PROCESS MODELING OPTIMIZATION ON ENERGY PERFORMANCE INDICATORS

A CASE STUDY OF A PUMPING SYSTEM IN AN OIL & GAS TREATMENT FACILITY

A Thesis

by

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Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER SCIENCE

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August 2023

Major Subject: Energy

ABSTRACT

Water pumping systems are widely used in Oil & Gas operations primarily due to water transferring and re-injection in oil treatment process. The energy consumed by these systems is significant, particularly in fields with a high water-to-oil ratio of water per oil produced. Assessing the performance of a process relies on two Key Performance Indicators (KPIs): the Energy Performance Indicator (EnPI), which assesses the energy performance of the system, and the Profitability Indicator (PI) which evaluates the profits derived from the process. These indicators are influenced by several process factors such as operational performance, restrictions in the system, system control, costs, and capacity of utilization.

Process and facility engineers are responsible for optimally managing resources and assets, focusing on enhancing the energy efficiency of the process. However, determining the optimal conditions for achieving desired KPIs is often challenging. It is difficult to find optimal solutions in a subjective manner, such as intuition and trial-and-error, which often rely on people's experiences and may cause process disturbances, economic penalties, or higher energy consumption. Therefore, it is necessary to propose a systematic decision-making approach to find optimal solutions considering the interaction of process variables (based on first principles or experimental relations) and economic or performance indicators.

In this study, a methodology was proposed to determine the optimal conditions for a water-pumping system. The first step involves adjusting the pump performance curves based on power consumption. Next, the system was simulated using a modular block-based hierarchy process model developed by IDAES (Lee, 2021). An optimization problem is then formulated to minimize

or maximize the KPI. The results were simulated using Aspen HYSYS to provide insight into the performance of each KPI.

This work proposes a framework for process model optimization that can be applied to operational decision-making that is both tractable and flexible. For the water pumping systems, three different scenarios were evaluated: the initial conditions, a discrete function to overhaul one pump, and modifications in the pressure conditions and performance curves. For each scenario, optimal solutions were found to improve the KPIs.

The optimization results showed that adjusting the variables in the system could reduce the EnPI by 2%–4% and increase the PI by 2%– 5%. The findings of this optimization study demonstrate the inverse relationship between PI and EnPI; therefore, improving the energy efficiency of pumps not only enhances production, but also reduces energy intensity. Consequently, applying this analysis to other high-energy-intensive systems such as steam processes, heat exchangers, power systems, and similar contexts is recommended. By extending this approach to different domains, valuable insights can be gained, leading to enhanced energy efficiency and improved system performance.

DEDICATION

To my wonderful parents, your continuous love and unwavering support have been a constant presence in every moment of my life. I deeply appreciate the sacrifices you have made and the efforts you have invested in shaping the person I have become. The values you have imparted to me have become the foundation of my character, and I am forever grateful for the invaluable principles I have learned from you. Your teachings have instilled in me the importance of maintaining faith in God, who plays the most relevant role in constructing the path of my life. I hold you both in the highest admiration, and your guidance will forever be respected.

To my beloved spouse, thank you for being my biggest support, for sharing my most wonderful moments of life and cheering me up difficult situations that encourage me to overcome everything for more challenging and difficult it seems to be. To my dear son and for always taking from me a big smile in your short time of life which I have enjoyed each second of it, just being part of our lives is the most important moment in our lives.

To my incredible sister, your personal and professional success and accomplishments have served as a great source of motivation for me. Your discipline, perseverance, and unwavering commitment to excellence have taught me that with dedication, anything is possible. You have shown me the importance of setting goals, working tirelessly towards them, and never giving up.

To my dear friends, Juan F and Daniela thank you for being present in all the most special and important moments of my life, you will always have my immense gratitude.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Professor Efstratios Pistikopoulos, and my committee members, Professor Mahmoud El-Halwagi, and Professor Le Xie, for their guidance and support throughout the course of this research.

I would also like to thank my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

I greatly appreciate the assistance of Dr. Andrew Lee from IDAES for his guidance and for sharing his meaningful insights through the incredible world of process of modeling optimization.

Finally, thanks to my mother, father, and aunt for their immense love and encouragement and to my wife and son for their substantial and unconditional support, patience, and love.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Efstratios Pistikopoulos, Director of the Energy Institute at Texas A&M University.

The database in this case studio was provided by Ecopetrol S.A. only for academic purposes. Aspen HYSYS software was used to analyze the initial conditions of the process, and the results of the optimization were provided by the University of Texas A&M. The platform used to model the system was a computational open source provided by the Institute for the Design of Advanced Energy Systems (IDAES).

All other work conducted for this thesis was completed independently by the student.

Funding Sources

Graduate study and thesis were supported by a sponsorship from Universidad Ecopetrol S.A.

NOMENCLATURE

Bl	Barrel
Bl/d	Barrel per day
CG	Control Guide
EnB	Energy Baseline
EnPI	Energy Performance Indicator
eff	Efficiency of the pump
hp	horsepower
hz	hertz
K	Kelvin
Kw	Kilowatt
mol/s	Mol per second
P	Pressure
P2	Pumps that belong to the set of pumps with tag P2
P4	Pumps that belong to the set of pumps with tag P4
Pa	Pascal
Pd	Discharge Pressure
Pi	Intake Pressure
DeltaP	Difference between Pd and Pi
Psi	Pound-force per square inch
Psia	Pound-force per square inch absolute
Psig	Pound-force per square inch gauge

Q	Flow
T	Temperature
U$	United States dollar
U$/Bl	United States dollar per unit barrel

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CHAPTER 1 INTRODUCTION

1.1. Strategies adopted to reduce CO2 emissions.

The Paris Climate Change Agreement addresses concerns over a 1.1°C temperature increase resulting from human activities by proposing a limit of 1.5°C (United Nations , 2023). At the recent Glasgow COP26 meeting, countries reaffirmed their commitment to achieving these goals, which directly implied the promise of governments, companies, institutions, and organizations to pursue the reduction of CO2 emissions. However, there are concerns regarding the potential effects of these agreements on the financial health of industries and societal welfare.

The Colombian government-owned Oil & Gas company Ecopetrol adopted a strategic vision called “Energy that transforms,” which responds to the current challenges regarding climate agreements and proposes to reduce its carbon footprint and achieve the target of becoming a net-zero carbon emissions company by 2050 (scopes 1 and 2). Additionally, Ecopetrol seeks to reduce 50% of its total emissions (scopes 1, 2, and 3) associated with the company's value chain, which includes the use of its products, by 2050. The goals of reducing carbon emissions include implementing good practices to improve energy efficiency, reducing gas emissions from fugitive escapes and flaring, switching energy generation to renewables, and carbon capture and sequestration. This transformation is based on the pillars of developing comprehensive science, technology, and innovation strategies to achieve environmentally responsible, safe, and efficient operations (Cision PR Newsware , 2023).

According to Unidad de Planeacion Minero-Energética (2022), digitalization has a potential to improve the energy efficiency of industrial processes by 12% which corresponds to the 5.8% total goal established by Colombia’s Government. It is estimated that optimization enabled by digitalization could help achieve energy savings of at least 10-20% (Dr. Piyush Verma, 2020).

1.2. Motivation

During the analysis of power consumption in oil field treatment plants with a high oil-water ratio, water pumping systems emerge as the primary contributor to energy consumption, often accounting for approximately 80% of the total power usage. Moreover, the operational efficiency of water pumping systems is generally lower than that of best practices in other industries (Jorge Filipe, 2019). As a result, enhancing the operational efficiency will lead to an increment in the life cycle of the system, reduce energy consumption (scope 1 and/or 2), reduce the number of corrective maintenance interventions, and improve the energy efficiency of the system.

Most oil and gas companies fail to capture the expected returns from advanced analytics and digital transformation efforts (Harclerode, 2022). However, improvements can lead to cost reductions, especially in energy-intensive companies, where energy costs account for more than 10% of total operational costs (Department of Energy , 2017). Process and facility engineers often face challenges in correctly identifying variables that affect the energy performance of the system.

Additionally, making the correct decision to improve performance is a time-consuming process. Improving the operational efficiency of the system implies compiling data, conducting comprehensive data analysis, and applying advanced analytics sensibilizing process variables. Thus, effectively performing these tasks in a short time frame is necessary to leverage digital solutions for process modeling and optimization techniques to solve complex problems, which may produce accurate results that underpin correct decision-making to improve the energy efficiency of the process.

1.3. Related work and contributions

Process Systems Engineering can be defined as an approach to modeling and optimization techniques that employs a range of numerical methods and computation techniques, including solver algorithms and software tools, to solve complex problems in process synthesis, design, and control. Various optimization algorithms, such as linear programming, nonlinear programming, and mixed-integer programming, can be used to determine the optimal process conditions that maximize the desired output while satisfying process constraints (Efstratios Pistikoupulus, 2020).

Some examples of different approaches for pumping system optimization have been recently developed. A method to develop a data-driven optimization model that proposes a new method of control philosophy based on statistical learning and reinforced learning for wastewater pumping systems was proposed to improve the optimal control of the pump and reduce the energy consumption of the system (Jorge Filipe, 2019). Although they can face limitations in cases where poor data quality or the absence of historical data exists, data-driven models have proven to be highly accurate in the case of sufficient reliable data to identify patterns from past events. Consequently, optimizing Energy Performance Indicators (EPIs) or Profitability Indicators with data-driven models becomes unfeasible due to the lack of information. However, in such scenarios, the significance of expertise knowledge and simulation models becomes paramount. Leveraging the insights and experience of domain specialists, along with the utilization of simulation models, proves to be invaluable for addressing these challenges effectively.

An optimization problem was developed to solve the pump a day-ahead scheduling problem for a class of branched water networks with one pumping station raising water to tanks at different locations and levels (Gratien Bonvin, 2016). This model assumed that all pumps had similar performance characteristics, which reduces non-linearities of the optimization problem.

However, this assumption will find incorrect results if you are evaluating Energy Performance Indicators.

Software tools can be very helpful in solving process optimization problems. They can provide a user-friendly interface for modeling and simulating the process, as well as for analyzing and optimizing the results. Over the years, several software packages have been developed for process modeling and optimization. (Luca Mencaralli, 2020) summarized the recent developments in synthesis modeling software packages, with integration of software algebraic modeling, software for process modeling via superstructures, and software process modeling with integration algebraic modeling via open-source packages.

Design of Advanced Energy Systems Integrated Platform (IDAES) recently developed a simulation software process platform, which involves the optimization of an objective function subject to constraints and incorporates all of these concepts within a Python-based optimization framework. The platform includes facilities for equation-oriented modeling for static and dynamic processes, exact gradients and Hessians from process models, automated initialization strategies, and seamless interaction with state-of-the-art large-scale optimization solvers. (Lorenz Biegler, 2022).

1.4. Energy performance evaluation

The guideline ISO-50001-2018 establishes systems and processes to continuously improve energetic performance, which includes energy efficiency and consumption of energy. (ICONTEC, 2019). First, an Energy Baseline (EnB) is calculated in a specific time frame and operational conditions, which is a reference, and is later compared with the Energy Performance Indicators (EnPI), which is a value or measure that quantifies results related to energy efficiency, use, and consumption in facilities, systems, processes, and equipment. This indicator is a reference that characterizes and quantifies an organization's energy performance during a specified period (ISO, 2014). The methodology proposes to improve energy performance relies on a continuous improvement cycle PDCA (Plan-Do-Check-Act), whose main purpose is to identify the relevant variables that affect the energy performance, and it is recommended to propose operational control boundaries as a Control Guide (CG) for each variable, process, or system.

1.5. Scope of this contribution

According to the analysis derived from the energy baseline in a time frame, the process is examined through simulation of the real process through a block-based hierarchy for full process modeling to identify the relevant variables of the system that need to be modified in order to minimize or maximize the key performance indicators. Three scenarios and three objectives for each scenario are proposed for different alternatives and analyses.

Three scenarios were assessed for the water pumping systems: initial conditions, discrete function to overhaul one pump, and variations in the pressure conditions and performance curves. For each scenario, three functions objectives are proposed: minimize Energy Performance Indicator (EnPI), Maximize Profitability Indicator (PI) and Minimize energy consumption.

Through the assessment of these three scenarios, we are also assessing whether the proposed framework is tractable and adaptative to different conditions and evaluations. Subsequently, the results were evaluated through a simulation of the process using the software Aspen HYSYS.

