Suggested Design Projects – 2017-2018

1. Process for Sustainably Sourced p-Xylene
   (recommended by Rick Bockrath, Consultant - formerly DuPont)

Problem Statement

You work for a biotechnology company that has a supply of isobutene produced from biomass. Your company is interested in converting this sustainably sourced isobutene to higher value products. You are part of a team tasked to develop a plant design and economic estimates for a para-xylene facility based on recent patents and other technical literature. The ultimate product is PET for fibers. At this point it is believed that PET bottles cannot “afford” the required pricing premium. The other part of the PET polymer is based on ethylene glycol. Producers in Brazil have apparently successfully started up commercial scale EG plants based on ethanol and are able to command a significant price premium over petrochemical EG (100%) for select markets. Your marketing organization is optimistic that the fibers segment can accept the needed upcharge. Your focus is on defining the magnitude of the needed premium to make the venture profitable.

Background

In 2014, global para-xylene demand was estimated at 36.83 million tons and is estimated to exceed 62.98 million tons at a CAGR of 7.0% from 2015 to 2022. This growth is due to increasing demand for fiber and polyester resin in numerous end-use applications across various industries. Growing utilization of purified terephthalic acid (PTA) for polyester production, particularly in Asia Pacific is expected to fuel growth in paraxylene market over the forecast period. Rising demand for bio-based alternatives and increasing consumer awareness subject to non-biodegradable nature of petrochemical products is expected to be the major obstacles for market participants. A sustainably sourced alternative may have a market advantage even at a price premium. The current market price for para-xylene is about $700 - $800/metric tonne.

In petrochemical processing, xylenes are produced via catalytic reforming. A low octane naphtha cut (typically a straight run or hydrocracked naphtha) is converted into high-octane aromatics, including, benzene, toluene, and mixed xylenes. The amount of xylenes contained in the catalytic reformate depends on the fraction and type of crude oil, the reformer operating conditions, and the catalyst used. The amount of xylenes produced can vary widely, typically ranging from 18 to 33 vol % of the reformate. The unrecovered reformate xylenes are used in the gasoline pool.

The mixed xylenes that are recovered from these sources are used as follows: 50 – 60% to make PX, 10 – 15% to make OX, 10 – 25% returned back to gasoline blending, and only 1% to make MX. The relative lack of end uses for MX is unfortunate, because the catalytic reformate sources typically contain twice as much MX as PX or OX. The majority of the MX in these sources is isomerized to PX and OX. The purified xylenes are used to synthesize plasticizers and polyester fibers, photographic films, and beverage bottles. PX is first oxidized to terephthalic acid or dimethyl terephthalate before being converted into polyesters. OX is oxidized to phthalic anhydride before being converted into plasticizers. MX is oxidized to isophthalic acid, which is used to make polyesters.

GEVO Process from Isobutanol

Your team has performed a detailed patent review of various processes and a clear conclusion is that isobutene to xylene catalysts are known to be prone to coking and low conversion. Recent patents from GEVO have outlined a route to relatively high purity p-xylene through careful selection of catalysts and
process conditions. A key difference in their patent is that the olefin to aromatic conversion step is done via the dimer of isobutene, isooctene. The IBN is converted to the dimer is a different reactor. The GEVO patent starts with isobutanol produced from fermentation. The isobutanol is dehydrated to isobutylene. The isobutylene is then oligomerized, preferably to the dimer, and then undergoes a dehydrocyclization to form xylenes. Unconverted feed can be separated from the product of each reaction step and recycled. It may be necessary to add diluent in addition to this recycle in order to optimize the reaction step conditions.

**Design Basis and Processing Alternatives**

Your company produces isobutylene from fermentation, and you have 500,000 metric tonnes of isobutylene available as feed for your p-xylene facility. For the purposes of this study, you will use 90% of the nominal market price as your isobutylene transfer price. An October, 2016 report by Grand View Research indicates that 2015 pricing was $1740/met. tonne and that this will rise to $1900/met. tonne by 2024. You have been tasked along with your team to adopt the GEVO patent, along with other relevant technical literature, to design a facility to convert isobutylene to p-xylene.

You will need to determine the best reaction parameters for each step of the process. These are energetic reactions; you will need to decide whether additional diluents are needed to optimize the process conditions. Since there are multiple reaction steps, you should explore various configurations of the facility to determine the most economic design. Depending on your yields and selectivities, you will need to design a purification system(s) to recycle unreacted feed components and to obtain a xylene fraction. Your research has indicated that the required p-xylene purity must be greater than 99.7 wt% to be used as a polymer grade terephthalic acid process feedstock. While the patent gives examples with selectivity in excess of 99%, it is not clear that you can achieve the required 99.7 wt% routinely over the life of the catalyst. Therefore, for purposes of this study assume that you will generate a xylene “crude” product that is 90+ wt% p-xylene. The rest would be meta and ortho-xylene. This material will then be sent to an existing xylene separation plant, which is owned by another company, where the pure isomers will be recovered. Assume that the separator will charge you $50/metric tonne of xylene processed to separate the isomers.

The dehydrocyclization catalysts are known to be prone to coking of the catalyst. The catalyst fouling will ultimately stop the reaction. You will need to explore options for catalyst regeneration to enable an operational design. At this early stage of the design, the dehydrocyclization catalyst life has not yet been determined. You have been asked to develop the sensitivity of the process economics as a function of catalyst life.

At this scale and with IBN as the feedstock, it is expected that biobased p-xylene will not be cost competitive with petrochemical p-xylene. Therefore, a pricing premium will be required. You are to determine what market premium or subsidy is needed to have your p-xylene market competitive. Your company requires a minimum 15% IRR on this venture to move forward. The marketing organization would like you to “bracket” the needed premium. Therefore you are to study two cases;

a) The IRR and NPV for a case where the p-xylene is sold at current market prices.

b) A 15% IRR case where the pricing premium is included. The marketing organization wants to know the magnitude of the premium and the resulting projects NPV.

**References:**


2


2. **Multiproduct Acetates Plant**  
*recommended by Gary Sawyer, CDI Corporation*

**Background**  Ethyl and butyl acetates are solvents used in surface coatings, inks, flavorings and pharmaceuticals, and other applications. As they are not on EPA’s list of Hazardous Air Pollutants, they have displaced some listed compounds formerly used as solvents. Global demand is roughly 2.5 million metric tons of ethyl acetate and 1.8 million metric tons of butyl acetate.\(^1\) They can be made from non-renewable or bio-sourced materials.

