policy tool might be given in terms of subsidy or incentives. As we know, fossil-based power plant emits abundant amount CO_2, and they are prone to be Twence's competitors in producing CO_2 and applying CCU-PtX concept. The risk is higher if their CO_2 cost is lower than current CO_2 capture cost in Twence. Beside having competitors in CO_2 producers, in a bigger energy market, CCU and PtX application to produce formic acid also faces competition in energy storage technology and another route of renewable formic acid production. On the other hand, a general support in reducing CO_2 emission may lead an opportunity for Twence to have subsidy in investment and/or incentives.

There are a lot of electrical energy storage system such as mechanical storage, electrochemical storage, electrical storage, chemical storage, and thermal storage. Among the mechanical system are pumped hydro storage, compressed air energy storage, and flywheel. Electrochemical energy system includes secondary battery and flow batteries. Electrical energy system relates to double layer capacitor and super conducting magnetic coil. Thermal methods for electricity storage is sensible heat storage using molten salt in phase change material. The most notable chemical electricity storage technology is hydrogen. However, hydrogen has very low density that needs very large storage volume, and it needs high pressure compression. Thus, some liquid chemicals are now produced and regarded as hydrogen carriers. Some of the intended chemicals are methanol, ethanol, and formic acid. The development of any electrical storage system can be a risk for this power-to-formic acid although it seems to be minor.

Renewable formic acid can be produced by CO_2 hydrogenation and CO_2 electrolysis. However, the cost of CO_2 hydrogenation is higher due to the needs of chemical synthesis and the post treatment [32, 33, 54]. If the development is faster than the enhancement of the electroreduction reactor the production cost of the thermochemical conversion becomes lower than the direct electroreduction conversion, the market price has the possibility to decrease.

7. 1. 4. Opportunities

Formic acid is a potential fuel for transportation purposes and is potential as an efficient hydrogen carrier. Formic acid is comparable with other reversible hydrogen storage alternatives as presented in Figure 16. The gravimetric capacity refers to hydrogen mass percentage in the storage system. While the volumetric capacity is the mass of hydrogen per volume of storage system and it corresponds to the energy density. Thus, it can be understood from the graph that formic acid has a better storage capacity than the compressed hydrogen.

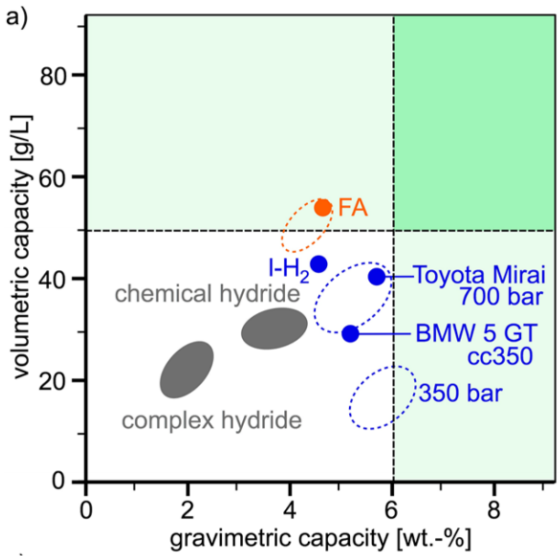

Figure 16. Several hydrogen storage technologies

Currently formic acid can be directly used in fuel cells. It cancels out the stage of converting it to hydrogen. The direct formic acid fuel cell (DFAFC) is an attractive alternative for small portable fuel cell applications [32]. Actually, Methanol can also be utilized in direct fuel cell, namely Direct Methanol Fuel Cell (DMFC), however DFAFC can produce higher electromotive force compared to DMFC and even H_2-O_2-PEMFC (H_2-O_2-polyer electrolyte membrane fuel cell), thus the performance of DFAFC is better. Besides, formic acid is more favourable compared to methanol as this alcohol is toxic. Methanol is also permeable through Nafion membrane that can reduce the cell performance. Unlike methanol, formic acid is non-toxic, non-flammable, and have low-fuel crossover through this Nafion membrane. The performance comparison of formic acid fuel cell vehicle and others vehicles is presented in Figure Z2 where ICV stands for internal combustion engine vehicle, FCV stands for fuel cell vehicle, and BEV stands for battery electric vehicle.

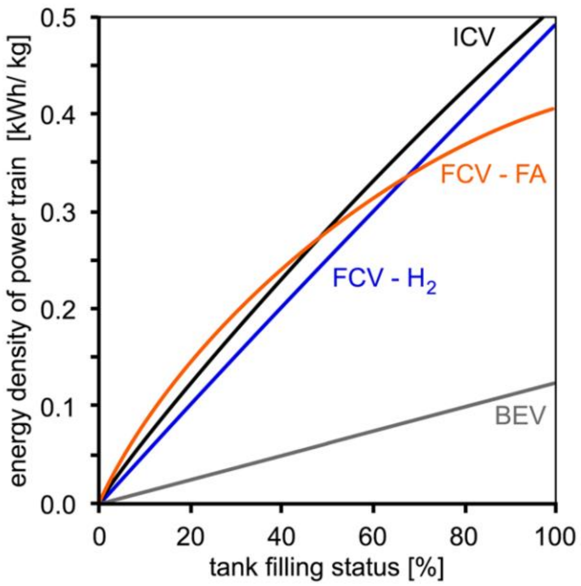

Figure 17. Fuel-cell-vehicle with formic acid performance compared to other systems

7. 2. Market Overview

As an important building block, formic acid has a broad application as listed in Table 21. The major applications are in preservation of animal feed, accounted for 34% and leather and tanning application of 32% of the global demand. The global capacity in 2013 reached 697 ktons/year while the demand was 579 ktons/year [53].