CHAPTER 2 PROBLEM DEFINITION AND METHODOLOGY PROPOSED

2.1 Problem

The oil and gas industries are now focused on emission reduction and the energy efficiency of their processes. In recent years, the industry has failed to improve its energy efficiency indicators through digitalization. Recently, several advancements have been made regarding advanced analytics in process systems engineering, which should help process and facilities for correct decision making to improve Key Performance Indicators of energy efficiency. This work aims to propose a framework to improve Energy Performance and Profitability Indicators for a case study of pumping systems in Oil & Gas plant treatment based on process modeling optimization.

2.2 Methodology proposed

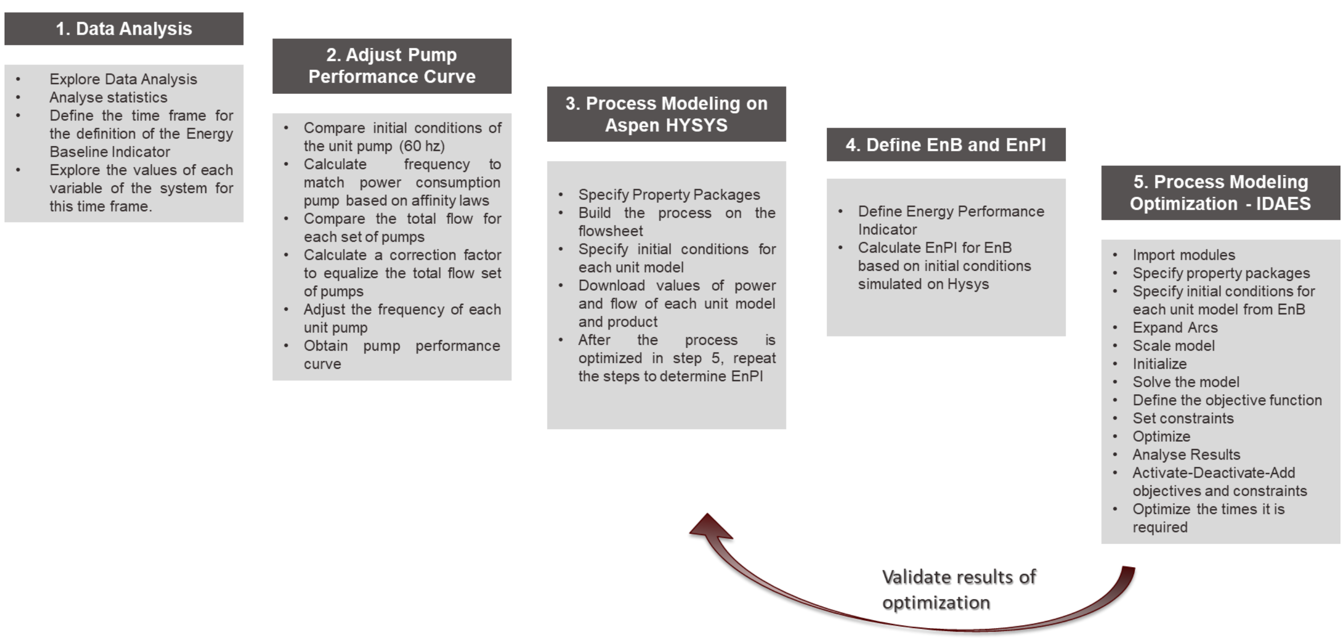

Figure 1. Methodology proposed for this study

CHAPTER 3 DEFINITION OF THE PROCESS

3.1 Description of the system

The system consists of two sets of pumps, which in the following document receive tags P2 and P4, and consists of six pumps, P4 (P4A, P4B, P4C, P4D, P4E, and P4F) and nine pumps P2 (P2A, P2B, P2C, P2D, P2E, P2F, P2G, P2H, and P2I). The function of this system is to transfer water to three destinations: INJ_4, INJ2_1, and INJ2_2. The connection between the two sets of pumps is located in the discharge pipe through the regulation valve PV_5, which regulates the amount of water transferred from pump P4 to destination INJ2_2. Before the two sets of pumps are connected, the water is split into INJ_4 and its recirculation through the regulation valve PV_4, which controls the pressure of the pipelines. Other accessories, such as pipes, valves, pressure relief valves, recycling valves, and other systems are not mentioned or simulated because they are outside the scope of the following work. The manufacturer characteristics of pumps P2 and P4 are summarized in the following charts:

Table 1. Manufacturer characteristics pump P4

P-4	Product	Flow rated (mol/s)	Head rated (ft)	Efficiency (%)
A	Treat Water	12.3	648.0	84.0
B	Treat Water	12.3	648.0	84.0
C	Treat Water	12.3	648.0	84.0
D	Treat Water	12.3	648.0	84.0
E	Treat Water	12.3	648.0	84.0
F	Treat Water	12.3	648.0	84.0

Table 2. Manufacturer characteristics pump P2

P-2	Product	Flow rated (mol/s)	Head rated (ft)	Efficiency (%)
A	Treat Water	6.1	346.5	86.0
B	Treat Water	6.1	346.5	86.0
C	Treat Water	6.1	346.5	86.0
D	Treat Water	6.1	346.5	86.0
E	Treat Water	6.1	346.5	86.0
F	Treat Water	6.1	346.5	86.0
G	Treat Water	6.1	346.5	86.0
H	Treat Water	6.1	346.5	86.0
I	Treat Water	6.1	346.5	86.0

The characteristics of valves PV_4 and PV_5 are summarized in Figure 2, and the process flowsheet is summarized in Figure 3, which was obtained from Aspen HYSYS.

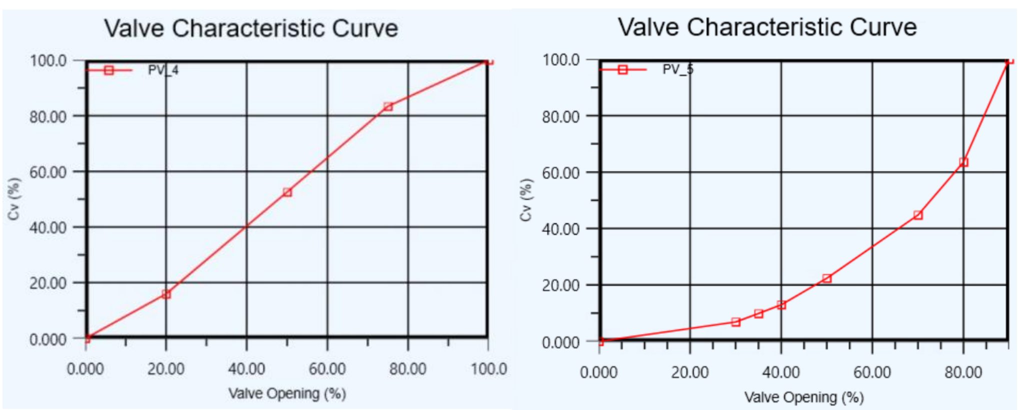

Figure 2. Characteristics valves PV_4 and PV_5 respectively

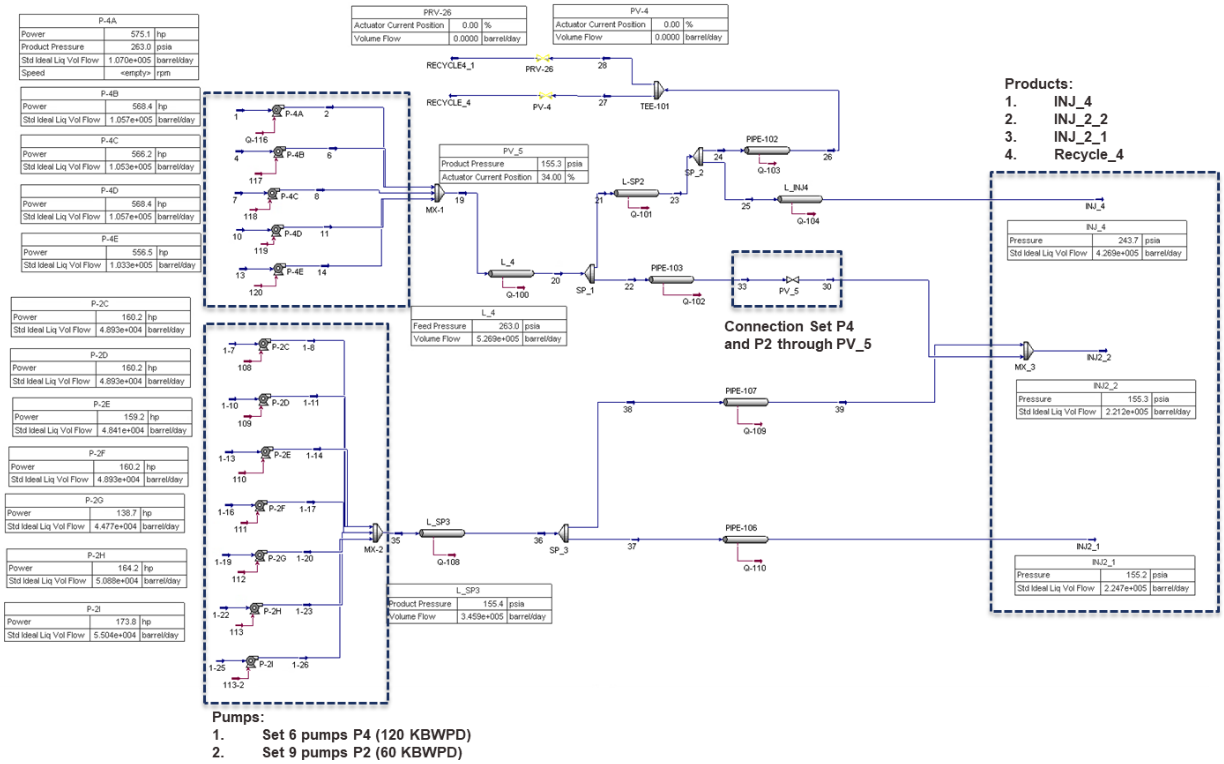

Figure 3. Process flowsheet Aspen HYSYS

3.2 Data analysis

As suggested in the standard ISO-5006-2014 (ISO, 2014), the baseline taken for this study was taken for a period of two months, in which several operational and environmental changes occurred during this period as operational conditions of the pumps, the number of pumps in operation, the quantity of fluid transferred to its destination, and changes in climate conditions.

The EnPI defined to evaluate the efficiency of the process is the unit power per unit of barrel transferred (hp/mol), as suggested by the standard (ISO, 2014), which defines the organization as the defined performance indicator to quantify and evaluate the energy performance of the system.

The data provided and analyzed for this study are as follows: pressure for P2 and P4 at the manifold; flow at each product recycle_4, INJ_4, and INJ_2, which are split in INJ2_1 and INJ2_2;

power consumed for each unit pump; opening percentage valve for PV_4 and PV_5; pump performance curve for each unit pump P2 and P4 at 60 Hz; and P&ID's and PFD's of the system as inputs for modeling.

The data on the energy performance are summarized in Figure 3 for the total system, systems P2, and system P4, where the fluctuation of this indicator over the days is noticeable. Figures 5 and 6 correlate the variables of the system to a better understanding of which variables affect the EnPI, in which a highly direct correlation is connected to the number of pumps P2 that are in operation and an inverse correlation is associated with the discharge pressure of pump P4.