Conventional technology to produce acetates is through the esterification of ethanol or butanol with acetic acid, using a heterogeneous or homogenous acid catalyst. The reaction is equilibrium limited, and the resulting acetates create multicomponent azeotropes with water and unreacted alcohols. Other routes to ethyl acetate have been commercialized\(^2\), but conventional technology lends itself to using the same equipment for a variety of ester products.

**Project Scenario**  Your company makes commodity and specialty solvents, including ethyl and butyl acetates. They are looking to expand production capacity and are in negotiation to purchase the assets of a toll manufacturing facility believed to be suitable for these products. Strategically, the long term plan is to produce other specialty acetates, but the project needs to be justified on its ability to produce the ethyl and butyl acetates.

Based on the equipment list provided by the toll manufacturer, you are asked to determine the production capacity for ethyl acetate and butyl acetate. An upper bound to what your company would pay is the cost to build a new grass roots unit of the same capacity. Also, determine the purchase cost such that the company would get a reasonable return on investment, assuming raw material margins of 5 to 20 cents per pound on making the acetates. (raw material margin = acetate selling price minus cost of contained raw materials)

Kinetic information is available for ethyl acetate\(^3\)\(^4\) and butyl acetate\(^5\).

Once you determine the instantaneous (hourly) production rate, consider and discuss the campaign strategy to supply both acetates, with a sales ratio of 3:2 ethyl to butyl acetate. The toller advises that a complete turn-around is 18 hours. Shipments are spread evenly through the year plus or minus 20% on a weekly basis, and may be up to 20,000 gallons in a single rail shipment. Monte-Carlo simulations of demand schedules are helpful to determine the likelihood that shipments can be made with a given campaign strategy.

**Equipment Description**  Below is a sketch of the available equipment. Piping is quite flexible in that any tower can be fed from just about any point in the process. Available utilities include 75 psig steam, and cooling water is supplied at 90F and returned at 110F. For heat exchangers, you can use shortcut rating techniques with \(U=120\) BTU/hr/ft\(^2\)-F for reboilers, 100 for condensers, and 80 for coolers or heaters with

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\(^2\)These include the Tishchenko reaction using acetaldehyde, and direct addition of ethylene to acetic acid. See SRI/IHS PEP Review 2007-9.


no process phase change. Not shown is vacuum equipment such that each column can work independently under vacuum if needed. All columns are rated for normal operation up to 60 psig. The reactor is rated for 150 psig. You may not need to use all the available equipment. All equipment is 316L stainless steel.

Reactor R-101: Packed acid resin bed. 8’ diameter by 18’ total packed bed height.

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3. **Lignin to Adipic Acid**  
*recommended by Bruce M. Vrana, DuPont*

Several cellulosic ethanol plants in the U.S. are beginning, or have recently begun, to produce fuel ethanol from cellulosic feedstocks such as corn stover. This second generation ethanol is mandated in the RFS2 regulations and production is expected to increase significantly over the next few years.

In addition to ethanol, these plants make a coproduct consisting primarily of lignin. Lignin is a heterogeneous mixture of largely-aromatic polymers that provides plant cell walls their structural strength and recalcitrance to biologic attack. The old joke in the industry has been that you can make anything from lignin except money. But the National Renewable Energy Lab (NREL) is working to change that.

They have genetically modified *Pseudomonas putida* to funnel many lignin model compounds to cis,cis-muconic acid. They also demonstrated an integrated process from plant-derived lignin to muconic acid, followed by high yield recovery and hydrogenation to adipic acid. Adipic acid is the aliphatic dicarboxylic acid produced industrially in the largest quantity. It is used primarily as a monomer to make nylon 6,6, used for fibers and engineering polymers.

Your company makes adipic acid from the conventional petrochemical process. You have been assigned the task of deciding whether this NREL process is a threat to your business in the near term, in the longer term with further work, or whether it needs significant new inventions to be competitive.

Thus, you should design the process that NREL has demonstrated to see if it is already competitive. However, it seems likely that further improvements in the process may be necessary for it to be competitive. So you should build all your process models (for example in ASPEN PLUS) and your economic model recognizing that you will likely need to test the sensitivity to various process parameters that have been demonstrated. Then determine where NREL should focus its effort to make the overall process commercially competitive with existing adipic production.

Assume that lignin is available at a price of half of its fuel value in your economic projections. This is because a boiler to generate steam and electricity from lignin is expensive, and this capital would be avoided if an alternative use for lignin is found. You may also assume that there will be several cellulosic ethanol plants operating in the U.S. corn belt in the 25-30MM gallon per year capacity range. You will need to decide the best commercialization path for the NREL technology – a small plant built at each ethanol plant, or a larger plant that takes lignin from several ethanol plants, paying to ship the lignin to a central location. The only relevant business information that your company has is its projection for adipic acid price, of $1,800/tonne and the price of hydrogen of $1,100/tonne. All prices are forecasts by your marketing organization for long term average prices, expressed in 2018 dollars.

You will need to make many assumptions to complete your design, since the data you have is far from complete. State them explicitly in your report, so that management may understand the uncertainty in your design and economic projections before deciding how to respond to this potential competitive threat (or opportunity) from NREL. Test your economics to reasonable ranges of your assumptions. If there are any possible “show-stoppers” (i.e., possible fatal flaws, if one assumption is incorrect that would make the design either technically infeasible or uneconomical), these need to be clearly communicated and understood by management.

The plant design should be as environmentally friendly as possible, at a minimum meeting Federal and state emissions regulations. Recover and recycle process materials to the maximum economic extent. Also, energy consumption should be minimized, to the extent economically justified. The plant design must also be controllable and safe to operate.
Reference

4. **Fermentation Route to Malonic Acid**  
(recommended by Bruce M. Vrana, DuPont)

Malonic acid is a specialty chemical used in a variety of applications ranging from fragrances to pharmaceuticals to adhesives. The conventional process is expensive and uses two highly toxic materials – hydrogen cyanide and chloroacetic acid. The process also produces copious quantities of salt coproducts that must be dealt with.

Lygos, a startup in California, is developing a fermentation route from glucose to malonic acid that is particularly interesting. They have engineered the yeast *Pichia kudriavzevii* to accomplish this transformation in high yield. They are currently producing small quantities for customer evaluation.