Table 21. Various application of formic acid [55]

Application	Industry
Neutralization and acidification	Textiles Leather Rubber Flue gas treatment
Preservation	Grass silage Feed Fish silage Drinking water
Cleaner and biocide	Industrial plants Household Dairy and beverages
Reactant	Plasticizers Pulp and paper Semiconductor board soldering
Starting material	Oil field Runway de-icing Refrigerant for cold stores

The global demand growth is forecasted to be 3.6%/year to 2018, with regional growth of Europe is 2.6%. Formic acid price depends on the purity. The most common formic acid grade is 85% with European price ranges between 500 – 600 EUR/ton. With this considerable high price, formic acid is believed to be a high valued product, which has low risk of substitution. The major global formic acid producers can be seen at Figure 18

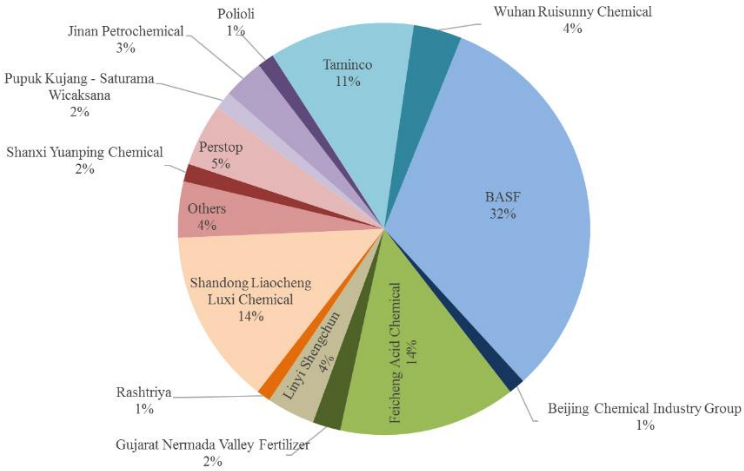

Figure 18. Major formic acid producers [53]

Chapter 8. Conclusion and Recommendation

8. 1. Conclusion

Recalling what has been delivered in Section 1. 3, the main objective of this study is to evaluate the most suitable CCU-PtX route which is decomposed into:

i. What is the most suitable CO_2 utilisation routes to be coupled with existing Twence installation?
ii. How is the economic analysis on the selected route?

This study revealed that Carbon Capture and Utilisation and Power-to-X concept are good alternatives for giving added value to CO_2 and electricity. The most suitable CCU-PtX idea for current Twence condition is formic acid production through direct electroreduction conversion. The by-product oxygen is not suggested to be sold for this alternative, but to be utilized in existing incinerator installation. Presently, the possible CO_2 uptake is 15 ktons/year to produce 18 ktons/year of formic acid. The selected route requires electricity consumption of 6 MW for the electroreduction and steam consumption of 7 MW for distillation. The alternative needs investment of € 43 million and will have internal rate of return of 13.3% corresponds to net present value of € 13 million. Once Twence can reserve a higher electricity allocation and investment, the company may also install a bigger plant capacity with CO_2 uptake of 50 ktons/year (or even more). This uptake capacity corresponds to formic acid production of 60 ktons/year in which Twence should put investment of € 99 million to give IRR of 23% and NPV of € 124 million.

Beside formic acid, other evaluated route is methanol and methane production. Methanol production evaluation shows that this alternative has an attractive business case if the oxygen as by-product is sold to the market, yet the economic result is lower than the formic acid synthesis. This study found that methane production has the possibility to be attractive if Twence can sell the methane and oxygen at higher price, have higher incentive from related government, can lower the operational cost especially the electricity and carbon dioxide cost, and have subsidy on the capital investment.

The market development of formic acid is positive at current estimation on 3% per year. The possibility of formic acid as hydrogen carrier and its utilisation by direct fuel cell is believed to boost the market growth further.

8. 2. Recommendation

This study still has room for improvements. The following recommendation are suggested for a deeper insight.

a. Optimization of business case model

The optimization of business case model can be done in a more detailed price estimation especially the major cost factors. A closer evaluation on electroreduction cell in formic acid production is strongly suggested. The electroreduction cell can be modeled to be linear, instead of following economic of scale rule as proposed in Eq.2.

To advance the scaling analysis, it is also good to see the economic performance as a function of capacity in a broad range. For sensitivity analysis, a non-ceteris-paribus analysis might be done. In reality, a price shift in a certain commodity/service can affect a price shift in other commodities/services. For example, when electricity price highly changes, the CO_2 cost should also be higher as the process for capturing CO_2 may need electricity.

b. Utilisation of oxygen

The possible utilization of oxygen as a by-product is to enhance the incinerator performance. It can lead to higher combustion temperature which is good for steam production. It also can reduce the flue gas volume and ease the flue gas treatment. For AEC 1 and AEC 2, it can decrease the investment that is needed to replace existing flue gas treatment facility. However, the financial study of this utilisation has not been evaluated. There is still possibility that compression and sales of the oxygen will promote to a more attractive business case. Thus, further analysis on oxygen utilisation is recommended.

c. Tax scenario

In the present study, electricity cost is still considered high due to the subjected tax. In fact, electricity cost is a significant operational cost item. If Twence can set up the tax in such a way that the company does not need to pay tax for own-use-electricity, Twence can expect a higher profit from the CCU-PtX implementation.

d. Comprehensive risk assessment

The possible risks for the realization of formic acid production from CCU-PtX concept have been identified. Brief mitigation has also been suggested. However, the frequency (possibility) and severity of consequences have not been analyzed and mapped. Hence, a more comprehensive risk assessment is advised.

e. Enhancement on process simulation

In this study, kinetic analysis has not been performed. The simulation is also done in a steady-state environment. An enhancement could be on the review of kinetic analysis, bring the simulation on dynamic environment, and complete the sizing of each unit operation.