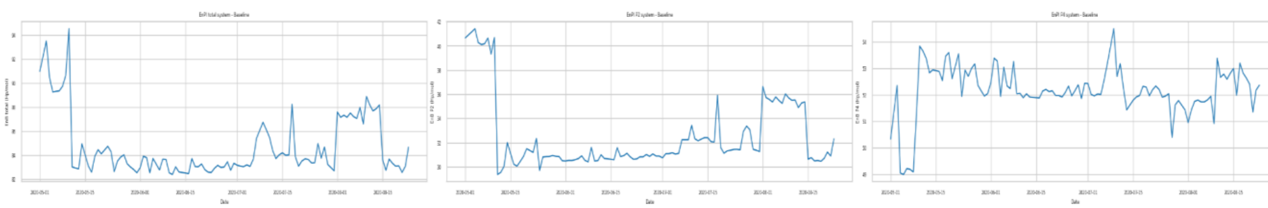

Figure 4. EnPI of the entire system, system P2, and system P4

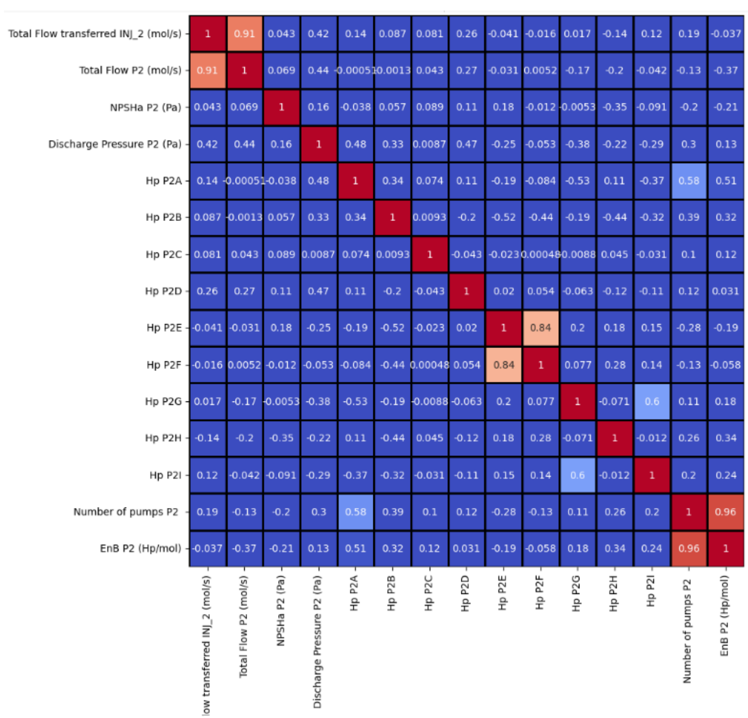

Figure 5. Correlation variables system P2 regarding EnPI

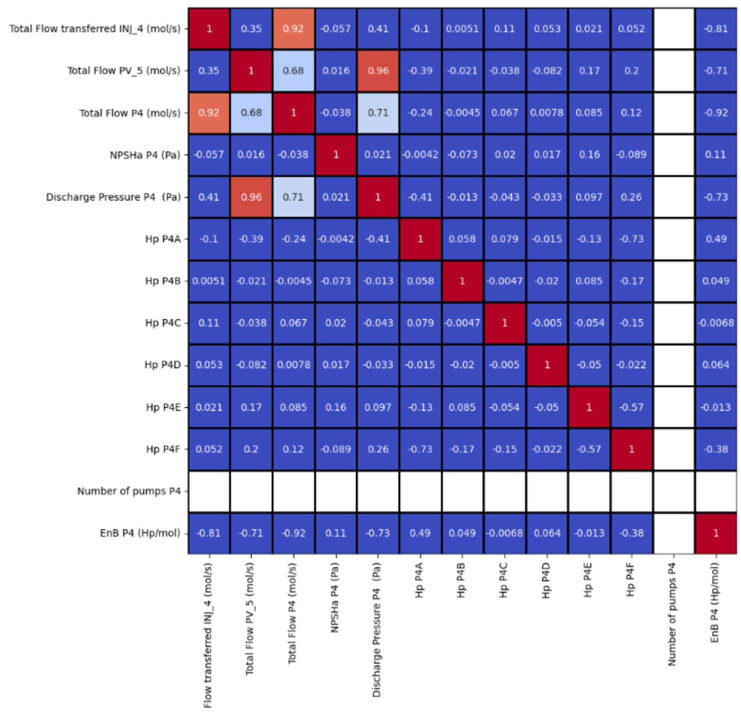

Figure 6. Correlation variables system P4 regarding EnPI

For a better understanding of the frequency and distribution of the EnPI with respect to the number of pumps P2, three histograms were plotted, as shown in Figure 6. When the number of pumps P2 is equal to seven, the graph is skewed to the left with a noticeable concentration of EnPI in the range of 43–45 hp/mol. When the number of pumps P2 is equal to eight, represents a Gaussian distribution with a lower frequency of events and a concentration of EnPI in the range of 40–46 hp/mol. When the number of pumps P2 is equal to nine, the graph is skewed to the right with a lower frequency of events and a concentration of EnPI in the range of 40–46 hp/mol. In this case, we can conclude that the number of pumps P2 affects EnPI.

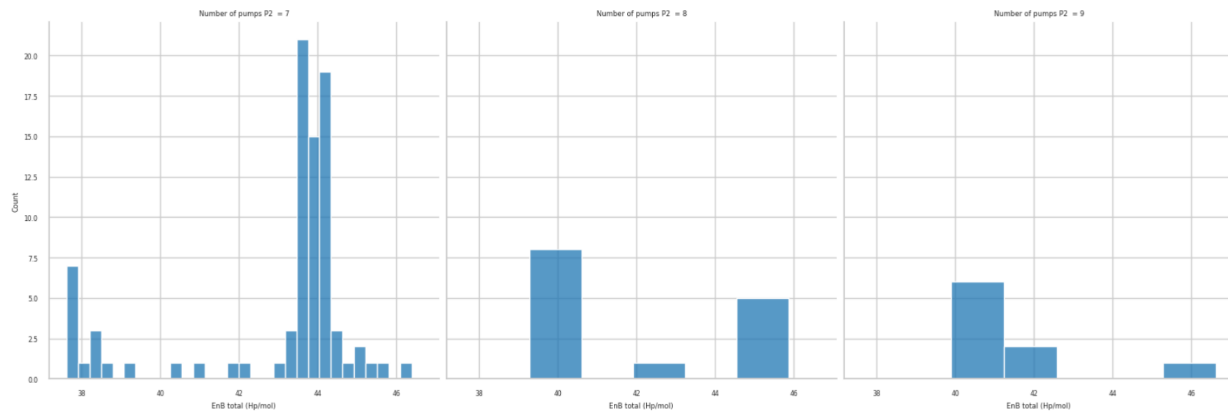

Figure 7. Histogram EnPI regarding number of pumps P2

However, the question remains as to whether the number of pumps P2 also affects the total quantity of water transferred, which also affects oil production in the field. Figure 7 shows the relation of EnPI with the number of pumps P2 and total fluid transferred in the system. It is noticeable that with the number of pumps P2 equal to 7, with an EnPI near 44 hp/mol, the total flow transferred was around 89 mol/s and 89.5 mol/s, and only with the number of pumps P2 equal to 9 the total water transferred surpass 90 mol/s with EnPI around 86 mol/s, affecting the energy performance of the system.

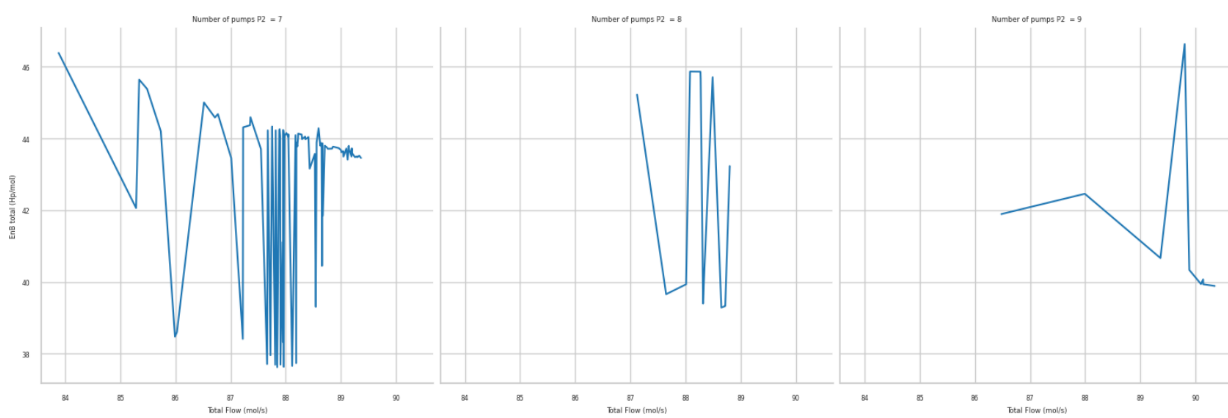

Figure 8. EnPI regarding the number of pumps P2 and total fluid transferred in the system

Despite having a higher number of pumps P2, the systems transferring a higher quantity of water with less energy consumption, the integrity of the pumps is also a main concern. Operating pumps inside the permissible region of the pump performance is imperative in order to preserve to reduce the cost of corrective maintenance and increase the life cycle of the pump. Figure 9 illustrates the effect of the number of pumps in operation in the region on the pump performance curve.

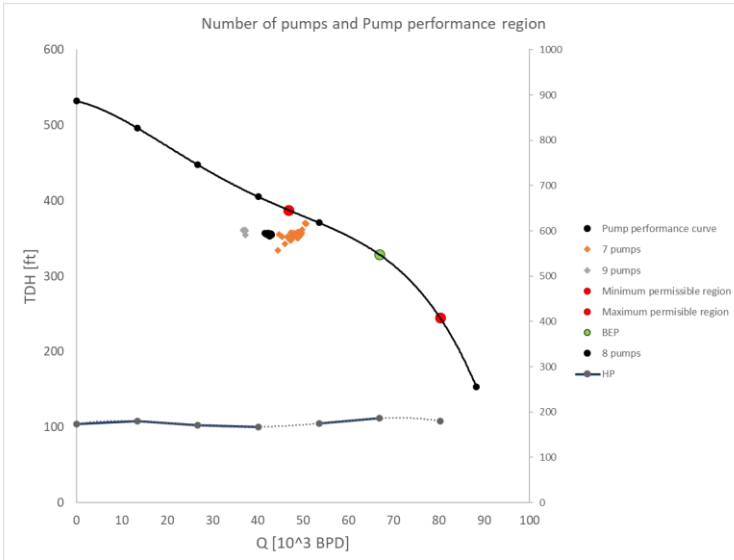

Figure 9. Pump performance region regarding number of pumps

The previous analysis can be found in the following link and summary in Annex A:

https://colab.research.google.com/drive/1LfatX7V8CX-rVcIdJ8k3y8yFJmaP2XTc?usp=sharing

3.3 Results of data analysis

According to Figure 7, the EnPI of EnB for this study was defined as the average value of the days when the water transfer was higher than 89 mol/s and the number of pumps P2 was equal to 7.

Table 3 lists the conditions of valves PV_5 and PV_4, and Tables 4 and 5 list the conditions of each unit system P4 and P2 on EnB, which is the basis of this study. The conditions of each unit pump that were not in operation during the previous calculation were defined based on a different time frame and similar operation characteristics, such as the discharge pressure and flow of each system.

Table 3. Conditions of the valves PV_5 and PV_4 on EnB

Parameter	PV_5	PV_4
Cv (mol/s*1/Pa)	0.03334	0.1
%open	34.0	0.0
Flow (mol/s)	9.59	0.0

Table 4. Conditions of the unit pump P4 on EnB

P-4	Product	Pd baseline (Pa)	Pi baseline (Pa)	Power Baseline (hp)	Flow Baseline (mol/s)
A	Treat Water	1812821.4	115110.7	565.6	10.76
B	Treat Water	1812821.4	115110.7	562.0	10.76
C	Treat Water	1812821.4	115110.7	559.5	10.76
D	Treat Water	1812821.4	115110.7	560.7	10.76
E	Treat Water	1812821.4	115110.7	550.3	10.76
F	Treat Water		115110.7	524.1	

Table 5. Conditions of the unit pump P2 on EnB

P-2	Product	Pd baseline (Pa)	Pi baseline (Pa)	Power Baseline (hp)	Flow Baseline (mol/s)
A	Treat Water		117178.6	143.7	
B	Treat Water		117178.6	155.1	
C	Treat Water	1092517.9	117178.6	155.1	5.04
D	Treat Water	1092517.9	117178.6	155.5	5.04
E	Treat Water	1092517.9	117178.6	154.4	5.04
F	Treat Water	1092517.9	117178.6	155.1	5.04
G	Treat Water	1092517.9	117178.6	148.7	5.04
H	Treat Water	1092517.9	117178.6	156.3	5.04
I	Treat Water	1092517.9	117178.6	163.9	5.04

As shown in Tables 4 and 5, the power value of each pump unit is different even when they are running at the same frequency (60 Hz). Hence, it is incorrect to affirm that the flow value is equal for all the unit pumps regarding the set to which they correspond. This value was corrected in the next section.