Your company would like to expand into the malonic acid market and is considering acquiring the technology via licensing, purchase, joint venture, acquisition, etc. Your team has been commissioned to develop an economical fermentation process design to make malonic acid. Since your management does not want to tip their hand before entering into discussions with Lygos, you must base your design only on what can be gleaned from public information, such as the references and any other published information you can find. You may not contact anyone affiliated with Lygos, including academic partners at UC-Berkeley and elsewhere.

Design a process and first plant to make 10MM lb/yr for specialty chemical applications. Glucose can be purchased for $0.20/lb. Malonic acid can be sold into specialty applications for $5.00/lb. This is a huge “value add”, but of course, capital and other fixed costs will be important at this small capacity. All prices are forecasts by your marketing organization for long term average prices, expressed in 2018 dollars.

Once the design and economics (without any cost to license or otherwise obtain the technology) are complete, recommend a path forward to your company management on how to gain access to the technology. Provide guidance on what the maximum you should be willing to pay to Lygos is so you still achieve a reasonable return on your investment. You may consider one or more scenarios and payment schemes – licensing the technology (in $/lb), purchase of the technology (total dollars), joint venture (how to structure the venture, including what each party brings to the venture and how the value is shared) or acquisition of the company outright (total dollars, including any other value Lygos may have). You may be able to eliminate some possible deals as not attractive to one or both entities, or unlikely to be acceptable, based on what you learn about Lygos.

You will need to make many assumptions to complete your design, since the data you have is far from complete. State them explicitly in your report, so that management may understand the uncertainty in your design and economic projections before approaching Lygos. Test your economics to reasonable ranges of your assumptions. If there are any possible “show-stoppers” (i.e., possible fatal flaws, if one assumption is incorrect that would make the design either technically infeasible or uneconomical), these need to be clearly communicated and understood before proceeding.

The plant design should be as environmentally friendly as possible, at a minimum meeting Federal and state emissions regulations. Recover and recycle process materials to the maximum economic extent. Also, energy consumption should be minimized, to the extent economically justified. The plant design must also be controllable and safe to operate. Remember that if the negotiations are successful, you will be there for the plant start-up and will have to live with whatever design decisions you have made.
References


http://www.lygos.com
5. Alternate Technology for Sour Water Stripping  
(recommended by P. C. Gopalratnam, Consultant – formerly DuPont, Invista)

Background

Sour water is produced in many petrochemicals crude processing plants and refining operations in making petroleum products. It contains significant amounts of ammonium and sulfur compounds in concentrations exceeding thresholds of tolerance for water treatment and reuse. In other words, sour water typically cannot be directly discharged to waste treatment and it cannot be reused in other parts of the refinery unless treated.

Process Description

Your task is to develop a strategy for sour water treatment that is potentially considered unconventional. Traditional technologies used to treat sour water involve some measure of air stripping. When air comes in contact with sour water, some of the ammonia and sulfur compounds will transfer to the air. This air is discharged assuming the exhaust to atmosphere is within permissible limits for the establishment. Should the permissible discharge be exceeded, fines will be incurred. Therefore, your task is to develop, and design an alternative to air stripping of sour water. Management at a facility in the state of Pennsylvania wishes to consider the use of natural gas as a substitute for air. Specifically, you are to develop a process for treating:

- 20-50 GPM sour water, containing 300-3000 ppm NH3, 5 ppm H2S and trace amounts of propane.
- Size the entire plant including upstream storage and downstream discharge or reuse to handle 75 kTons of sour water per year.

Note that there is a range of flow and composition, which will be addressed in a sensitivity analysis for any design that is submitted. It is assumed the natural gas stream containing the ammonia and sulfur compounds will be burned in some capacity. You will strip these components from the water, which can have a maximum of 20 ppm NH3.

Two options for the water (once the water is under 20 ppm NH3) are direct discharge as waste or further cleanup as BFW for steam generation. A final design should consider these two options and choose accordingly.

Detailed kinetics, thermodynamics, and key physical properties will be provided to the design group after project selection.

Your design submission must present the following:

- Information that will allow management a basic understanding of sour water treatment
- A description of a process using natural gas for sour water stripping, complete with a cost analysis of capital and operating expenses
- A description of a conventional design for traditional air stripping, which also requires an analysis of capital and operating expenses for comparison
- A description of the water treatment option to produce BFW, complete with capital and operating expense

Calculating the return on investment for this project also is a bit unconventional, as your economic analysis must consider the penalty associated with violating any air and water permit, the tradeoff between natural gas as a treatment option vs. selling the fuel, and a decision to treat the water. The PA state penalty for air and surface emissions may be found on the EPA website.

Specific Deliverables of this Design Project
1. Determine the best design for this system: a) determine the capital investment, and b) include and emphasize the appropriate use of design, corrosion considerations and safety features.

2. Consider the options of using Natural Gas in place of air in your design. Provide economic justifications for these alternatives. Remember the safety and environmental considerations associated with the use of Natural Gas.

3. Include details for all gas emission (NH₃, NOₓ, SOₓ, etc.) to the environment as well as in liquid waste discharge to the river and calculate the penalty for such discharge exceeding the limits.

4. Include storage considerations for process and other raw materials as well as the final product with technical specifications.

5. Determine if there is any impact on plant capacity as a function of sour water composition and pH.

6. Conduct and document a safety review that contains two parts: a) Hazards: a clear description of the major hazards of this process and what design features are incorporated to circumvent these hazards, and b) Inherent Safety highlights of one or more of the following inherent safety concepts: i) design features for easier and effective maintainability, and ii) design features using inherent safety concepts that circumvent accidents even when instruments fail or operators make mistakes.

7. Develop recommendations for the best design and state your reasons for these recommendations.

8. Provide a list of all equipment used in the process, including type, description, function, materials of construction to minimize corrosion, size, operating conditions, purchase and installed costs, and all important specifications.

Appendices

1. A1 A detailed investment analysis appears in the body of your design report. This appendix includes spreadsheet calculations showing formulas, sample calculations, and sources of the methods used.

2. A2 Safety Review- Enclose the MSDSs to this Appendix.

3. A3 Computer Process Simulators and Other Programs - Use generally available process simulators (ASPEN PLUS®, etc.) together with spreadsheets and student-developed computer programs. Include a description of when and where each simulation package was used, and the important input and output sheets. Relate this information (using the appropriate labels) to the PFD or the P&ID.