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Appendix A: Mass Balance

a. Methane Production

Stream	1	2	3	4	5	6	7	8	9
T (Celcius)	20.0	70.0	84.8	376.8	277.1	275.2	40.0	40.0	40.0
P (bar)	1.0	9.0	9.0	8.0	7.7	2.0	2.0	2.0	2.0
mass flow (t/h)	6.3	6.3	7.5	7.5	7.5	7.5	7.5	2.7	4.8
%-m CO_2	1.00	1.00	0.84	0.04	0.04	0.04	0.04	0.11	0.00
%-m H_2	0.00	0.00	0.16	0.01	0.01	0.01	0.01	0.02	0.00
%-m CH_4	0.00	0.00	0.00	0.29	0.29	0.29	0.29	0.81	0.00
%-m H_2O	0.00	0.00	0.00	0.66	0.66	0.66	0.66	0.05	1.00
%-m CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
%-m O_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Stream	10	11	12	13	14	15	16	17	18
T (Celcius)	40.0	40.0	20.0	30.0	30.0	90.0	20.0	90.0	170.0
P (bar)	7.0	7.0	1.0	1.0	1.0	9.0	4.7	4.4	4.0
mass flow (t/h)	2.5	0.2	5.6	9.2	1.2	1.2	6.2	6.2	6.2
%-m CO_2	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
%-m H_2	0.00	0.33	0.00	0.00	1.00	1.00	0.00	0.00	0.00
%-m CH_4	0.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
%-m H_2O	0.00	0.67	1.00	0.00	0.00	0.00	1.00	1.00	1.00
%-m CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
%-m O_2	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00

b. Methanol production

Stream	1	2	3	4	5	6	7	8	9	10
T (Celcius)	20.0	178.8	56.8	230.0	285.0	112.0	70.0	69.0	40.0	45.6
P (bar)	1.0	51.0	51.0	50.7	49.7	49.3	49.0	49.0	48.6	51.0
mass flow (t/h)	6.3	6.3	48.5	48.5	48.5	48.5	48.5	41.3	41.3	41.3
% CO_2	1.00	1.00	0.82	0.82	0.69	0.69	0.69	0.81	0.81	0.81
%H_2O	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.00	0.00	0.00
%H_2	0.00	0.00	0.18	0.18	0.17	0.17	0.17	0.19	0.19	0.19
%CH_3OH	0.00	0.00	0.00	0.00	0.10	0.10	0.10	0.00	0.00	0.00
%O_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Stream	11	12	13	14	15	16	17	18	19	20
T (Celcius)	69.0	69.4	74.2	25.0	113.3	40.0	20.0	30.0	30.0	30.0
P (bar)	49.0	1.7	1.4	1.1	1.6	1.3	1.3	1.3	1.0	1.0
mass flow (t/h)	7.2	7.2	4.9	4.9	2.4	2.4	5.7	8.1	7.2	0.9
% CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
%H_2O	0.36	0.36	0.05	0.05	1.00	1.00	1.00	1.00	0.00	0.00
%H_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
%CH_3OH	0.64	0.64	0.95	0.95	0.00	0.00	0.00	0.00	0.00	0.00
%O_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00

Stream	21
T (Celcius)	124.9
P (bar)	51.0
mass flow (t/h)	0.9
% CO_2	0.00
%H_2O	0.00
%H_2	1.00
%CH_3OH	0.00
%O_2	0.00

c. Formic acid production (base case scenario)

Stream	1	2	3	4	5	6	7	8	9
T (Celcius)	40.0	37.4	35.0	35.0	37.0	35.0	35.0	35.0	37.1
P (bar)	4.5	4.5	4.4	4.4	4.5	4.4	4.4	4.4	4.2
mass flow (t/h)	6.3	42.0	2.3	35.7	35.7	0.0	26.8	12.6	0.2
%-m CO_2	1.00	1.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00
%-m HCOOH	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.45	0.29
%-m H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.55	0.55	0.71
%-m H_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
%-m O_2	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00

Stream	10	11	12	13	14	15	16	17	18
T (Celcius)	35.0	61.0	153.7	80.7	40.0	142.7	40.0	40.0	25.0
P (bar)	4.4	4.1	4.0	3.7	3.3	3.9	3.9	4.2	4.5
mass flow (t/h)	14.2	14.2	7.6	7.6	7.6	6.7	6.7	6.7	3.8
%-m CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
%-m HCOOH	0.45	0.45	0.85	0.85	0.85	0.00	0.00	0.00	0.00
%-m H_2O	0.55	0.55	0.15	0.15	0.15	1.00	1.00	1.00	1.00
%-m H_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
%-m O_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

d. Formic acid production (down scaled scenario)

Stream	1	2	3	4	5	6	7	8	9
T (Celcius)	40.0	37.4	35.0	35.0	37.0	35.0	35.0	35.0	38.1
P (bar)	4.5	4.5	4.4	4.4	4.5	4.4	4.4	4.4	4.2
mass flow (t/h)	1.9	12.6	0.7	10.7	10.7	0.0	6.3	1.8	0.0
%-m CO_2	100%	100%	0%	100%	100%	100%	0%	0%	0%
%-m HCOOH	0%	0%	0%	0%	0%	0%	45%	45%	21%
%-m H_2O	0%	0%	0%	0%	0%	0%	55%	55%	79%
%-m H_2	0%	0%	0%	0%	0%	0%	0%	0%	0%
%-m O_2	0%	0%	100%	0%	0%	0%	0%	0%	0%