CHAPTER 4 PERFORMANCE CURVES AND EnB

4.1 Affinity laws

Affinity laws can be defined as a series of rules that predict pump performance. These rules help to understand the performance of the pump when it runs at a different frequency from when it was designed generally at 60 Hz. (Custodio, 2003)

The rules can be defined as:

- Flow changes directly proportional to a change in velocity
- Head changes directly proportional to the square of the change in velocity
- Power changes directly proportional to the cube of the change in velocity

$$Q_2 = Q_1 \times \left(\frac{Hz_2}{Hz_1}\right) \qquad \mathrm{h}_2 = \mathrm{h}_1 \times \left(\frac{Hz_2}{Hz_1}\right)^2 \qquad \mathrm{hp}_2 = \mathrm{hp}_1 \times \left(\frac{Hz_2}{Hz_1}\right)^3$$

Equation 1. Equation affinity laws (Custodio, 2003)

Where:

Q corresponds to the flow at two different frequencies

h corresponds to the head at two different frequencies

hp corresponds to the power at the two different frequencies.

4.2 Pump performance curve adjustment

Various test methods have been defined to adjust the pump performance curve.

- Pressure Head Measurement: As mentioned in Equation 1, the head changes to the square of the change in velocity, and the flow changes directly to the change in velocity. This indirect method involves measuring the changes in the pressure head and changes in the flow of the pump with a pressure gauge. This study does not use this method because of a lack of information.

- Field test Calculator: This method is also called a direct method, which consists of the measurement of different variables, such as intake pressure, discharge pressure, temperature, and flow at different rates of flow, to check the variance in power and head. A field-test calculator can be used to compile the data and generate an accurate pump performance curve. (PUMPS&SYSTEMS, 2023)

- Power Measurement: As mentioned in Equation 1, the power changes in order 3 of the change in velocity, and the flow changes directly with the change in velocity. This is the indirect method used in this study, in which an approximation is calculated for the current pump curve. The following method is proposed, which involves iterative and interpolation methods based on a curve at 60 Hz. An approximation of the current pump can be defined, owing to the pump operating at 60 Hz; however, the value of power consumption does not correspond to the value calculated in the pump performance, so we are approximating which new pump performance corresponds to the actual value of power consumption. Subsequently, an adjustment factor was necessary to match the total flow of the system.

4.3 Methodology proposed to adjust pump performance with respect to power consumption

The following methodology is proposed to adjust the new performance curve for each pump unit through an indirect method of power measurement with the following assumptions:

a. The following methodology was performed using an Excel spreadsheet:

b. No temperature correction was applied.

c. The conversion factor to convert the head into psi was 0.433 psi per foot for H20.

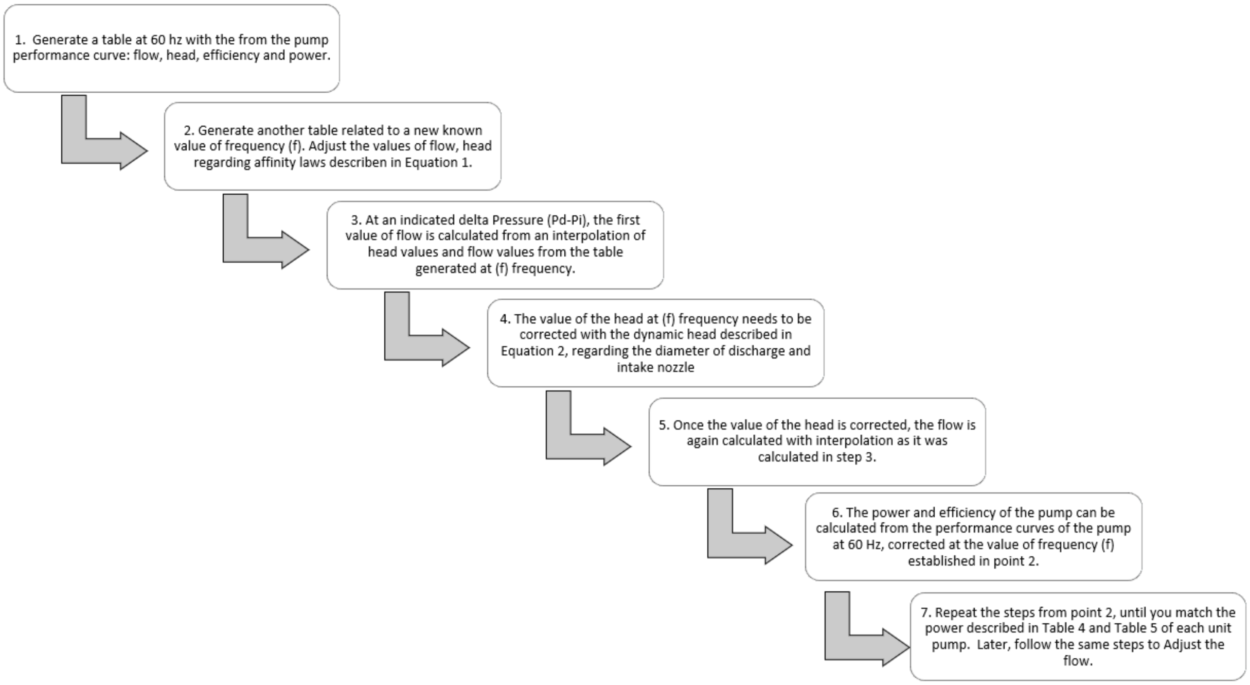

Figure 10. Methodology proposed to adjust pump performance

$$h = \frac{P_d - P_i}{\rho\, g} + \frac{c_d^2 + c_s^2}{2\, g}$$

Equation 2. Dynamic head modified from (Gülic, 2020)

Where:

H corresponds to the dynamic head

Pd corresponds to the discharge pressure

Pi corresponds to the intake pressure

g corresponds to the gravity force

ρ corresponds to the density

cd corresponds to the velocity at the discharge

cs corresponds to the velocity at intake.

$$Q = \frac{h_1 - h}{h_1 - h_2} \times (Q_1 - Q_2) + Q_1$$

Equation 3. Interpolation equation applied in step 5

4.4 Results pump performance adjusted for each unit pump

The results of the performance pump adjustment are shown in Tables 6 and Table 7for each unit pump, which were later used to model the system.

Table 6. Frequency adjusted for pump P-4

P-4	Product	Frecuency adj. Power (hz)	Q frecuency adj. Power (Bls/d)	Frecuency adj. Baseline(hz)	Q adjusted Q (Bl/d)	Q adjusted Q (mol/s)	Power Adjusted Q (hp)
A	Treat Water	56.4	104070.0	56.75	106802.9	10.91	578.38
B	Treat Water	56.3	103027.0	56.60	105732.5	10.80	572.55
C	Treat Water	56.2	102470.0	56.55	105160.9	10.74	570.61
D	Treat Water	56.3	103027.0	56.60	105732.5	10.80	572.55
E	Treat Water	56.0	100870.0	56.33	103518.9	10.57	562.02
F	Treat Water	55.0		55.35	0.0	0.00	

Table 7. Frequency adjusted for pump P-2

P-2	Product	Frecuency adj. Power (hz)	Q frecuency adj. Power (Bls/d)	Frecuency adj. Baseline(hz)	Q adjusted Q (Bl/d)	Q adjusted Q (mol/s)	Power Adjusted Q (hp)
A	Treat Water	55.00		57.0			143.6
B	Treat Water	56.60		58.6			159.67
C	Treat Water	58.20	45500.0	58.6	48971.3	5.00	159.67
D	Treat Water	58.23	45730.0	58.6	48971.3	5.00	159.67

P-2	Product	Frecuency adj. Power (hz)	Q frecuency adj. Power (Bls/d)	Frecuency adj. Baseline(hz)	Q adjusted Q (Bl/d)	Q adjusted Q (mol/s)	Power Adjusted Q (hp)
E	Treat Water	58.13	45150.0	58.5	48300.5	4.93	158.53
F	Treat Water	58.20	45500.0	58.6	48971.3	5.00	159.67
G	Treat Water	57.55	41800.0	57.9	44302.3	4.52	152.05
H	Treat Water	58.30	46130.0	59.0	50286.2	5.14	164.40
I	Treat Water	58.95	49930.0	59.9	55652.9	5.68	175.40

The factors used to adjust the flow for pump P-4 was 1.03 and pump P-2 were 1.08. Table 8 summarizes the initial conditions of the general system and establishes the EnPI for the baseline.

Table 8. Summary of EnPI of EnB corrected

Total flow of the system (mol/s)	Total power consumed (hp)	EnPI (hp/mol)
89.09	3985.50	44.7

5.1 Superstructure definition

The first step before starting modeling is designing a superstructure of our process, which will guide this study to describe the process and capture possible alternatives to analyze, evaluate, and optimize in a comprehensive manner in terms of performance and cost, and can lead to better decision-making.

Several superstructures have been defined by (Luca Mencaralli, 2020). For this study, a state task superstructure was defined for this process that was already specified, with the same inputs and outputs as shown in Figure 3 and described in CHAPTER 2.

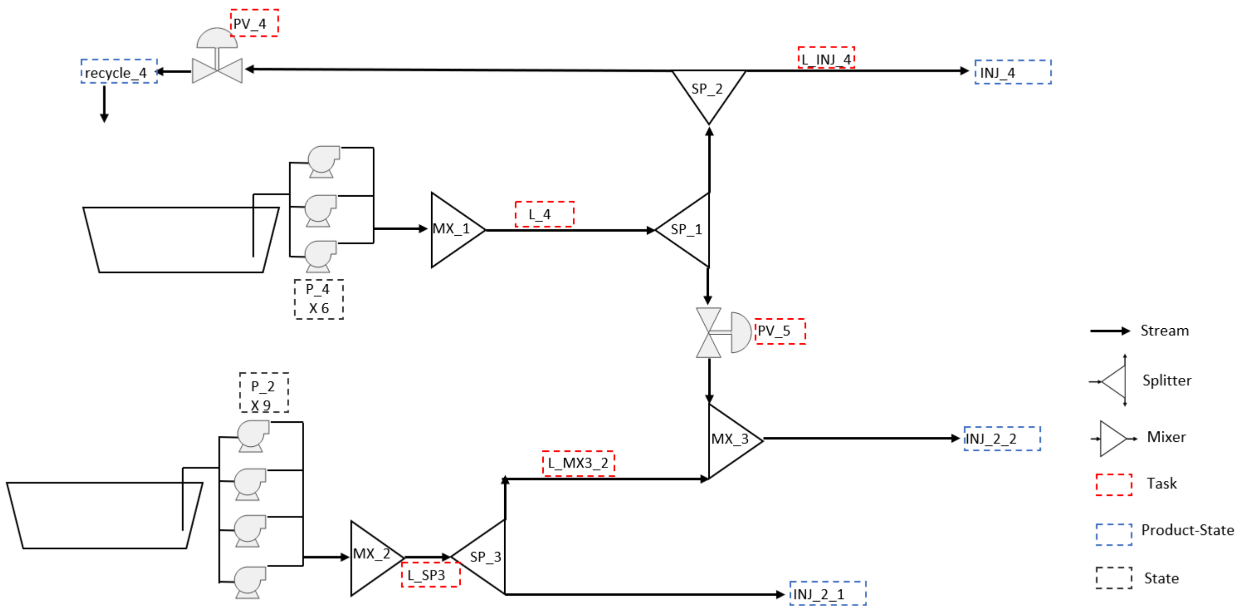

Figure 11. Superstructure state task network pumping systems

5.2 Process modeling on Aspen HYSYS

Aspen Hysys in a mathematical and chemical process simulator which performs in this case study the calculations concerned to unit models as pumps, pipes and valves calculations, taking into account mass and energy balance, mass transfer, and pressure drop in the system.

The input corresponds to the initial conditions, which are described in Tables 9 and 10, for the P_2 and P_4 systems. Valves P_4 and P_5 are shown in Figure 2 and described in Table 3. The data input to configure the pipeline network to calculate the entire pressure drop was supplied by Ecopetrol, and the results are shown in Table 12.