4. A4 Back-up/Support Data and Calculations - Provide documentation for the calculations made by hand at least on a sample basis, but preferably include all hand calculations made for the design. Include flow charts where possible. All special-purpose computer programs must be documented by including a brief description, input, and output files. This means that cell formulas must be included for your spreadsheet calculations.

References

6. Production of Universal Red Blood Cells via Enzymatic Conversion
(recommended by Brandon Hayes and Carly Catella, UPenn)

**Background**

Blood is an essential part of healthcare, listed on the World Health Organization’s List of Essential Medicines [1]. Its components are always in high demand, of which red blood cells (RBCs) are the most used in transfusions. Globally, around 85 million units of packed RBCs are used annually, of which approximately 13.6 million are used in the United States alone [2, 3]. Despite the importance of RBC transfusions, the compatibility of donated blood, based on the ABO system, with patients’ immune systems often hinders treatment efficiency [4]. Plasma of blood group A individuals contains naturally occurring antibodies to the B antigen present on RBCs. Similarly, plasma of blood group B contains antibodies against A antigen. Thus, individuals with blood of group A cannot receive transfusions from group B blood and vice-versa. Group O RBCs, however, do not contain A or B antigens. Therefore, they are compatible with recipients of any blood type – A, B, AB, or O – and can be safely transfused. For this reason, type O blood is typically considered the “universal” blood type [4-6]. Both blood banks and hospitals strive to keep supplies of group O RBCs for this reason [4].

The global blood collection market size was valued at $7.6 billion in 2015, to which RBC transfusions contribute $1.8 billion [7]. This market is projected to grow at 6.1% by the 2021-2022 period. RBC demand is also expected to increase due to the increasing prevalence of infectious disease and non-communicable disease, cancer, accidents, and trauma cases [8]. Blood-intensive procedures are also expected to grow, according to the World Health Organization, such as solid organ transplants, hematopoietic stem cell transplants, and aggressive chemotherapy against cancer, all of which will require increased blood supplies [8]. Lastly, the continually growing population over 65 years of age is also expected to increase demand for blood.

Despite the need for packed RBCs in transfusion medicine, supply has decreased significantly, especially in the last decade. Although an estimated 38% of the US population is eligible to donate blood at any given moment, less than 10% of that eligible population donates [2]. Another problem for transfusion medicine is how quickly packed RBCs expire. Typically, any given unit of RBCs is only usable for 42 days. Due to their short life span, packed RBC units are constantly being discarded, forcing hospitals to replenish their stock. It has become increasingly difficult to maintain inventories, however, because demand is expected to grow while supply is being hindered by stricter donation regulations and fewer donors.

**Technology overview**

In the 1980s, a procedure was established to convert group B RBCs into group O by using an α-galactosidase derived from green-roasted coffee beans (*Coffea canephora*) [9]. This coffee bean-derived enzyme completed phase I and phase II clinical trials, and the treated RBCs were shown to be safe and functional. Unfortunately, the amount of enzyme needed to treat a single unit of group B RBCs was too high to create a cost-effective process with which these universal blood cells could be manufactured. Additionally, the coffee bean-derived α-galactosidase could only treat group B RBCs, not group A, limiting its efficiency.

In 2007, however, another research group identified two prokaryotic glycosidase gene families that could be used to potentially convert any group RBC into the universal type: one containing α-N-acetylgalactosaminidase (GH109), which has high activity with group A antigens, and another containing α-galactosidase (GH110), which targets group B antigens [4]. Because the enzymes have very similar properties, a single common conversion buffer system and process can be implemented to remove A and B antigens from group A, B, and AB red blood cells. Additional progress in the field was made in 2015 when
the family 98 glycoside hydrolase from *Streptococcus pneumoniae* SP3-BS71 was found to cleave the entire terminal trisaccharide antigenic determinants of both A- and B-antigens on the RBC surface [10]. Thus, research has led to numerous enzyme candidates that can be used to convert RBCs into the universal type.

**Project statement**

You are PDG, LLC (Penn Design Group), a startup company formed to commercialize universal RBCs. Assume the technology has been demonstrated in small scale, as described in the supplemental material and any other research you can find. Your job is to profitably bring this to market in the first commercial facility. Once you have chosen which enzyme you find most suitable for this venture, the process your engineering team designs will be responsible for both producing the glycosidase enzyme(s) needed and treating the RBCs. You must identify the preferred system with which you will isolate your enzyme(s) of choice and provide a purification procedure. Your process must also ensure that loose enzymes are completely separated from treated RBCs after conversion, as these loose enzymes can cause potentially lethal autoimmune reactions if also transfused into patients.

You are free to design any size facility to serve any size region in the United States, based on your market analysis, attempting to maximize the NPV of your venture. Due to the limited shelf life of your product, you will need to include logistics and supply chain constraints into your plant design and business plan. The design of this first commercial facility will be used to scale-down to the facility required for clinical trial quantities, which you also need to design and include in your economic analysis and timeline. These designs, market and techno-economic analysis will form the basis of your funding proposal for VC firms for the clinical trials, followed by a later sale of PDG to a large industry player (pharmaceutical company, hospital chain, blood bank network, etc.). Your proposal is scheduled for April 2018, shortly before your initial cash investment will run out.

![Schematic of the bench-scale process](image)

**Figure 1.** Schematic of the bench-scale process to convert group A, B, or AB RBCs into enzymatically converted group O (ECO) RBCs [10].

**References:**


Useful Supplemental Information


7. **Monoclonal Antibody Production Purification and Packaging**  
*(recommended by Jeffrey D. Cohen, Janssen Biopharmaceuticals Division of Johnson & Johnson)*

Monoclonal antibody (mAb) therapy is a form of immunotherapy that uses monoclonal antibodies to bind monospecifically to certain cells or proteins [1]. This may then stimulate the patient's immune system to attack those cells. MAbs are used to treat medical conditions such as cancer, diabetes, arthritis, psoriasis, Crohn’s Disease.

MAbs may be produced suspended in fed-batch bioreactors [2,3] using genetically engineered cells originally obtained from Chinese Hamster Ovaries (CHO). During production, the MAbs are transferred through the cell membrane into the liquid growth medium. Following production, the cell suspension undergoes a series of downstream process steps to concentrate, stabilize, and package the MAbs using methods that preserve medicinal efficacy and ensure a virus-free product.