Stream	10	11	12	13	14	15	16	17	18
T (Celcius)	35.0	56.0	153.7	94.7	40.0	142.7	40.0	40.0	25.0
P (bar)	4.4	4.1	4.0	3.7	3.3	3.9	3.9	4.2	4.5
mass flow (t/h)	4.4	4.4	2.3	2.3	2.3	2.1	2.1	2.1	1.1
%-m CO_2	0%	0%	0%	0%	0%	0%	0%	0%	0%
%-m HCOOH	45%	45%	85%	85%	85%	0%	0%	0%	0%
%-m H_2O	55%	55%	15%	15%	15%	100%	100%	100%	100%
%-m H_2	0%	0%	0%	0%	0%	0%	0%	0%	0%
%-m O_2	0%	0%	0%	0%	0%	0%	0%	0%	0%

Appendix B Business Case

a. Scenario 1 – Methane production with sales of oxygen

Quickcalc total	Methane	v2,SBL,17nov17

Disconteringsvoet	9.50%	
FINAL CAPEX	140,902,323	
Depreciation/lifetime	20	year (max 50)
Inflation	2.0%	
Availability (E-price)	7,884	h/year
CO2 uptake	50,000	ton/year
1 CO2 into	0.55	methane 85%

OPEX			ANNUAL VOLUME			BASE VOLUME		PRICES	
Revenue methane		6,951,796	Methane (mass)	27,603	ton methanol 95%	3.5	ton methane 88%/hour	Methane	30 €/MWh Methane
Revenue Incentives		18,538,122	Methane (energy)	231,726.53	MWh/y	29.39	MW		252 €/ton Methane 85%
Revenu Steam		151,373	Steam	37,843.20	MWh st/y	4.80	MW	Oxygen	100 €/ton O2
Revenue Oxygen		7,253,280	Oxygen	72,533	ton oxygen 100%	9.2	ton/h	Incentive	80 €/MWh
Electricity cost	-	24,826,716	CO2	50,000	ton/year	6.3	ton CO2/hour	Steam	4 €/MWh
CO2 cost	-	1,500,000	electricity	528,228	MWh e/y	67	MW	Electricity	47 €/MWh
Steam		-	Cooling water	258,279.84	t/y	33	t/h	CO2	30 €/ton CO2
Cooling water	-	387,420	Process Water	47,304.00	t/y	6	t/h	Water	1.5 €/ton water
Process water	-	70,956	Operator	3.5	operators/shift	5	shifts	Transport O2	20 €/ton O2
Transport O2	-	1,450,656						Salary	55,000 €/FTE
Operators	-	962,500						Maintenance-Aux	3% of CAPEX
SA&G									
Maintenance	-	4,227,070							
Savings / year	-	530,747	yearly						

PROJECT TOTAL	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Year	0	1	2	3	4	5	6	7	8	9	10
Savings / year		(530,747)	(541,362)	(552,189)	(563,233)	(574,497)	(585,987)	(597,707)	(609,661)	(621,854)	(634,291)
Depreciation/lifetime		(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)
Winst voor belasting	-	(7,575,863)	(7,586,478)	(7,597,305)	(7,608,349)	(7,619,613)	(7,631,103)	(7,642,823)	(7,654,777)	(7,666,970)	(7,679,407)
Investment maj.equipm.	(140,902,323)										
Depreciation/lifetime		7,045,116	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116
Cash flow	**(140,902,323)**	(530,747)	(541,362)	(552,189)	(563,233)	(574,497)	(585,987)	(597,707)	(609,661)	(621,854)	(634,291)
Cash flow cumulative		(141,433,070)	(141,974,431)	(142,526,620)	(143,089,852)	(143,664,350)	(144,250,337)	(144,848,043)	(145,457,704)	(146,079,559)	(146,713,850)

PROJECT TOTAL	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Year	11	12	13	14	15	16	17	18	19	20
Savings / year	(646,977)	(659,917)	(673,115)	(686,577)	(700,309)	(714,315)	(728,601)	(743,173)	(758,037)	(773,198)
Depreciation/lifetime	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)	(7,045,116)
Winst voor belasting	(7,692,093)	(7,705,033)	(7,718,231)	(7,731,693)	(7,745,425)	(7,759,431)	(7,773,717)	(7,788,289)	(7,803,153)	(7,818,314)
Investment maj.equipm.										
Depreciation/lifetime	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116	7,045,116
Cash flow	(646,977)	(659,917)	(673,115)	(686,577)	(700,309)	(714,315)	(728,601)	(743,173)	(758,037)	(773,198)
Cash flow cumulative	(147,360,827)	(148,020,744)	(148,693,859)	(149,380,436)	(150,080,745)	(150,795,060)	(151,523,661)	(152,266,834)	(153,024,871)	(153,798,069)

PROJECT TOTAL	
DCF (9.5%, 20 year)	(146,266,774)
IRR (20 year)	#NUM!
PaybackPeriod (excl intere	

b. Scenario 2 - Methane production without sales of oxygen

Quickcalc total	Methane	v2,SBL,17nov17

Disconteringsvoet	9.50%	
FINAL CAPEX	129,780,284	
Depreciation/lifetime	20	year (max 50)
Inflation	2.0%	
Availability (E-price)	7,884	h/year
CO2 uptake	50,000	ton/year
1 CO2 into	0.55	methane 88%