Table 9. Initial conditions simulation P_4

P-4	Frecuency adj. Baseline(hz)	Intake Pressure (Pa)	Discharge Pressure (Pa)	Q adjusted Q (mol/s)	Performance curve (Pd)	Performance curve (eff)
A	56.75	115110.71	1812821.43	10.91	(-3874*Q^2)+(-35736*Q)+(2646467)	(-0.0073*Q^2)+(0.1541*Q)+(0.00252)
B	56.60	115110.71	1812821.43	10.80	(-3874*Q^2)+(-35642*Q)+(2632495)	(-0.0074*Q^2)+ (0.1546*Q)+0.0252)
C	56.55	115110.71	1812821.43	10.74	(-3874*Q^2)+(-35610*Q)+(2627846)	(-0.0074*Q^2)+(0.1547*Q)+(0.0252)
D	56.60	115110.71	1812821.43	10.80	(-3874*Q^2)+(-35642*Q)+(2632495)	(-0.0074*Q^2)+(0.1546*Q)+(0.0252)
E	56.33	115110.71	1812821.43	10.57	(-3874*Q^2)+(-35472*Q)+(2607439)	(-0.0075*Q^2)+(0.1557*Q)+(0.0252)
F	55.35	115110.71		0.00	(-3874*Q^2)+(-34855*Q)+(2517503)	(-0.0078*Q^2)+(0.158*Q)+(0.0252)
F_new						(-0.0066*Q^2)+(0.1458*Q)+(0.0252)

Table 10. Initial conditions simulation P_2

P-2	Frecuency adj. Baseline(hz)	Intake Pressure (Pa)	Discharge Pressure (Pa)	Q adjusted Q (mol/s)	Performance curve (Pd)	Performance curve (eff)
A	57.0	117178.6		0.0	(-3670.5*Q^2)+(-65799*Q)+(1432707)	(-0.0197*Q^2)+(0.2627*Q)+ (-0.0288)
B	58.6	117178.6		0.0	(-3670.5*Q^2)+(-67646*Q)+(1514269)	(-0.0187*Q^2)+(0.2555*Q)+(-0.0288)
C	58.6	117178.6	1092517.9	5.00	(-3670.5*Q^2)+(-67646*Q)+(1514269)	(-0.0187*Q^2)+(0.2555*Q)+(-0.0288)
D	58.6	117178.6	1092517.9	5.00	(-3670.5*Q^2)+(-67646*Q)+(1514269)	(-0.0187*Q^2)+(0.2555*Ql)+(-0.0288)
E	58.5	117178.6	1092517.9	4.93	(-3670.5*Q^2)+(-67530*Q)+(1509105)	(-0.0187*Q^2)+(0.2559*Ql)+(-0.0288)
F	58.6	117178.6	1092517.9	5.00	(-3670.5*Q^2)+(-67646*Q)+(1514269)	(-0.0187*Q^2)+(0.2555*Q)+(-0.0288)
G	57.9	117178.6	1092517.9	4.52	(-3670.5*Q^2)+(-66837*Q)+(1478308)	(-0.0191*Q^2)+(0.2586*Q)+(-0.0288)
H	59.0	117178.6	1092517.9	5.14	(-3670.5*Q^2)+(-68107*Q)+(1535012)	(-0.0184*Q^2)+(0.2538*Q)+(-0.0288)
I	59.9	117178.6	1092517.9	5.68	(-3670.5*Q^2)+(-69146*Q)+(1582200)	(-0.0179*Q^2)+(0.25*Q)+ (-0.0288)

$$P_d = (A * Q^2) + (B * Q) + C$$

Equation 4. Equation applied for performance curves

The first simulation aimed to obtain the outputs of the pressure drop in the system for the initial conditions for process modeling later IDAES. A summary of the inputs and outputs is provided in Table 11.

Table 11. Initial conditions on Aspen HYSYS

Object	Variable	Value	Units	Object	Variable	Value	Units
P2C	Power	160.2	hp	P4C	Power	566.2	hp
P2C	Std Ideal Liquid	48930.0	Bl/day	P4C	Std Ideal Liquid	105300.0	Bl/day
P2D	Power	160.2	hp	P4D	Power	568.4	hp
P2D	Std Ideal Liquid	48930.0	Bl/day	P4D	Std Ideal Liquid	105700.0	Bl/day
P2E	Power	159.2	hp	P4E	Power	556.5	hp
P2E	Std Ideal Liquid	48410.0	Bl/day	P4E	Std Ideal Liquid	103300.0	Bl/day
P2F	Power	160.2	hp	INJ_4	Pressure	243.7	psia
P2F	Std Ideal Liquid	48930.0	Bl/day	INJ_4	Std Ideal Liquid	426887.0	Bl/day
P2G	Power	138.7	hp	INJ_2_2	Pressure	155.3	psia
P2G	Std Ideal Liquid	44770.0	Bl/day	INJ_2_2	Std Ideal Liquid	221235.0	Bl/day
P2H	Power	164.2	hp	INJ_2_1	Pressure	155.2	psia
P2H	Std Ideal Liquid	50880.0	Bl/day	INJ_2_1	Std Ideal Liquid	224668.0	Bl/day
P2I	Power	173.8	hp	PV_5	Delta P	104.8	psia
P2I	Std Ideal Liquid	55040.0	Bl/day	PV_5	%Open	34.0	%
P4A	Power	575.1	hp	PV_4	%Open	0.0	%
P4A	Std Ideal Liquid	107000.0	Bl/day	RECYCLE_4	Std Ideal Liquid	0.0	Bl/day
P4B	Power	568.4	hp				
P4B	Std Ideal Liquid	105700.0	Bl/day				

5.3 Process modeling on IDAES

The design of the Advanced Energy Systems Integrated Platform (IDAES) incorporates all of these concepts within a Python-based optimization framework. The platform includes facilities for equation-oriented modeling for static and dynamic processes, exact gradients and Hessians from process models, automated initialization strategies, and seamless interaction with state-of-art large-scale optimization solvers (Lorenz Biegler, 2022).

As an equation-oriented modeling platform, which is based on Pyomo which supports the formulation and analysis of mathematical models for complex optimization applications commonly associated with algebraic modeling languages (AMLs) (Michael L. Bynum, 2021).

A model simulation was carried out by applying an object-oriented glass box optimization model, as shown in Figure 12, which helps this study to analyze trade-offs, identify and adjust out of the bounder parameters of the unit process, model different scenarios, and identify key factors that influence the results of the optimization process based on the insights taken from the superstructure represented in Figure 10, such as the capacities and constraints of each unit model and the system per se, streams, and connections among unit models, and outputs required as flow, pressure, and others.

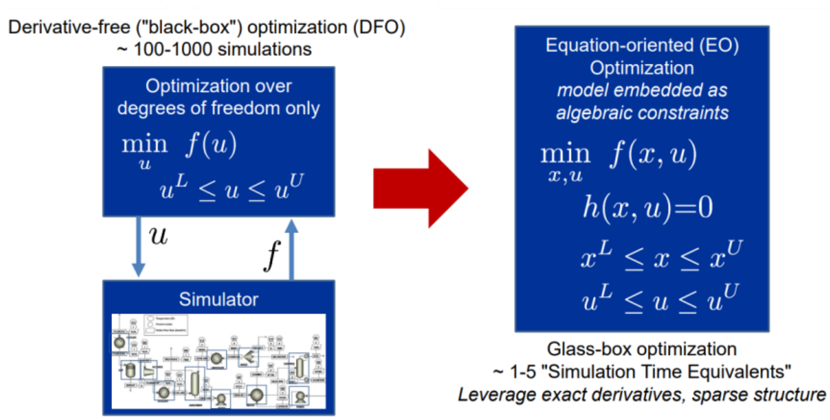

Figure 12. Generality difference black and glass box optimization. Reprinted from (Miller, 2022)

The methodology is described in Figure 1, based on the core framework block hierarchy of the IDEAS, which is shown in Figure 13.

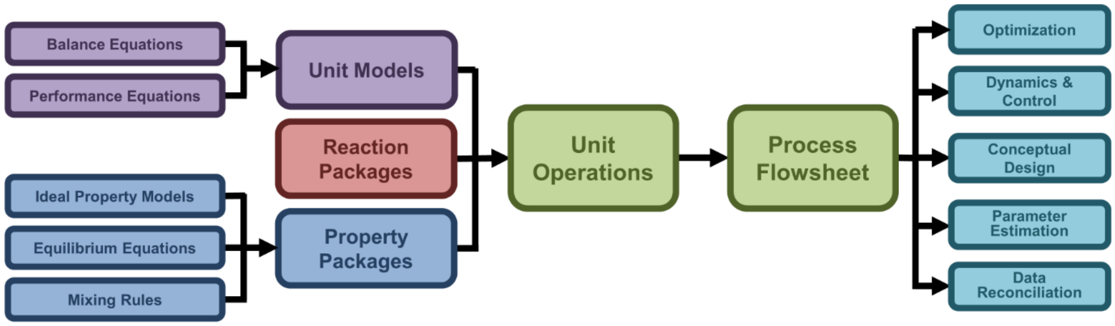

Figure 13. IDAES core modeling framework. Reprinted from (IDAES, 2023)

The simulation on IDAES also includes the pressure drop in the system if it is a factor of energy optimization. The pressure drop in the pipe and accessories is simulated as a valve, and for this study, we considered those with a pressure drop higher than 1.5 psia to reduce nonlinearities in the problem. Therefore, Cv is specified for each valve, as described in Table 13.

The initial conditions prior to carrying out the optimization problem are shown in Table 9, as well as the visualization of the flowsheet of the model in figure 13 after importing blocks, building, scaling, specifying, initializing, and solving the model. It should be noted that the model representation is similar to that of the superstructure model shown in Figure 10.

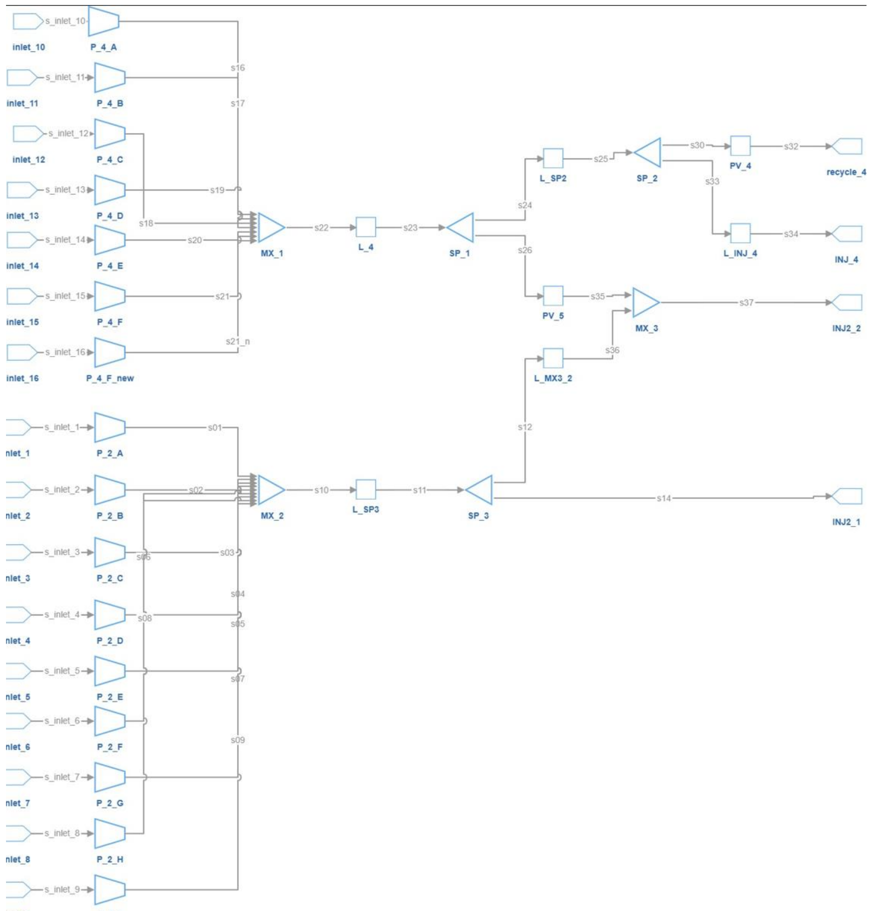

Figure 14. Flowsheet model visualization on IDAES

Equation 3 describes the pressure-flow relation based on the valve coefficient Cv, which supports the calculation of the pressure drop in the segment of the pipeline described as a valve.

$$Q^2 = Cv^2 \times (Pinlet - Poutlet)$$

Equation 5. Cv equation

Where:

where Cv corresponds to the valve coefficient.

Pinlet corresponds to pressure at the valve inlet.

Poutlet corresponds to the pressure at the valve outlet.