The objective of this project is to determine the cost of manufacture, capital cost, and required selling price to achieve a reasonable return on the investment, by specifying the details of:

- the upstream, fed-batch, process equipment capable of growing CHO cells and producing MAbs
- the downstream process equipment capable of isolating a yield of 100 Kgs of mAb annually
- the packaging equipment capable of containing the bulk drug substance in preparation for transport and storage.
- estimating the cost and investment of biological and analytical laboratory support
- estimating the cost of utilities
- the required reagents for cell growth and mAb production, pH control, elution and regeneration of sorption processes, and cleaning equipment.

With a wide variety of possible medical applications of MAbs, calculate the required selling price per gram of mAb including a 15% IRR on the investment in two ways. First, calculate the IRR assuming all the R&D has been completed and you only need to include the capital investment in the cash flow analysis. This is the selling price needed once all the R&D has been sunk, but does not justify that R&D. Second, calculate the IRR assuming that none of the R&D has been completed, so you need to include both the capital investment and the R&D cost and timeline in your cash flow analysis, as well as the probability of success. This is the selling price needed at the beginning of a development program in order to justify the development itself – a price that sustains R&D to develop new life-saving drugs. Reference 10 may be helpful in estimating these aspects of the cost, using industry averages which you may assume are reasonable for MAbs.

Process details:

- cell doubling time at maximum growth rate: 20 hours
- peak viable cell density: 9 x 10^6 cells/ml
- specific productivity: 3.3 x 10^-10 g mAb/viable cell
- 90% process uptime

Background information regarding upstream and downstream mAb production is contained in the listed references.

References:

1. [https://en.wikipedia.org/wiki/Monoclonal_antibody_therapy](https://en.wikipedia.org/wiki/Monoclonal_antibody_therapy)


8. **Chemical Recycling of Plastics by Pyrolysis**  
*(recommended by Dr. Matthew Targett, LP Amina)*

**Overview**

Plastic items are a critical part of modern society and they are used in almost every aspect of our lives. One of the values of plastics for packaging and as manufactured articles is their inherent strength and durability, however, this means that plastics remain durable after use and continue to accumulate in the environment indefinitely. As we use more and more plastic, we also discard an ever growing amount of plastic that will last for centuries.

Today, plastics are disposed of in several ways including recycling, landfilling, incineration, composting and littering. In the US, nearly 90% of plastics are being discarded into landfills. To be more sustainable, it is important to understand what our environmental and economical options are for waste plastic recycling and embrace techno-economically viable methods that will address these issues.

Plastics Recovery and Generation  
Source: US EPA

Thermal pyrolysis of plastic wastes has been considered for a number of polymer types over the past several decades as a means of reconstituting the monomer feedstock material and other useful fuels, solvents and specialty chemicals. The pyrolysis of polystyrene in particular has been investigated by a number of researchers [1,2,3].

For the purposes of this project, the objective will be to determine the optimal commercial thermal pyrolysis process configuration for converting waste polystyrene to useful liquid, gaseous and solid products. It is recommended to base the main conversion process directly on the experimental data reported in [1] Karaduman, 2002.

- Thermal pyrolytic degradation of polystyrene only (no added compounds)
- Temperature range of 350°C to 450°C and residence time of 60 min
- Product Outputs: solid residue, liquids, gaseous products as reported in [1]
- Liquid Product Composition: styrene, ethyl benzene, toluene, methyl styrene, benzene, other as reported in [1]
Analyzed Liquid Product Composition at 350°C-450°C & 60 minutes residence time  

In terms of a rigorous and detailed project structure, the following approach is recommended at the outset.

The key to a techno-economic evaluation success is a sufficiently accurate process simulation model covering major processing steps; namely, pyrolytic conversion, product refining steps and an integrated heat integration process. The process simulation model should take into account user-defined Key Input Variables (KIVs) and have the ability to predict Key Output Variables (KOVs). Some of the key input variables will be fixed.

Project Statement – defined criteria
- Capacity: 100 TPD PS Feed
- Liquid Products Purity, polymer grade purity of >99.9%
- Fuel Gas composition, to be determined by other references and mass balance estimations
- Solids Residue composition, assume to be a coke-type of composition
- Liquids selling prices, to be estimated by analysis of long term market trends
- Waste polymer purchase/delivery costs, to be estimated based on best practices

Key Input Variables – to be varied for the purposes of determining lowest Capex-Opex operation
- type of pyrolyzer (heating media, batch vs continuous, fluidized bed vs screw extruder type, etc)
- temperature of pyrolyzer (use model predictions based on available data range, 350°C-450°C)
- heat integration (purchased fuels/power for pyrolysis heating vs waste heat integration)
- fuel gas utilization (separation and sales of components vs use as heating media)

Key Output Variables – to be determined by modelling/optimization via varying of Key Input Variables
- OPEX cost, $ per ton of liquid products
- Capex investment, $ per ton of annual PS consumption
- IRR/NPV

Note: The creator of this project is not based in Philadelphia. Many or all interactions will be through SKYPE, phone and/or email.
References


9. Design of a flexible high-volume direct flue gas-to-algae conversion process for value-added bioproducts
(recommended by Mikaela Preston, UPenn)

Background

Algae consume CO₂ and convert it into highly valuable biomass and lipids. The biomass has many applications such as nutraceuticals (Matos et al.), and the lipids can be converted to biofuels (Ghadiryanfar et al.). There is massive potential for the use of industrial flue gases as a source of CO₂ for large scale algae sequestration operations (Huang et al.). Flue gasses from power and industry sectors account for over 60% of global CO₂ emissions (Gale et al.) – not only could algae significantly contribute to keeping atmospheric CO₂ levels below currently dangerous (and rising) levels, but the value-added bioproducts containing sequestered carbon would have many profitable applications.

However, there are challenges associated with flue gas usage that currently limit large scale success (Zhu et al.). Algae grow optimally with an input CO₂ concentration of around 5%, but flue gases can contain much higher concentrations of CO₂ that can inhibit growth, mainly due to the resulting drop in pH of the algae slurry (most algae maintain high growth in pH’s between 6 and 9). Achieving adequate dissolution of CO₂ in solution is also a challenge, especially at the high input velocities of the flue gas, due to the low mass transfer rate between the gas and liquid solutions (Sadeghizadeh et al.). High temperatures of flue gases also inhibit CO₂ dissolution and algae growth; algae grow optimally around 26°C, but flue gases can reach much higher temperatures and often need to be cooled before entering the algae slurry. Finally, the presence of NOx and SOx in flue gases can also cause a drop in pH and further inhibit growth, and often need to be at least partially removed in pre-treatment. Successful commercialization of large scale algae carbon capture operations will require the use of flue gas as directly and efficiently as possible by overcoming these constraints in an economically viable manner.