OPEX			ANNUAL VOLUME			BASE VOLUME		PRICES	
Revenue methane		6,951,796	Methane (mass)	27,603	ton methanol 95%	3.5	ton methane 88%/hour	Methane	30 €/MWh Methane
Revenue Incentives		18,538,122	Methane (energy)	231,726.53	MWh/y	29.39	MW		252 €/ton Methane 85%
Revenu Steam		151,373	Steam	37,843.20	MWh st/y	4.80	MW	Oxygen	0 €/ton O2
Revenue Oxygen		-	Oxygen	72,533	ton oxygen 100%	9.2	ton/h	Incentive	80 €/MWh
Electricity cost	-	24,826,716	CO2	50,000	ton/year	6.3	ton CO2/hour	Steam	4 €/MWh
CO2 cost	-	1,500,000	electricity	528,228	MWh e/y	67	MW	Electricity	47 €/MWh
Steam		-	Cooling water	258,279.84	t/y	33	t/h	CO2	30 €/ton CO2
Cooling water	-	387,420	Process Water	47,304.00	t/y	6	t/h	Water	1.5 €/ton water
Process water	-	70,956	Operator	3.5	operators/shift	5	shifts	Transport O2	0 €/ton O2
Transport O2		-						Salary	55,000 €/FTE
Operators	-	962,500						Maintenance-Aux	3% of CAPEX
SA&G									
Maintenance	-	3,893,409							
Savings / year	-	5,999,709	yearly						

PROJECT TOTAL	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Year	0	1	2	3	4	5	6	7	8	9	10
Savings / year		(5,999,709)	(6,119,704)	(6,242,098)	(6,366,940)	(6,494,278)	(6,624,164)	(6,756,647)	(6,891,780)	(7,029,616)	(7,170,208)
Depreciation/lifetime		(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)
Winst voor belasting	-	(12,488,724)	(12,608,718)	(12,731,112)	(12,855,954)	(12,983,293)	(13,113,178)	(13,245,661)	(13,380,794)	(13,518,630)	(13,659,222)
Investment maj.equipm.	(129,780,284)										
Depreciation/lifetime		6,489,014	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014
Cash flow	**(129,780,284)**	(5,999,709)	(6,119,704)	(6,242,098)	(6,366,940)	(6,494,278)	(6,624,164)	(6,756,647)	(6,891,780)	(7,029,616)	(7,170,208)
Cash flow cumulative		(135,779,993)	(141,899,696)	(148,141,794)	(154,508,734)	(161,003,012)	(167,627,176)	(174,383,823)	(181,275,603)	(188,305,219)	(195,475,427)

PROJECT TOTAL	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Year	11	12	13	14	15	16	17	18	19	20
Savings / year	(7,313,612)	(7,459,885)	(7,609,082)	(7,761,264)	(7,916,489)	(8,074,819)	(8,236,315)	(8,401,042)	(8,569,062)	(8,740,444)
Depreciation/lifetime	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)	(6,489,014)
Winst voor belasting	(13,802,626)	(13,948,899)	(14,098,096)	(14,250,278)	(14,405,503)	(14,563,833)	(14,725,329)	(14,890,056)	(15,058,077)	(15,229,458)
Investment maj.equipm.										
Depreciation/lifetime	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014	6,489,014
Cash flow	(7,313,612)	(7,459,885)	(7,609,082)	(7,761,264)	(7,916,489)	(8,074,819)	(8,236,315)	(8,401,042)	(8,569,062)	(8,740,444)
Cash flow cumulative	(202,789,040)	(210,248,924)	(217,858,006)	(225,619,270)	(233,535,759)	(241,610,578)	(249,846,893)	(258,247,935)	(266,816,997)	(275,557,441)

PROJECT TOTAL	
DCF (9.5%, 20 year)	(190,421,550)
IRR (20 year)	#NUM!
PaybackPeriod (excl intere	

c. Scenario 3 – Methanol production with sales of oxygen

Quickcalc total	Methanol	v2,SBL,17nov17
Disconteringsvoet	9.50%	
	87,158,910	
Depreciation/lifetime	20	year (max 50)
Inflation	2.0%	
Availability (E-price)	7,884	h/year
CO2 uptake	50,000	ton/year
1 CO2 into	0.77	methanol 95%

OPEX			ANNUAL VOLUME			HOURLY VOLUME		PRICES	
Revenue methanol		12,848,975	Methanol (mass)	38,644	ton methanol !	4.9	ton methanol 95%/hour	Methanol	350 €/ton Methanol
Revenue Incentives		17,568,075	Methanol (energy)	219600.936	MWh/year	27.85	MW		333 €/ton Methanol 95%
Revenue Oxygen		5,676,480	Oxygen	56,765	ton oxygen 10	7.2	ton/h	Oxygen	100 €/ton O2
Electricity cost	-	19,268,496	Electricity	50,000	ton/year	6.3	ton CO2/hour	Incentive	80 €/MWh
CO2 cost	-	1,500,000	CO2	409,968	MWh e/y	52	MW	Electricity	47 €/MWh
Steam		-	Steam	23,652	MWh st/y	3	MW	CO2	30 €/ton CO2
Cooling water	-	723,751	Cooling water	482,500.80	t/y	61	t/h	Water	1.5 €/ton water
Process water	-	70,956	Process Water	47,304.00	t/y	6	t/h	Transport Liquid	10.0 €/ton
Transportation Cost Methanol	-	386,435	Operator	5	operators/shifi	5	shifts	Transport O2	20.0 €/ton
Transportation Cost O2	-	1,135,296						Salary	55,000 €/FTE
Revenue								Maintenance-Aux	3% of CAPEX
Operators	-	1,375,000							
SA&G									
Maintenance	-	2,614,767							
Savings / year		9,018,828							