Q corresponds to the flow through the valve

Table 12. Pressure drop pipeline segment

Pipeline Segment	Pressure drop (psig)	% open	Cv
L-4	2.5	45.0	0.9
L_INJ_4	15.5	45.0	0.3
L_SP_3	2.7	45.0	0.6
L_MX3_2	2.2	45.0	0.2

Both Aspen HYSYS and IDEAS calculate the power of the pump as a function of flow, the difference in intake and discharge pressure, and the efficiency of the pump, which is described in Equation 4. The results for the initial conditions are presented in Table 13.

$$Power = \frac{(Pdisc - Pint) * Q}{\eta_{pump}}$$

Equation 6. Pump power calculation

Where:

Power corresponds to the power executed by the pump

Pdisc corresponds to discharge pressure of the pump

Pint corresponds to pressure at intake of the pump

Q corresponds to the flow through the pump

Table 13. Initial conditions on IDAES

Object	Variable	Value	Units	Object	Variable	Value	Units
P2C	Power	113.35	Kw	P4C	Power	397.38	Kw
P2C	Std Ideal Lquid	4.96	mol/s	P4C	Std Ideal Lquid	10.74	mol/s
P2D	Power	113.35	Kw	P4D	Power	399.58	Kw
P2D	Std Ideal Lquid	4.96	mol/s	P4D	Std Ideal Lquid	10.80	mol/s
P2E	Power	112.50	Kw	P4E	Power	388.80	Kw
P2E	Std Ideal Lquid	4.90	mol/s	P4E	Std Ideal Lquid	10.57	mol/s
P2F	Power	113.35	Kw	INJ_4	Pressure	1788500.00	Pa

Object	Variable	Value	Units	Object	Variable	Value	Units
P2G	Power	108.62	Kw	INJ_2_2	Pressure	1075500.00	Pa
P2G	Std Ideal Lquid	4.49	mol/s	INJ_2_2	Std Ideal Lquid	22.30	mol/s
P2H	Power	115.72	Kw	INJ_2_1	Pressure	22.42	Pa
P2H	Std Ideal Lquid	5.10	mol/s	INJ_2_1	Std Ideal Lquid	1075500.00	mol/s
P2I	Power	121.94	Kw	PV_5	Delta P	1078085.00	Pa
P2I	Std Ideal Lquid	5.64	mol/s	PV_5	%Open	34.00	%
P4A	Power	411.96	Kw	PV_4	%Open	0.01	%
P4A	Std Ideal Lquid	10.91	mol/s	RECYCLE_4	Std Ideal Lquid	0.02	mol/s
P4B	Power	399.58	Kw				
P4B	Std Ideal Lquid	10.80	mol/s				

5.4 Summarize correction and modeling results

At this point, this study has analyzed the initial conditions of power consumption (Table 14), making corrections regarding power Table 15 and flow described in Table 16, and modeling the initial conditions through two different platforms, namely HYSYS Table 17 and IDEAS Table 18. These results are the baseline of the optimization proposed in Chapter 6.

Table 14. Results indicators EnB

Total flow of the system (mol/s)	Total power consumed (hp)	EnPI (hp/mol)
89.09	3887.05	43.6

Table 15. Results indicators EnB corrected by power

Total flow of the system (mol/s)	Total power consumed (hp)	EnPI (hp/mol)
85.08	3887.05	45.7

Table 16. Results indicators EnB corrected by power and flow

Total flow of the system (mol/s)	Total power consumed (hp)	EnPI (hp/mol)
89.09	3985.50	44.7

Table 17. Results indicators EnB simulated Aspen HYSYS

Total flow of the system (mol/s)	Total power consumed (hp)	EnPI (hp/mol)
89.12	3951.1	44.33

Table 18. Results indicators EnB simulated IDEAS

Total flow of the system (mol/s)	Total power consumed (hp)	EnPI (hp/mol)
88.85	3781.77	42.6

CHAPTER 6 OPTIMIZATION DEFINITION

6.1 Objectives and scenarios definition

This study aims to propose three different objectives for a comprehensive analysis of decision-making. All the optimization models for this work are defined as mixed integer nonlinear programming (MINLP) based on discrete variables as a decision for the operation of each unit pump, and the non-linearities are based on the constraints defined for the pumps and valves.

A convex MINLP problem can be described without loss of generality as:

$$\min_{x,y} f\ (x, y)$$

$$s.t.\ \ h(x, y) = 0$$

$$g\ (x, y) \leq 0$$

$$x \in \mathbb{R}^n, y \in \{0,1\}^t$$

Equation 7. Generality MINLP problem. Reprinted from (Biegler, 2010)

Where $f\ (x, y)$ is the objective function, in this study, the objective function is related to minimize or maximize KPI, as it is shown Equation 6, 7 and 8, $h\ (x, y)$ describes the performance in the case of this is where is defined the flow transferred to each product or the energy performance indicator and $g\ (x, y)$ that are defined the constraints of the systems as the maximum of minimum flow of each pump or the pressure of each node.

The optimization problem is formulated to minimize or maximize the KPI, which is constrained by process variables defined as integer, discrete, and continuous variables that are considered the decision variables and parameters. Each optimization problem formulation, which is described in the following subsection, is defined by

Integer variables:

N_{aibi} represents the number of available pumps, represented as a unit model.

Continuous variables:

Q_{aibi} represents the flow discharged for each N_{aibi}

W_{aibi} represents the mechanical work for N_{aibi}

Z_4 represents the quantity of fluid required for state-product INJ_4

Z_{rec4} represents the quantity of fluid required for state-product recycle_4

PV_5 represents the pressure in the outlet of task PV_5

P_{mx1} represents the pressure in the outlet of mixer MX_1

P_{aibi} $ represents the discharge pressure of each N_{aibi}

Discrete variables:

y_{aibi} respresents the binary variable for each N_{aibi}

Parameters:

T_o & T_w $ represents the cost of treatment of barrel of oil and barrel of water respectively

W/O represents the relation between the barrels of water and the barrels of oil produced.

C represents the cost of electric energy

$F_{a+i\ b+i}$ represents the maximum quantity of flow delivered by N_{aibi} in order to fulfill the requirement to perform the efficiency of the pump in the permissible zone regarding P_{aibi}

$F_{a-i\ b-i}$ represents the minimum quantity of flow delivered by N_{aibi} in order to fulfill the requirement to perform the efficiency of the pump in the permisible zone regarding P_{aibi}

where Po represents the price of the oil barrel.

6.1.1. Energy performance indicator

This objective is to find an optimal solution that minimizes the power consumption per quantity of water transferred (hp/mol). The problem is formulated as follows:

$$
\begin{aligned}
&\min \quad \sum_{N a_i b_i} W a_i b_i \div Q a_i b_i \\
&\text{s.t.} \quad \sum_{N a_i b_i} W a_i b_i \div Q a_i b_i \leq 32 \quad (value\ taken\ from\ the\ baseline) \\
&Q a_i b_i \geq F a_{-i} b_{-i} \times y_{aibi} \\
&Q a_i b_i \leq F a_{+i} b_{+i} \times y_{aibi} \\
&Q a_i b_i \geq 0 \\
&Z_{rec4} \leq 0.1 \\
&Z_{rec4} \geq 0 \\
&\sum_{N a_i b_i} Q a_i b_i \geq 88 \\
&\sum_{N a_i b_i} Q a_i b_i \leq 91 \\
&Z_4 \geq 43 \\
&Z_4 \leq 46 \\
&P_{pv5} - P_{mx1} \leq 1
\end{aligned}
$$

Equation 8. Formulation MINLP problem minimize EnPI

6.1.2. Profitability indicator

This objective is to find an optimal solution that maximizes the profitability of the process in dollars. The problem is formulated as follows:

$$
\begin{aligned}
&\max \quad \sum_{N a_i b_i} Q a_i b_i \div W/O \times Po - \sum_{N a_i b_i} Q a_i b_i \div W/O \times T_o - \sum_{N a_i b_i} Q a_i b_i \times T_w - \sum_{N a_i b_i} C \times W a_i b_i \\
&\text{s.t.} \quad \sum_{N a_i b_i} Q a_i b_i \div W/O \times Po - \sum_{N a_i b_i} Q a_i b_i \div W/O \times T_o - \sum_{N a_i b_i} Q a_i b_i \times T_w - \sum_{N a_i b_i} C \times W a_i b_i \geq 5.12e5 \quad (value\ taken\ from\ the\ baseline) \\
&Q a_i b_i \geq F a_{-i} b_{-i} \times y_{aibi} \\
&Q a_i b_i \leq F a_{+i} b_{+i} \times y_{aibi} \\
&Q a_i b_i \geq 0 \\
&Z_{rec4} \leq 0.1 \\
&Z_{rec4} \geq 0 \\
&\sum Q a_i b_i \geq 88 \\
&\sum Q a_i b_i \leq 91 \\
&Z_4 \geq 43 \\
&Z_4 \leq 46 \\
&P_{pv5} - P_{mx1} \leq 1
\end{aligned}
$$

Equation 9. Formulation MINLP problem maximize profits

6.1.3. Energy consumption

This objective aims to find an optimal solution that minimizes the power consumption in the process with similar conditions taken from the baseline in kW. The problem is formulated as follows:

$$
\begin{aligned}
&\min \quad \sum_{N a_i b_i} W a_i b_i \\
&\text{s.t.} \quad \sum_{N a_i b_i} W a_i b_i \leq 2.8e3 \quad (value\ taken\ from\ the\ baseline) \\
&Q a_i b_i \geq F a_{-i} b_{-i} \times y_{aibi} \\
&Q a_i b_i \leq F a_{+i} b_{+i} \times y_{aibi} \\
&Q a_i b_i \geq 0 \\
&Z_{rec4} \leq 0.1 \\
&Z_{rec4} \geq 0 \\
&\sum Q a_i b_i \geq 88 \\
&\sum Q a_i b_i \leq 91 \\
&Z_4 \geq 43 \\
&Z_4 \leq 46 \\
&P_{pv5} - P_{mx1} \leq 1
\end{aligned}
$$

Equation 10. Formulation MINLP problem minimizes power consumption.

6.1.4. Scenarios

Three scenarios were considered to solve the optimization problem:

1. Original system
2. Propose a retrofit for a particular pump.
3. Changing conditions of discharge pressure due different conditions of water transferring

CHAPTER 7 RESULTS

7.1 Solvers

The systematic determination of the optimal solutions relies on mathematical methods and algorithms. The following solvers are used to solve the initialized model to set the initial state and solve the optimization problem:

7.1.1. Ipopt

IPOPT is an open-source based on interior-point optimization algorithm that is designed to find optimal solutions for nonlinear optimization problems with n dimensions.

The algorithm is based on a filter line search approach that incorporates second-order corrections and an efficient and robust feasibility-restoration phase. The algorithm works by iteratively solving a sequence of linearized subproblems, which are obtained by approximating the nonlinear constraints and objective function using Taylor series expansion. At each iteration, the algorithm computes the search direction by solving a linear system of equations, which is obtained by applying the Newton method to the linearized subproblem. The search direction is then used to update the current iteration, and the algorithm checks whether the new iteration satisfies the termination criteria. If the termination criteria are not satisfied, the algorithm repeats the process using a new linearized subproblem.

The IPOPT also incorporates several heuristics and techniques to improve its efficiency and robustness, including automatic problem scaling, inertia correction of the linear system, treatment of unbounded solution sets, and two acceleration heuristics. (Andreas Wächter, 2006)

7.1.2. Bonmin

Basic open-source nonlinear mixed-integer programming is an open-source solver used for solving MINLP problems. The solver used in this study uses the convex branch-and-bound method (B-BB). To find the optimality, the method performs an extensive tree search on integer variables. It first solves the continuous relaxation of the MINLP. If the solution assigns integer values to all integer variables, then it is optimal and the algorithm stops. If it is not, an integer variable whose value at the current node is not integer is selected ($y_i = y_i^{(0)}$). A branching is performed in this variable, giving rise to two new NLP problems. One NLP includes the bound ($y_i \leq [\, y_i^{(0)}]$), while the other one ($y_i \geq [\, y_i^{(0)}]$). If an integer feasible solution is found (i.e., the solution provides integer values to all the integer variables), then it provides an upper bound. There are two cases in which some of the nodes are pruned, which makes the branch and bound method faster than enumerating every node. The first case in which a node is pruned occurs when the NLP that corresponds to the node is infeasible. The second case occurs when the NLP solution of the node is larger than the current upper bound.

The performance of the algorithm strongly depends on the selection of branching variables and node selection strategies. (Ignacio Grossman, 2014/07/01)

7.2 Optimization problem results on IDAES

7.2.1. Original system

The First problem proposed in this study is to find optimal solutions for the actual system, the initial conditions of which are listed in Table 13.

7.2.1.1 Minimize energy performance indicator (EnPI)

The optimal solution was found using the solver Bonmin, and is shown in Table 19.