Some of the design requirements of this project are motivated by the ongoing $20M NRG COSIA Carbon XPRIZE, a high-profile international competition that aims to find and accelerate the development of the world’s most innovative CO₂ capture technologies. The competition is currently in Round 2, where leading businesses and engineers from a wide range of fields are competing to build pilot scale demonstrations of a process that can convert at least 30% of 200kg/day of input CO₂ from simulated flue gas into a highly valuable and marketable product. These requirements are based on significant scientific consulting into what a world-changing technology would have to accomplish. Outcomes of the following design project would be on-par with current industry goals for large scale value-added CO₂ conversion technologies.

Problem Statement

This project involves solving problems of optimization and flexibility. A pilot scale CO₂-to-biomass conversion process will be designed for maximum steady-state biomass production. The goal will be to convert at least 30% (ideally over 50%) of input CO₂ from a typical simulated flue gas into algal biomass (approximately 50% of algae biomass is carbon). Table 1 describes the properties of this typical simulated flue gas. The process must be able to support an input flow rate of at least 200kg of CO₂/day from this simulated flue gas. “Optimal” conditions presume constant operation at the flow rate, temperature, and composition of this typical flue gas, however, real conditions will vary. The designed bioreactor system will operate at steady state (ie. operating conditions will not respond dynamically to any change in input flue gas characteristics – though a dynamic model could arise as an extension of this steady state work). However, since algae growth will respond either positively or negatively to changes in flue gas characteristics, it is necessary to understand how sensitive the algae are to such disturbances. The design must be flexible enough to support algal growth when the steady state is disturbed. Evidence from literature (for example, Yadav et al. on carbon dioxide concentration and chlorella growth) will be gathered.
to inform design requirements for operation under conditions between these upper and lower deviations from the optimal steady state.

Process equipment and systems that will need to be designed include a heat exchanger for the input flue gas, a closed-tank constant-flow bioreactor with adequate light distribution and effective CO₂ mass transfer throughout the volume, a gas sparging and mixing system, a pH balancing system, and potentially a pre-treatment mechanism for partial removal of NOₓ and SOₓ (Eynde et al.). Attention must be paid to heat and mass transfer rates within both pre-treatment systems and the algae slurry. A biomass harvesting system could also be included, as efficient and inexpensive harvesting is a challenge. Methods such as flocculation and subsequent drying are options, including the possibility of using recovered heat from the flue gas heat exchanger to dry the wet biomass.

The specific algae strain(s) that the process would be designed for must be determined based off biomass product value as well as robustness under the stated conditions. For example, Chlorella vulgaris is a commonly used strain in value-added carbon conversion processes and should be considered. This strain is robust, relatively easy to cultivate at larger scales, and has valuable market applications (Zhao et al., Garcia-Cubero et al., Li et al.).

<table>
<thead>
<tr>
<th>Property</th>
<th>Optimal SS Condition</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate (kg/day)</td>
<td>1320</td>
<td>1300</td>
<td>1340</td>
</tr>
<tr>
<td>Temperature (F)</td>
<td>250</td>
<td>220</td>
<td>280</td>
</tr>
<tr>
<td>CO₂ (%v/v)</td>
<td>10</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>NOₓ (PPM)</td>
<td>150</td>
<td>140</td>
<td>160</td>
</tr>
<tr>
<td>SOₓ (PPM)</td>
<td>100</td>
<td>130</td>
<td>70</td>
</tr>
</tbody>
</table>

**Table 1** Optimal steady state and minimum/maximum bounds of a typical simulated flue gas properties. The remaining volume consists approximately of O₂, H₂O, and N₂ in %v/v ratios of 11:11:78.

**Economic analysis**

Attention must be paid to the economic viability of the process. High initial and operating costs of large scale algae carbon capture operations are significant challenges, but returns from produced biomass are extremely promising. The costs associated with building and maintaining both pilot- and commercial-scale systems for the designed process will be determined. As well, an analysis of the emissions sequestration capacity and the value of biomass produced will be performed. Specifically, overall economic viability should be determined using, in part, published values of algal biomass to determine the cost per ton of sequestered carbon dioxide, including a reasonable IRR on the capital. This should be compared with published values for competing proposed carbon sequestration techniques. Economic repercussions could also be extended to explore the potential for further scale-up, or to explore impacts on algae carbon capture technology in a larger range of industries and markets.

**References**


10. Sodium and Specialty Cyanides Production Facility
(recommended by Stephen M. Tieri, DuPont)

Sodium cyanide and specialty cyanides are commercially valuable materials used in wide variety of applications and industries; including electroplating, mining and metal processing, and organic chemicals production. Sodium cyanide is used throughout the world and is instrumental in the extraction of gold, silver, and other precious metals naturally occurring in low concentrations in ore. As a chemical intermediate, it provides a supply of hydrogen cyanide in regions where a local supply is not available, since sodium cyanide can be transported and stored.

Driven by the current and forecasted growth in precious metals, consumer electronics, and electronics materials, the global sodium cyanide demand is expected to grow by 4 percent annually, with a forecasted global demand of 1.1 million tones in 2018. While there have been initiatives to substitute sodium cyanide in gold recovery because of potential environmental danger if not handled responsibly, it remains the most environment-friendly of the possible substitutes.

For this project, your company’s business team identified and is negotiating an agreement for a manufacturing site in Rochester, Nevada. This partner site location is a currently undeveloped section of an existing manufacturing site, with access to natural gas and electricity, but with limited aqueous waste treatment. The site host company is a medium sized gold/silver ore mining and recovery company, interested in an on-site partner for future capacity expansion.

Sodium cyanide is typically produced by the neutralization of hydrocyanic acid with aqueous sodium hydroxide, following the chemistry shown below (1). Water is evaporated from the aqueous solution to generate solid product.

\[
\text{HCN} + \text{NaOH} \rightarrow \text{NaCN} + \text{H}_2\text{O}
\]  

(1)

Dry NaCN solids are then compacted into briquettes prior to loading into their final shipping container. Specialty cyanides (KCN, LiCN, etc.) are produced using similar chemistry, but using their respective cation caustic solutions in place of NaOH.