PROJECT TOTAL	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Savings / year		9,018,828	9,199,204	9,383,188	9,570,852	9,762,269	9,957,515	10,156,665	10,359,798	10,566,994	10,778,334	10,993,901	11,213,779	11,438,054	11,666,815	11,900,152	12,138,155	12,380,918	12,628,536	12,881,107	13,138,729
Depreciation/lifetime		(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)
Winst voor belasting	-	4,660,882	4,841,259	5,025,243	5,212,907	5,404,324	5,599,569	5,798,719	6,001,853	6,209,049	6,420,389	6,635,955	6,855,833	7,080,109	7,308,870	7,542,206	7,780,209	8,022,972	8,270,591	8,523,162	8,780,784
Investment maj.equipm.	(87,158,910)																				
Depreciation/lifetime		4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945
Cash flow	**(87,158,910)**	9,018,828	9,199,204	9,383,188	9,570,852	9,762,269	9,957,515	10,156,665	10,359,798	10,566,994	10,778,334	10,993,901	11,213,779	11,438,054	11,666,815	11,900,152	12,138,155	12,380,918	12,628,536	12,881,107	13,138,729
Cash flow cumulative		(78,140,082)	(68,940,877)	(59,557,689)	(49,986,837)	(40,224,567)	(30,267,053)	(20,110,388)	(9,750,589)	816,405	11,594,739	22,588,640	33,802,418	45,240,473	56,907,288	68,807,440	80,945,595	93,326,513	105,955,049	118,836,156	131,974,885

PROJECT TOTAL	
DCF (9.5%, 20 year)	3,997,696
IRR (20 year)	10.1%
PaybackPeriod (excl interest)	9 year

d. Scenario 4 - Methanol production without sales of oxygen

Quickcalc total	Methanol	v2,SBL,17nov17
Disconteringsvoet	9.50%	
FINAL CAPEX	87,158,910	
Depreciation/lifetime	20	year (max 50)
Inflation	2.0%	
Availability (E-price)	7,884	h/year
CO2 uptake	50,000	ton/year
1 CO2 into	0.77	methanol 95%

OPEX			ANNUAL VOLUME			BASE VOLUME		PRICES	
Revenue methanol		12,848,975	Methanol (mass)	38,644	ton methanol 95%	4.9	ton methanol 95%/hour	Methanol	350 €/ton Methanol
Revenue Incentives		17,568,075	Methanol (energy)	219600.936	MWh/year	27.85	MW		333 €/ton Methanol 95%
Revenue Oxygen		5,676,480	Oxygen	56,765	ton oxygen 100%/	7.2	ton/h	Oxygen	100 €/ton O2
Electricity cost	-	19,268,496	Electricity	50,000	ton/year	6.3	ton CO2/hour	Incentive	80 €/MWh
CO2 cost	-	1,500,000	CO2	409,968	MWh e/y	52	MW	Electricity	47 €/MWh
Steam		-	Steam	23,652	MWh st/y	3	MW	CO2	30 €/ton CO2
Cooling water	-	723,751	Cooling water	482,500.80	t/y	61	t/h	Water	1.5 €/ton water
Process water	-	70,956	Process Water	47,304.00	t/y	6	t/h	Transport Liquid	10.0 €/ton
Transportation Cost Methanol	-	386,435	Operator	5	operators/shift	5	shifts	Transport O2	20.0 €/ton
Transportation Cost O2	-	1,135,296						Salary	55,000 €/FTE
Revenue								Maintenance-Aux	3% of CAPEX
Operators	-	1,375,000							
SA&G									
Maintenance	-	2,614,767							
Savings / year		9,018,828							

PROJECT TOTAL	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Savings / year		9,018,828	9,199,204	9,383,188	9,570,852	9,762,269	9,957,515	10,156,665	10,359,798	10,566,994	10,778,334	10,993,901	11,213,779	11,438,054	11,666,815	11,900,152	12,138,155	12,380,918	12,628,536	12,881,107	13,138,729
Depreciation/lifetime		(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)	(4,357,945)
Winst voor belasting	-	4,660,882	4,841,259	5,025,243	5,212,907	5,404,324	5,599,569	5,798,719	6,001,853	6,209,049	6,420,389	6,635,955	6,855,833	7,080,109	7,308,870	7,542,206	7,780,209	8,022,972	8,270,591	8,523,162	8,780,784
Investment maj.equipm.	(87,158,910)																				
Depreciation/lifetime		4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945	4,357,945
Cash flow	**(87,158,910)**	9,018,828	9,199,204	9,383,188	9,570,852	9,762,269	9,957,515	10,156,665	10,359,798	10,566,994	10,778,334	10,993,901	11,213,779	11,438,054	11,666,815	11,900,152	12,138,155	12,380,918	12,628,536	12,881,107	13,138,729
Cash flow cumulative		(78,140,082)	(68,940,877)	(59,557,689)	(49,986,837)	(40,224,567)	(30,267,053)	(20,110,388)	(9,750,589)	816,405	11,594,739	22,588,640	33,802,418	45,240,473	56,907,288	68,807,440	80,945,595	93,326,513	105,955,049	118,836,156	131,974,885

PROJECT TOTAL	
DCF (9.5%, 20 year)	3,997,696
IRR (20 year)	10.1%
PaybackPeriod (excl interest)	9 year

e. Scenario 5 – Formic acid production with sales of oxygen

Quickcalc total	Formic Acid	v2,SBL,17nov17
Disconteringsvoet	9.50%	
FINAL CAPEX	106,987,359	
Depreciation/lifetime	20	year (max 50)
Inflation	2.0%	
Availability (E-price)	7,884	h/year
CO2 uptake	50,000	ton/year
1 CO2 into	1.20	formic acid 85%