Table 19. Optimal solution energy performance indicator scenario 1

Energy Barrel BONMIN optimal solution					
P2 (Pa)	**P4 (Pa)**		**Product**	**Q (mol/s)**	**Q (Bls/d)**
1432700	1760300		RECYCLE	0.021	205.65
1514300	1812800		PV_5 INLET	11.181	109492.46
1063300	1755300		INJ_4	43.319	424211.05
1063300	1812800			Bls/d (IDAES)	533909.16
1069200	1749400				
1063300	2517500				
1072900	2957900				
1070900			**Product**	**Q (mol/s)**	**Q (Bls/d)**
1068800			MX_3_2	13.14	128676.41
1067385.714	1778120.00		INJ_2_1	23.36	228758.06
154.85	257.97	Pd (psi)	INJ_2_2	24.321	238168.86
152.6	256.0	ΔP (psi)		Bls/d (IDAES)	357434.46
PV_5	36.40%				
CV pv_5	0.033817034	mols/s*psi			
SP fraction	0.7949	%			

7.2.1.2 Maximize profitability indicator (PI)

The optimal solution was found using the solver Bonmin, and is shown in Table 20.

Table 20. Optimal profitability indicator scenario 1

Profit BONMIN optimal solution					
P2 (Pa)	**P4 (Pa)**		**Product**	**Q (mol/s)**	**Q (Bls/d)**
1432700	1760300		RECYCLE	0.021	205.65
1514300	1812800		PV_5 INLET	11.181	109492.46
1063300	1755300		INJ_4	43.319	424211.05
1063300	1812800			Bls/d (IDAES)	533909.1589
1069200	1749400				
1063300	2517500				0
1072900	2957900				
1070900			**Product**	**Q (mol/s)**	**Q (Bls/d)**
1068800			MX_3_2	13.14	128676.41
1067385.7	1778120.00		INJ_2_1	23.36	228758.0556
154.85	257.97	Pd (psi)	INJ_2_2	24.321	238168.8643
152.6	256.0	ΔP (psi)		Bls/d (IDAES)	357434.46
PV_5	36.40%				
CV pv_5	0.03381703	mols/s*psi			0
SP fraction	0.7949	%			

7.2.1.3 Minimize power consumption

The optimal solution was found using solver Ipopt, as shown in Table 21. However, this result was validated later in comparison to Scenario 2.

Table 21. Optimal solution power consumption scenario 1

IPOPT optimal solution					
P2 (Pa)	**P4 (Pa)**		**Product**	**Q (mol/s)**	**Q (Bls/d)**
1426700	1759400		RECYCLE	0.021	205.6472247
1508000	1959500		PV_5 INLET	8.262	80907.49382
1063100	1793300		INJ_4	43.35	424514.6281
1063500	1959500			Bls/d (IDAES)	505627.7691
1069200	1749400				
1063100	2517500				
1073000	2957900				
1072700					
1105300			MX_3_2	13.098	128265.1118
1072842.857	1844220.00		INJ_2_1	23.388	229032.2519
155.65	267.56	Pd (psi)	INJ_2_2	21.36	209172.6057
153.3	265.6	ΔP (psi)		Bls/d (IDAES)	357297.3638
PV_5	36.00%				
CV pv_5	0.033817034	mols/s*psi			
SP fraction	0.8398	%			

7.2.2. Discrete decision to overhaul one pump

The second problem proposed in this study is to find optimal solutions with a discrete decision to assess whether it is convenient to overhaul the pump P4F (chosen because of its low efficiency in comparison to other pumps) with a cost of $250.000 and a lifetime cycle of 10 years. The following constraints are activated in the optimization problem:

$$s.t.\ Q_{P4F_{new}}\ (unfix) \geq 0$$

$$y_{P4F} + y_{P4F_{new}} \leq 1$$

Equation 11. Constraints for new pump P4F

7.2.2.1 Minimize energy performance indicator (EnPI)

The optimal solution was found using the solver Bonmin, and is shown in Table 22.

Table 22. Optimal solution energy performance indicator scenario 2

Energy Barrel BONMIN optimal solution					
P2 (Pa)	**P4 (Pa)**		**Product**	**Q (mol/s)**	**Q (Bls/d)**
1432700	1760300		RECYCLE	0.021	205.6472247
1514300	1812200		PV_5 INLET	11.181	109492.458
1063300	1755300		INJ_4	43.319	424211.0536
1063300	1812200			Bls/d (IDAES)	533909.1589
1069200	1749400				
1063300	2517500				
1072900	2958300				
1070900					
1068800			MX_3_2	13.14	128676.4063
1067385.71	1777880.00		INJ_2_1	23.36	228758.0556
154.85	257.93	Pd (psi)	INJ_2_2	24.321	238168.8643
152.6	255.9	ΔP (psi)		Bls/d (IDAES)	357434.4619
PV_5	36.40%				
CV pv_5	0.033817034	mols/s*psi			
SP fraction	0.7949	%			

7.2.2.2 Maximize profitability indicator (PI)

The optimal solution was found using solver Ipopt and is shown in Table 23. For this optimization problem, a new objective was included, considering the cost of the new pump described in Equation 10.

$$\max \quad \sum_{N a_i b_i} Q a_i b_i \div W/O \times Po - \sum_{N a_i b_i} Q a_i b_i \div W/O \times T_o - \sum_{N a_i b_i} Q a_i b_i \times T_w - \sum_{N a_i b_i} C \times W a_i b_i - ((250.000/(10 * 365)) * y_{P4Fnew})$$

Equation 12. Objective function PI for new pump P4F

Table 23.Optimal solution profitability indicator scenario 2

IPOPT Optimal solution					
P2 (Pa)	**P4 (Pa)**		**Product**	**Q (mol/s)**	**Q (Bls/d)**
1432700	1760300		RECYCLE	0.021	205.6472247
1513700	1812200		PV_5 INLET	11.181	109492.458
1063400	1755300		INJ_4	43.319	424211.0536
1063600	1812200			Bls/d (IDAES)	533909.1589
1069400	1749400				
1063300	2517500				
1073100	2958300				
1071000					
1068900			MX_3_2	13.14	128676.4063
1067528.571	1777880.00		INJ_2_1	23.36	228758.0556
154.87	257.93	Pd (psi)	INJ_2_2	24.321	238168.8643
152.6	255.9	ΔP (psi)		Bls/d (IDAES)	357434.4619
PV_5	36.40%				
CV pv_5	0.033817034	mols/s*psi			
SP fraction	0.7949	%			

7.2.2.3 Minimize power consumption

The optimal solution was determined using the solver Bonmin, and is shown in Table 24.

Table 24. Optimal solution power consumption scenario 2

ENERGY BONMIN Optimal solution					
P2 (Pa)	**P4 (Pa)**		**Product**	**Q (mol/s)**	**Q (Bls/d)**
1432700	1764700		RECYCLE	0.021	205.65
1514300	1843300		PV_5 INLET	9.963	97564.92
1097200	1759700		INJ_4	43.901	429910.42
1097200	1843300			Bls/d (IDAES)	527680.986
1106000	1749400				
1097400	2517500				
1105200	2958300				
1102000			**Product**	**Q (mol/s)**	**Q (Bls/d)**
1108800			MX_3_2	12.343	120871.60
1101971.429	1792080.00		INJ_2_1	21.884	214303.994
159.87	259.99	Pd (psi)	INJ_2_2	22.306	218436.523
157.6	258.0	ΔP (psi)		Bls/d (IDAES)	335175.60
PV_5	36.00%				
CV pv_5	0.033817034	mols/s*psi			
SP fraction	0.814	%			

7.2.3. Variation on pump performance curves, pressure and constraints

A new problem was proposed with new conditions of the system, to assess the adaptability of the problem optimization facing other conditions of the system that was not evaluated before. The new conditions are summarized in Table 25. The optimization problem is the same as it was proposed in Equations 6, 7 and 8.

Table 25. New conditions of the system proposed for scenario 3

P-4	Frecuency adj. Baseline(hz)	Discharge Pressure (Pa)	Pmin (Pa)	Pmax (Pa)	P-2	Frecuency adj. Baseline(hz)	Discharge Pressure (Pa)	Pmin (Pa)	Pmax (Pa)
A	59.00	1998928.57	1895536.00	1950679.00	A	55.4		1095964.0	1116643.0
B	58.90	1998928.57	1895536.00	1950679.00	B	57.5	1069771.429	1095964.0	1116643.0
C	58.70	1998928.57	1895536.00	1950679.00	C	56.4	1069771.429	1095964	1116642.999
D	58.90	1998928.57	1895536.00	1950679.00	D	56.5	1069771.4	1095964.0	1116643.0
E	58.70	1998928.57	1895536.00	1950679.00	E	56.1	1069771.4	1095964.0	1116643.0
F	57.90		1895536.00	1950679.00	F	56.5	1069771.429	1095964	1116643
					G	55.7	1069771.4	1095964.0	1116643.0
					H	57.4	1069771.4	1095964.0	1116643.0
					I	58.2	1069771.429	1095964	1116643

7.2.3.1 Minimize energy performance indicator (EnPI)

The optimal solution was found with the solver Bonmin and shown in Table 26.

Table 26. Optimal solution energy performance indicator scenario 3

BONMIN optimal solution					
P2 (Pa)	**P4 (Pa)**		**Product**	**Q (mol/s)**	**Q (Bls/d)**
1066800	1970800		RECYCLE	0	0.0
1054800	1974000		PV_5 INLET	10.918	106917.0
1080600	1980400		INJ_4	43.782	428745.1
1076800	1974000			Bls/d (IDAES)	535662.1
1075300	1980400				
1076800	2754800				
1070700					
1061300			**Product**	**Q (mol/s)**	**Q (Bls/d)**
1055600			MX_3_2	8.426	82513.5
1071014.286	1975920.00		INJ_2_1	29.874	292547.9
155.38	286.66	Pd (psi)	INJ_2_2	19.344	189430.5
152.4	284.7	ΔP (psi)		Bls/d (IDAES)	375061.4
PV_5	35.47%				
CV pv_5	0.031254572	mols/s*psi			
SP fraction	0.8				

7.2.3.2 Maximize profitability indicator (PI)

The optimal solution was found with the solver Bonmin and shown in Table 27.

Table 27. Optimal solution profitability indicator scenario 3

		BONMIN optimal solution			
P2 (Pa)	**P4 (Pa)**		**Product**	**Q (mol/s)**	**Q (Bls/d)**
1057400	1908200		RECYCLE	0	0.0
1054800	1899300		PV_5 INLET	11.303	110687.2
1402700	1894000		INJ_4	46.497	455332.3
1059400	1899300			Bls/d (IDAES)	566019.5
1055900	1894000				
1059400	2754800				
1052200					
1055300			**Product**	**Q (mol/s)**	**Q (Bls/d)**
1055600			MX_3_2	16.153	158181.9
1056250	1898960.00		INJ_2_1	19.047	186522.0
153.24	275.50	Pd (psi)	INJ_2_2	27.456	268869.1
150.9	273.5	ΔP (psi)		Bls/d (IDAES)	344703.9
PV_5	35.47%				
CV pv_5	0.031254572	mols/s*psi			
SP fraction	0.804				

7.2.3.3 Minimize power consumption

For this objective, was not possible to find an optimal solution, so it is declared as infeasible.

7.3 Optimization problem results on HYSYS

The output results derived from the results of the optimization problem were simulated on Aspen HYSYS.

7.3.1. Original system and discrete decision to overhaul one pump

Due to the similar results of scenario 1 and scenario 2, both scenarios were merged and is shown the best results of optimization. Table 28 describes the summary of results of each objective function. The objective function minimizes energy per barrel and maximizes profit and has the same results. On the other hand, if the objective aims to reduce power consumption, it will impact negatively on other indicators such as energy per barrel and profit. The results of the simulation are shown from Annex B to Annex E.

Table 28. Summary simulation optimization results HYSYS scenario 1 and 2

Scenario 1-2 - HYSYS								
		Objective	Energy_Barrel	Profit	Energy	Energy_Barrel	Profit	Energy
Parameter	Units	Baseline	Bonmin	Ipopt	Bonmin	%	%	%
Oil production	Bls/day	8997.84	9235.30	9235.31	8841.60	3%	3%	-2%
Water injection	Bls/day	872790.00	895824.00	895825.00	857635.00	3%	3%	-2%
Power consumption	Kw	2946.38	2975.24	2975.24	2948.77	1%	1%	0%
Power per water injection	Kw/Bl	44.33	43.61	43.61	45.15	-2%	-2%	2%
Revenue oil production	U$/day	512876.60	526412.04	526412.63	503971.08	3%	3%	-2%
Electric cost	U$/day	6128.71	6188.74	6188.74	6133.68	1%	1%	0%
Treatment cost	U$/day	3438.61	3529.36	3529.37	3378.91	3%	3%	-2%
Total profit	U$/day	503309.27	516693.94	516694.52	494458.50	3%	3%	-2%
Carbon Taxes	U$/day		6.46	6.46	0.53			

As is shown in Figure 15, the profits generated from objectives minimize energy per barrel and maximizes profit, increase the profits from USD 503K per day to USD 516K, decreasing the energy per barrel from 44,33 hp/mol to 43,61 hp/mol, is relevant to highlight that the power consumption will increase, however it is reflected in USD 6,46 in Carbon Taxes.