There are several options for commercial production of hydrogen cyanide (HCN). However, for this location and capacity requirement, HCN is expected to be generated on-site, produced directly by either the Andrussow or Degussa process. While both react ammonia and methane over a precious metal catalyst, oxygen is present in the Andrussow process reaction (2) and excluded in the Degussa process reaction (3). Additionally, there are different impurity profiles generated by the two processes.

\[
\text{CH}_4 + \text{NH}_3 + 1.5 \text{O}_2 \rightarrow \text{HCN} + 3 \text{H}_2\text{O}
\]  

(2)

\[
\text{CH}_4 + \text{NH}_3 \rightarrow \text{HCN} + 3 \text{H}_2
\]  

(3)

Your project team has been assembled to design this new cyanides production facility using the best commercially demonstrated, sustainable, and economically viable technology. The business objective is to deliver a commercial scale facility with the capacity to produce 60 k Tones/yr (60,000 MT/yr, 60 MM kg/yr) of sodium cyanide (NaCN) and 2 k Tones/yr (2,000 MT/yr, 2 MM kg/yr) of total specialty cyanides (KCN, LiCN, CaCN). Your team is also responsible for identifying and minimizing the required investment and operating costs, and identifying any critical economic sensitivities to raw materials, product, utility, or equipment pricing, use quantity, and quality.

The product quality and purity should meet or exceed current industry expectations, 98% ±1% product as solid briquettes or as a 10 - 25 wt% solution of NaCN in water. All solution product must be used/consumed
onsite, with a maximum of 15% total solution sales (dry cyanide basis). Sodium cyanide product price is expected to be in the range of $1.80 - $2.00, and fluctuate with demand and gold pricing. Natural gas is available onsite at market price and at average US composition. The team is expected to identify whether additional purification of the natural gas feed is necessary prior to use, depending on the resulting product quality, investment, and cost impacts. Ammonia, NaOH, and other alkali metal hydroxides are available at market prices. The facility should have the capability to ship briquettes in rail cars, ISO containers, hopper trailers, and 1 ton bags/supersacks. Any unconverted ammonia is expected to be thermally treated, recovered, or converted to a co-product to minimize air emissions.

While sodium and specialty cyanides provide meaningful benefits to society, they have the potential for harm if not managed properly. Cyanide is acutely toxic to humans. Liquid or gaseous hydrogen cyanide and alkali salts of cyanide can enter the body through inhalation, ingestion or absorption through the eyes and skin. The toxicity of these materials represent a potential environmental or health hazard if the product is not used, transported, and handled correctly. The process, systems, and equipment will need to minimize the potential for material contact with personnel and the environment, including safety systems with extensive alarm and monitoring systems designed to detect, mitigate, and contain an HCN release.

The plant design should be as environmentally friendly as possible, and as necessary as required by state and federal emissions legislation. It is expected that the facility will include emission control equipment as a part of the process design and operation. Recover and recycle process materials to the maximum economic extent. Also, energy consumption should be minimized, to the extent economically justified. The plant design must also be controllable and safe to operate. As the process technology integration and design team, you will be there for the start-up and will have to live with whatever design decisions you have made.

Undoubtedly, you will need additional data beyond that given here and listed in the references below. Cite any literature data used. If required, make reasonable assumptions, state them, and identify whether your design or economics are sensitive to the assumptions you have made.

**References**
1. Int'l. Cyanide Management Code For the Manufacture, Transport, and Use of Cyanide In the Production of Gold, [www.cyanidecode.org](http://www.cyanidecode.org)
11. ECN Phyllis Database for Biomass and Waste - [https://www.een.nl/phyllis2/](https://www.een.nl/phyllis2/)
11. Bio-Dodecanedioic Acid (DDDA) Production  
(recommended by Stephen M. Tieri, DuPont)

Dodecanedioic Acid (DDDA) is a C$_{12}$ dicarboxylic acid, with applications across a range of products including antiseptics, adhesives, coatings, corrosion inhibitors, surfactants, and as a monomer in the production of Nylon 6,12. The demand for DDDA is expected to grow at a steady 5-6% annual rate, with a global market predicted to reach the $450$ MM - $600$ MM range by 2022. This growth is driven by increasing demand for Nylon 6,12 in several end-use industries including polymers, detergents, and coatings. Regionally, Asia Pacific is anticipated to have the greatest growth potential, followed by North America. The traditional petrochemical route to DDDA is a multi-step chemical process starting from butadiene.

As a result of climate change, dwindling petroleum resources, material pricing volatility, and desire for energy independence; there has been significant research and investment in the last decade to develop technologies which reduce energy consumption, improve efficiency, and produce materials and fuels from renewable resources. Government grants and subsidies as well as consumer demand are driving the intense industrial and academic competition to develop bio-based and sustainable materials; with equivalent functionality to the traditional petrochemical derived materials, but derived from renewable sources and with reduced environmental burden.

Through its research efforts, your company has developed new and innovative technologies to produce DDDA and other diacids, through conversion of biomass-derived and renewable feedstocks, rather than traditional petrochemical feedstocks. Specifically, the research group developed a microorganism (yeast) which is the catalyst and basis for this bio-based production route. As the DDDA and other diacids from this technology have the identical structure and functionality of traditional petrochemical materials, they serve as a direct replacements to enable renewably sourced polymers without modifications to downstream equipment or processes. Similarly, the engineered yeast is also capable of producing renewable sebacic acid using predominantly shorter chain fatty acid (C$_{10}$, vs. C$_{12}$ for DDDA) feed materials.

The microorganism and process have been tested across a variety of commercial feedstocks. The currently identified suitable feedstocks include, but are not limited to, fatty acid distillates or soapstocks of renewable oils (palm oil fatty acid distillate, soybean oil soapstock, coconut oil soapstock), renewable oils (coconut oil, palm oil, palm kernel oil, soybean oil, corn oil, etc.), fatty acids of chain length equal to or greater than C$_{10}$ (in substantially single form (e.g., in substantially pure form) and/or in mixture form, and alkanes of chain length equal to or greater than C$_{10}$ in both substantially pure form and mixtures.

This new proprietary technology enables a fermentation process with flexibility to utilize a variety of feedstocks and target specifically desired chemicals with exceptionally high selectivity. This ingredient flexibility facilitates using materials that are not only renewable, but that do not compete with food and/or fuel applications. Therefore, the company’s preferred feedstock alternatives can cost less and are not subject to price volatility and uncertainty of supply as other renewable feedstocks. Additionally, these feedstock options help the company to avoid food vs. fuel and food vs. bio-material controversy and debates. At a technology platform level, the company believes this innovation enables low-value by-products of palm oil processing to become a high-value “green” products, while that reduces the demand for and use of fossil resources.