OPEX			ANNUAL VOLUME			BASE VOLUME		PRICES	
Revenue formic acid 85%		32,965,300	Formic acid (mass)	59,937	ton formic acid 8!	7.6	ton formic acid 85%/hour	Formic acid 85%	550 €/ton Formic Acid 85%
Revenue Incentives		6,117,984	Formic acid (energy)	76,475	MWh/y	9.70	MW	Oxygen	100 €/ton O2
Revenue Oxygen		1,576,800	Oxygen	15,768	ton oxygen/year	2	ton/h	Incentive	80 €/MWh
Electricity cost	-	7,503,597	Electricity	159,651	MWh e/y	20.25	MW	Electricity	47 €/MWh
CO2 cost	-	1,500,000	CO2	50,000	ton/year	6.3	ton CO2/hour	CO2	30 €/ton CO2
Steam		-	Steam	157,680	MWh st/y	20	MW	Water	1.5 €/ton water
Cooling water	-	1,404,929	Cooling water	936,619	t/y	119	t/h	Transport Liquid	10.0 €/ton
Process water	-	63,072	Process Water	31,536	t/y	4	t/h	Transport O2	20.0 €/ton
Transportation Cost FA	-	599,369	Operator	3.5	operators/shift	5	shifts	Salary	55,000 €/FTE
Transportation Cost O2	-	315,360						Maintenance-Aux	5.0% of CAPEX
Operators	-	962,500							
SA&G									
Maintenance	-	5,349,368							
Savings / year		22,961,889							

PROJECT TOTAL	2018	2019	2020	2021	2022	2023	2024	2025
Year	0	1	2	3	4	5	6	7
Savings / year		22,961,889	23,421,127	23,889,549	24,367,340	24,854,687	25,351,781	25,858,816
Depreciation/lifetime		(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)
Winst voor belasting	-	17,612,521	18,071,759	18,540,181	19,017,972	19,505,319	20,002,413	20,509,448
Investment maj.equipm.	(106,987,359)							
Depreciation/lifetime		5,349,368	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368
Cash flow	**(106,987,359)**	22,961,889	23,421,127	23,889,549	24,367,340	24,854,687	25,351,781	25,858,816
Cash flow cumulative		(84,025,470)	(60,604,343)	(36,714,794)	(12,347,454)	12,507,233	37,859,014	63,717,830

PROJECT TOTAL	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Year	8	9	10	11	12	13	14	15	16	17	18	19	20
Savings / year	26,375,993	26,903,513	27,441,583	27,990,414	28,550,223	29,121,227	29,703,652	30,297,725	30,903,679	31,521,753	32,152,188	32,795,232	33,451,136
Depreciation/lifetime	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)	(5,349,368)
Winst voor belasting	21,026,625	21,554,145	22,092,215	22,641,046	23,200,855	23,771,859	24,354,284	24,948,357	25,554,311	26,172,385	26,802,820	27,445,864	28,101,768
Investment maj.equipm.													
Depreciation/lifetime	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368	5,349,368
Cash flow	26,375,993	26,903,513	27,441,583	27,990,414	28,550,223	29,121,227	29,703,652	30,297,725	30,903,679	31,521,753	32,152,188	32,795,232	33,451,136
Cash flow cumulative	90,093,823	116,997,335	144,438,918	172,429,333	200,979,555	230,100,782	259,804,434	290,102,159	321,005,838	352,527,591	384,679,779	417,475,010	450,926,147

PROJECT TOTAL	
DCF (9.5%, 20 year)	125,096,887
IRR (20 year)	23.0%
PaybackPeriod (excl intere	5 year

f. Scenario 6 – Formic acid production without sales of oxygen

Quickcalc total	Formic Acid	v2,SBL,17nov17
Disconteringsvoet	9.50%	
FINAL CAPEX	99,136,507	
Depreciation/lifetime	20	year (max 50)
Inflation	2.0%	
Availability (E-price)	7,884	h/year
CO2 uptake	50,000	ton/year
1 CO2 into	1.20	formic acid 85%

OPEX			ANNUAL VOLUME			BASE VOLUME		PRICES	
Revenue formic acid 85%		32,965,300	Formic acid (mass)	59,937	ton formic acid 8!	7.6	ton formic acid 85%/hour	Formic acid 85%	550 €/ton Formic Acid 85%
Revenue Incentives		6,117,984	Formic acid (energy)	76474.8	MWh/y	9.70	MW	Oxygen	0 €/ton O2
Revenue Oxygen		-	Oxygen	15,768	ton oxygen/year	2	ton/h	Incentive	80 €/MWh
Electricity cost	-	7,503,597	Electricity	159,651	MWh e/y	20.25	MW	Electricity	47 €/MWh
CO2 cost	-	1,500,000	CO2	50000	ton CO2/year	6.3	ton CO2/hour	CO2	30 €/ton CO2
Steam		-	Steam	157,680	MWh st/y	20	MW	Water	1.5 €/ton water
Cooling water	-	1,404,929	Cooling water	936619.2	t/y	119	t/h	Transport Liquid	10.0 €/ton
Process water	-	63,072	Process Water	31536	t/y	4	t/h	Transport O2	0.0 €/ton
Transportation Cost FA	-	599,369	Operator	3.5	operators/shift	5	shifts	Salary	55,000 €/FTE
Transportation Cost O2		-						Maintenance-Aux	5.0% of CAPEX
Operators	-	962,500							
SA&G									
Maintenance	-	4,956,825							
Savings / year		22,092,991							

PROJECT TOTAL	2018	2019	2020	2021	2022	2023	2024	2025
Year	0	1	2	3	4	5	6	7
Savings / year		22,092,991	22,534,851	22,985,548	23,445,259	23,914,164	24,392,448	24,880,297
Depreciation/lifetime		(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)
Winst voor belasting	-	17,136,166	17,578,026	18,028,723	18,488,434	18,957,339	19,435,622	19,923,471
Investment maj.equipm.	(99,136,507)							
Depreciation/lifetime		4,956,825	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825
Cash flow	**(99,136,507)**	22,092,991	22,534,851	22,985,548	23,445,259	23,914,164	24,392,448	24,880,297
Cash flow cumulative		(77,043,516)	(54,508,664)	(31,523,116)	(8,077,857)	15,836,308	40,228,755	65,109,052

PROJECT TOTAL	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Year	8	9	10	11	12	13	14	15	16	17	18	19	20
Savings / year	25,377,903	25,885,461	26,403,170	26,931,233	27,469,858	28,019,255	28,579,640	29,151,233	29,734,258	30,328,943	30,935,522	31,554,232	32,185,317
Depreciation/lifetime	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)	(4,956,825)
Winst voor belasting	20,421,077	20,928,635	21,446,345	21,974,408	22,513,033	23,062,430	23,622,815	24,194,408	24,777,432	25,372,117	25,978,696	26,597,407	27,228,491
Investment maj.equipm.													
Depreciation/lifetime	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825	4,956,825
Cash flow	25,377,903	25,885,461	26,403,170	26,931,233	27,469,858	28,019,255	28,579,640	29,151,233	29,734,258	30,328,943	30,935,522	31,554,232	32,185,317
Cash flow cumulative	90,486,955	116,372,415	142,775,585	169,706,819	197,176,676	225,195,932	253,775,572	282,926,805	312,661,062	342,990,005	373,925,527	405,479,759	437,665,076

PROJECT TOTAL	
DCF (9.5%, 20 year)	124,165,472
IRR (20 year)	23.8%
PaybackPeriod (excl intere	5 year

g. Downscale scenario – Formic acid production without sales of oxygen, CO_2 uptake 15 ktons/y

Quickcalc total	Formic Acid	v2,SBL,17nov17
Disconteringsvoet	9.50%	
FINAL CAPEX	43,517,759	
Depreciation/lifetime	20	year (max 50)
Inflation	2.0%	
Availability (E-price)	7,884	h/year
CO2 uptake	15,000	ton/year
1 CO2 into	1.20	formic acid 85%

OPEX			ANNUAL VOLUME			BASE VOLUME		PRICES	
Revenue formic acid 85%		10,081,665	Formic acid (mass)	18,330	ton formic acid 8!	2.3	ton formic acid 85%/hour	Formic acid 85%	550 €/ton Formic Acid 85%
Revenue Incentives		1,879,546	Formic acid (energy)	23,494.32	MWh/y	2.98	MW	Oxygen	0 €/ton O2
Revenue Oxygen		-	Oxygen	5,434	ton oxygen/year	0.6892	ton/h	Incentive	80 €/MWh
Electricity cost	-	2,241,815	Electricity	47,698	MWh e/y	6.05	MW	Electricity	47 €/MWh
CO2 cost	-	450,000	CO2	15,000	ton/year	1.9	ton CO2/hour	CO2	30 €/ton CO2
Steam		-	Steam	55,188	MWh st/y	7	MW	Water	1.5 €/ton water
Cooling water	-	319,302	Cooling water	212,868.00	t/y	27	t/h	Transport Liquid	10.0 €/ton
Process water	-	17,345	Process Water	8,672.40	t/y	1	t/h	Transport O2	0.0 €/ton
Transportation Cost FA	-	183,303	Operator	3.5	operators/shift	5	shifts	Salary	55,000 €/FTE
Transportation Cost O2		-						Maintenance-Aux	5% of CAPEX
Operators	-	962,500							
SA&G									
Maintenance	-	2,175,888							
Savings / year		5,611,057							

PROJECT TOTAL	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Savings / year		5,611,057	5,723,279	5,837,744	5,954,499	6,073,589	6,195,061	6,318,962	6,445,341	6,574,248	6,705,733	6,839,848	6,976,645	7,116,178	7,258,501	7,403,671
Depreciation/lifetime		(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)	(2,175,888)
Winst voor belasting	-	3,435,169	3,547,391	3,661,856	3,778,611	3,897,701	4,019,173	4,143,074	4,269,453	4,398,360	4,529,845	4,663,960	4,800,757	4,940,290	5,082,613	5,227,783
Investment maj.equipm.	(43,517,759)															
Depreciation/lifetime		2,175,888	2,175,888	2,175,888	2,175,888	2,175,888	2,175,888	2,175,888	2,175,888	2,175,888	2,175,888	2,175,888	2,175,888	2,175,888	2,175,888	2,175,888
Cash flow	**(43,517,759)**	5,611,057	5,723,279	5,837,744	5,954,499	6,073,589	6,195,061	6,318,962	6,445,341	6,574,248	6,705,733	6,839,848	6,976,645	7,116,178	7,258,501	7,403,671
Cash flow cumulative		(37,906,702)	(32,183,423)	(26,345,679)	(20,391,180)	(14,317,591)	(8,122,530)	(1,803,568)	4,641,773	11,216,021	17,921,755	24,761,602	31,738,247	38,854,424	46,112,926	53,516,597

PROJECT TOTAL		
DCF (9.5%, 20 year)	13,195,260	
IRR (20 year)	13.3%	
PaybackPeriod (excl intere	8 year	7