Successful pilot trials over the past several years demonstrated the bio-based DDDA process at both the 4,000-liter and 25,000 L fermentation scales, generating material at greater than 99% purity. This testing confirmed process scalability and produced polymer-grade material for potential customers and partners. Results from pilot plant operation indicated that product yield, microbiological productivity, separation, and purification were on-target to deliver cost advantages at commercial scale.
Now that the research, development, and pilot teams have succeeded in achieving their milestone targets, corporate leadership is eager to proceed to the first commercial scale production facility. Your company and its technology development partners intend to use this technology to attract additional industrial partners for both feedstock supply and sustainably branded intermediates and polymers. Your company expects to build and operate this commercial facility, with potential for future sister facilities, and does not currently plan to license this specific technology as an additional revenue source.

Your project team has been assembled to design the first commercial plant for this new sustainable technology. The business objective is to design a commercial scale facility to produce 14,000 MT/yr (metric tons per year) of Bio-DDDA, from non-food biomass, using the company’s new proprietary engineered yeast strain. The Bio-DDDA product, and renewable diacid co-products, product purity and quality will need to meet or exceed current commercial requirements for polymer grade material, to be acceptable for internal use and for additional sales to prospective external customers. As the company has already advertised this innovative fermentation based process is both cost advantaged and will reduce greenhouse gas emissions compared to the traditional petrochemical production processes, your team is expected to quantify and verify both claims.

While your technology has the potential for global application, the business selected Malaysia as the location for the 1st manufacturing facility. Your company’s renewable products division is currently working with regional suppliers in Malaysia to secure reliable sources of non-food palm based raw materials; however, your team will need to confirm both the desired/optimal feedstock(s) or feedstock blends, and the required supply quantities.

The plant design should be as environmentally friendly as possible, and as necessary as required by state and federal emissions legislation. It is expected that the facility will include emission control equipment as a part of the process design and operation. Recover and recycle process materials to the maximum economic extent. Also, energy consumption should be minimized, to the extent economically justified. The plant design must also be controllable and safe to operate. As the process technology integration and design team, you will be there for the start-up and will have to live with whatever design decisions you have made.

You will need additional data beyond that given here and listed in the references below. Cite any literature data used. If required, make reasonable assumptions, state them, and identify whether your design or economics are sensitive to the assumptions you have made.

References
12. Oxy Fuel for Clean Energy Generation  
(recommended by Adam A. Brostow, Consultant)

Background

Fig. 1

Fig. 1 shows a typical Oxy Fuel power plant. Instead of air, it uses “pure” oxygen (about 95%) to reduce the flue gas flow by about 75% for easy CO₂ capture/sequestration and equipment size reduction.


Fig. 2

Fig. 2 shows Linde’s Oxy Fuel process
It produces oxygen at lower purity to save on cryogenic ASU (air separation unit) cost.

Excerpts:
“Linde has responded to this challenge by adapting the cryogenic air separation process for oxyfuel applications that do not require high-purity oxygen. The adapted solution can reduce energy consumption by around 25 percent compared with conventional air separation methods. This gives plant operators a new way to produce oxygen with a reduced energy bill and lower costs.”

US20030000248 Air Products patent application (Brostow et al.) shows a conventional cryogenic ASU making pure (95-99%+) oxygen and nitrogen. Fig. 3, modified from the application, shows the simplest implementation of the idea.

Fig. 3

Air stream 100 is separated into oxygen and nitrogen. Pure high-pressure gaseous nitrogen stream 168 and gaseous oxygen stream 186 are main products. Oxygen product is compressed to the fuel header pressure in compressor 184. Gaseous low-pressure nitrogen stream 172 can be utilized as an additional product or taken out as waste.
Fig. 4 shows a simple gaseous nitrogen (GAN) generator, from Air Products’ US patent 4,867,773. Such a plant produces pure nitrogen and a waste stream containing 32-40% oxygen. Here, waste recycle (compressor 230) is an additional improvement that increases O₂ content in the “low-pressure waste” stream.

Compared to using air (21% oxygen), using 40% oxygen stream can reduce the flue gas by a factor of almost two. In one of the examples in the above patent, the “waste” O₂ content is 58.3%. It reduces the flue gas flow to 64% of the flow while using air.

**Project statement**

Students are to design an Oxy Fuel power generation pilot plant similar to the one planned at Linde’s Schwarze Pumpe but (a) using Air Products ASU technology as shown on Fig. 4, (b) using natural gas instead of coal/lignite.

The beauty of such a solution is that the waste stream from the ASU is turned into something useful (“lemons to lemonade” principle). It is also an improvement over Linde’s cycle, assuming Linde’s process uses a simple GAN generator.

The pilot plant is expected to produce 30 MW of electricity using a conventional steam turbine, which determines the fuel and oxygen demand. Oxygen concentration will determine the size and cost of the ASU. The above-mentioned 30 MW is the net energy export: energy produced by the steam turbine minus energy required to run the ASU and other unit operations.

Students are expected to model the simplest double-column cryogenic ASU producing 95% oxygen, as shown on Fig. 3 and estimate the cost of the Oxy Fuel plant, a conventional one with flue gas recycle. Air purification does not have to be modeled rigorously.
Then they will model a single-column ASU shown on Fig. 4 and producing 58% oxygen, and again estimate the cost of the corresponding Oxy Fuel plant, without flue gas recycle (unless needed). Then they can compare cost savings. In both cases, nitrogen is sold as valuable product. Consistency in these two models, capital and cost estimates is essential to ensure a fair comparison is made.

Outside of the ASU, the remaining unit operations can be modeled more rigorously, time permitting, or treated as black boxes, with cost estimated from literature or by scaling percentage cost. For example, if the ASU cost is 30% of the conventional plant’s cost, costing the ASU establishes the total cost. If the ASU cost is reduced to, say, 15%, the total cost can be established accordingly. The general strategy is to get cost comparison results early and then refine the answer. You may refer to recent Penn senior design projects involving CO₂ sequestration.

A good estimate of fixed and operating cost breakdown from the Linde article can be used as a sanity check:

“Calculations thus far have shown that oxygen accounts for a third of investment costs in an oxyfuel plant and almost a quarter of total energy requirements. So the ten percentage points or so of efficiency losses associated with Carbon Capture and Storage (CCS) are largely attributable to the oxygen bill.”