This calculation of Carbon Taxes is calculated based on the emission of 0.00023314 of Ton CO2 (eq) generated per Kwh from the grid (RenSMART, 2023) at a cost of USD 40 per Ton CO2 according to the Alberta Tier ETS (eq) (The World Bank, 2023).

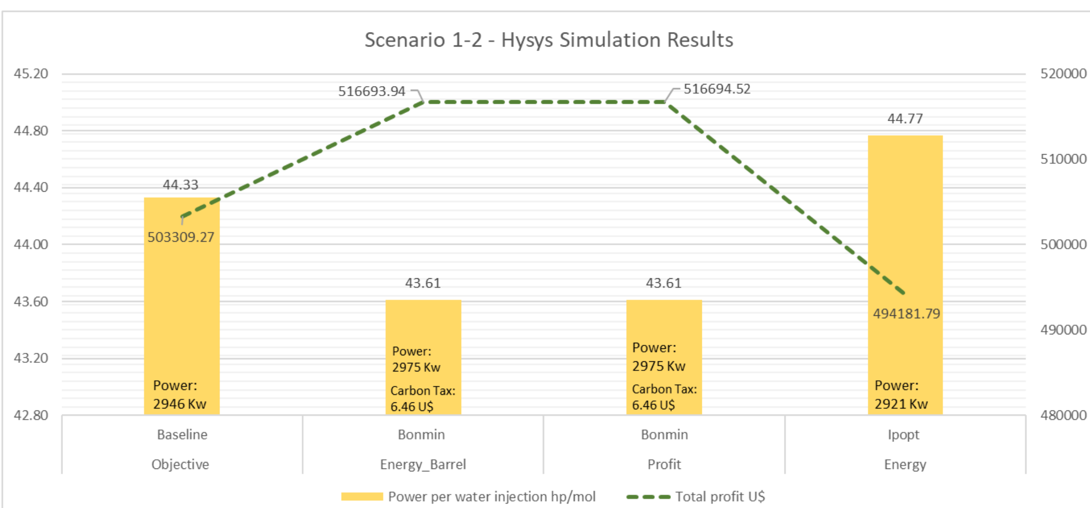

Figure 15. Optimization results HYSYS scenario 1 and 2

7.3.2. Variation on pump performance curves, pressure and constraints

Table 29 describes the summary of results of each objective function. The objective function minimizes energy per barrel and maximizes profit and has the same results. On the other hand, if the objective aims to reduce power consumption, it will impact negatively on other indicators such as energy per barrel and profit. The results of the simulation are shown from Annex F to Annex H.

Table 29. Summary simulation optimization results HYSYS scenario 3

Scenario 3 - HYSYS						
		Objective	Energy_Barrel	Profit	Energy_Barrel	Profit
Parameter	Units	Baseline	Bonmin	Bonmin	%	%
Oil production	Bls/day	8929.09	8967.56	9402.57	0%	5%
Water injection	Bls/day	866122.00	869853.00	912049.00	0%	5%
Power consumption	Kw	3213.46	3224.33	3277.82	0%	2%
Power per water injection	hp/mol	48.72	48.68	47.20	0%	-3%
Revenue oil production	U$/day	508958.29	511150.73	535946.32	0%	5%
Electric cost	U$/day	6684.25	6706.87	6818.13	0%	2%
Treatment cost	U$/day	3412.34	3427.04	3593.29	0%	5%
Total profit	U$/day	498861.69	501016.82	525534.90	0%	5%
Carbon Taxes	U$/day		2.43	14.41		

As is shown in Figure 16, the profits generated from objectives minimize energy per barrel and maximizes profit, increase the profits from USD 498K per day to USD 525K, decreasing the energy per barrel from 48,72 hp/mol to 47,20 hp/mol, is relevant to highlight that the power consumption will increase, however it is reflected in USD 14,41 in Carbon Taxes.

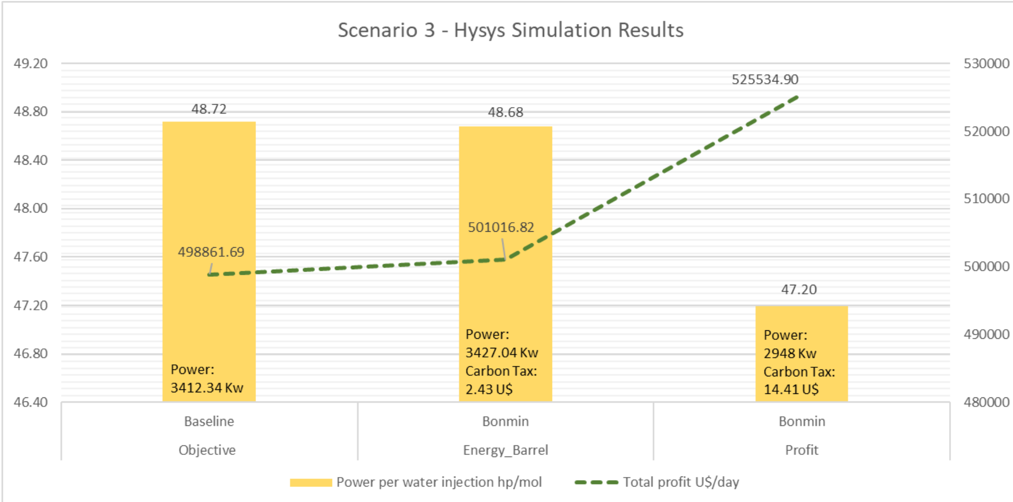

Figure 16.Optimization results HYSYS scenario 3

CHAPTER 8 ANALISIS AND CONCLUSIONS

An optimization problem is proposed in this study as a systematic approach for decision making to improve the energy performance indicator and profitability indicator for a pumping system in an oil & gas treatment facility. Several steps were necessary to correctly formulate the optimization problem. First, an exploratory data analysis was carried out in order to identify the variables with high and strong correlation to the energy performance of the system, and also to set the baseline values of the performance of the system that the optimization problem needs to improve.

Afterwards, a correction of the pump performance curve was applied to each operation unit to adjust the power performance to the flow that was delivered by each unit as a correct identification of the current performance of each unit pump. Subsequently, the system was modeled on Aspen Hysys to assess pressure drop in the system and to calculate the KPI that later will be assessed from the results provided from the solution of the optimization problem.

After that, the model was simulated on the equation-oriented platform IDAES, the inputs were provided from the correction of pump performance curve and Aspen Hysys simulation in order to obtain the initial conditions of the system. The optimization problem was formulated for each scenario, optimal solutions were found for each objective proposed showing that adjusting the variables in the system could reduce the EnPI by 2% to 4% and increase the PI by 2% to 5%.

Reducing non-linearities of the systems (as pipes), correct formulation of the optimization problem and constraints (avoiding poorly or over-specify constraints) and relaxing the constraints were essential to finding optimal solutions. At the end, the results provided from the optimization problem solved on IDAES were consistent with the results simulated on Aspen Hysys.

This systematic approach for decision-making should also be implemented on other high energy intensive systems such as heat exchangers, power plants, steam processes, gas compression systems and others that are part of the highest energy consumption of each treatment facility plant. Also, the versatile approach is required to be competitive to analyze, evaluate and optimize new energy generation in different areas such as generation or production, distribution, scheduling, and usage to be inexpensive regarding the traditional energy generation.

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ANNEX A DATA ANALISYS

Statistics description

	count	mean	std	min	25%	50%	75%	max
Total Flow transferred INJ_4 (mol/s)	9.0	4.413172e+01	0.085889	4.399021e+01	4.407619e+01	4.410989e+01	4.421711e+01	4.424754e+01
Total Flow transferred INJ_2 (mol/s)	9.0	4.497416e+01	0.287587	4.421078e+01	4.503588e+01	4.507264e+01	4.507428e+01	4.511594e+01
Total Flow PV_5 (mol/s)	9.0	9.678392e+00	0.044885	9.633224e+00	9.645526e+00	9.659265e+00	9.717450e+00	9.760907e+00
Total Flow P2 (mol/s)	9.0	3.529298e+01	0.304971	3.448410e+01	3.536820e+01	3.539132e+01	3.542046e+01	3.542921e+01
Total Flow P4 (mol/s)	9.0	5.381011e+01	0.081988	5.372882e+01	5.375111e+01	5.379364e+01	5.386264e+01	5.397422e+01
NPSHa P4 (Pa)	9.0	1.155437e+05	202.755290	1.152623e+05	1.153742e+05	1.155368e+05	1.157107e+05	1.157816e+05
NPSHa P2 (Pa)	9.0	1.177368e+05	400.671071	1.170058e+05	1.177047e+05	1.178193e+05	1.180200e+05	1.181242e+05
Discharge Pressure P4 (Pa)	9.0	1.812821e+06	2623.753025	1.806444e+06	1.812600e+06	1.813092e+06	1.813885e+06	1.815436e+06
Discharge Pressure P2 (Pa)	9.0	1.092517e+06	11028.735082	1.068393e+06	1.088592e+06	1.092984e+06	1.100463e+06	1.103611e+06
Hp P4A	9.0	5.657372e+02	0.668620	5.650916e+02	5.651967e+02	5.654531e+02	5.661068e+02	5.670086e+02
Hp P4B	9.0	5.619590e+02	1.090136	5.607071e+02	5.609780e+02	5.615986e+02	5.624516e+02	5.638019e+02
Hp P4C	9.0	5.608931e+02	0.746533	5.598725e+02	5.606965e+02	5.609474e+02	5.611288e+02	5.624484e+02
Hp P4D	9.0	5.616702e+02	0.757888	5.603735e+02	5.612592e+02	5.615282e+02	5.620257e+02	5.629471e+02
Hp P4E	9.0	5.506721e+02	0.662731	5.493550e+02	5.502456e+02	5.508912e+02	5.509115e+02	5.515448e+02
Hp P4F	9.0	0.000000e+00	0.000000	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00
Number of pumps P4	9.0	5.000000e+00	0.000000	5.000000e+00	5.000000e+00	5.000000e+00	5.000000e+00	5.000000e+00
EnB P4 (Hp/mol)	9.0	5.205229e+01	0.116115	5.188328e+01	5.197607e+01	5.209098e+01	5.214357e+01	5.220738e+01
Hp P2A	9.0	0.000000e+00	0.000000	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00
Hp P2B	9.0	1.721055e+01	51.631643	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	1.548949e+02
Hp P2C	9.0	1.550990e+02	0.749391	1.541309e+02	1.546670e+02	1.551678e+02	1.553857e+02	1.565552e+02
Hp P2D	9.0	1.555246e+02	0.899939	1.541533e+02	1.550923e+02	1.554482e+02	1.558549e+02	1.573890e+02
Hp P2E	9.0	1.543956e+02	0.889248	1.530444e+02	1.538020e+02	1.545057e+02	1.549172e+02	1.559980e+02
Hp P2F	9.0	1.551294e+02	0.879164	1.540934e+02	1.544220e+02	1.552011e+02	1.553379e+02	1.569643e+02
Hp P2G	9.0	1.486912e+02	0.857939	1.474947e+02	1.482525e+02	1.485614e+02	1.488743e+02	1.504556e+02
Hp P2H	9.0	1.400171e+02	52.513731	0.000000e+00	1.564389e+02	1.574033e+02	1.576131e+02	1.592397e+02
Hp P2I	9.0	1.638686e+02	0.868390	1.626870e+02	1.633710e+02	1.639549e+02	1.641205e+02	1.655814e+02
Number of pumps P2	9.0	7.000000e+00	0.000000	7.000000e+00	7.000000e+00	7.000000e+00	7.000000e+00	7.000000e+00
EnB P2 (Hp/mol)	9.0	3.088448e+01	0.309254	3.058397e+01	3.064489e+01	3.082672e+01	3.092048e+01	3.157888e+01

ANNEX B SCENARIO 1 AND 2 INITIAL CONDITIONS

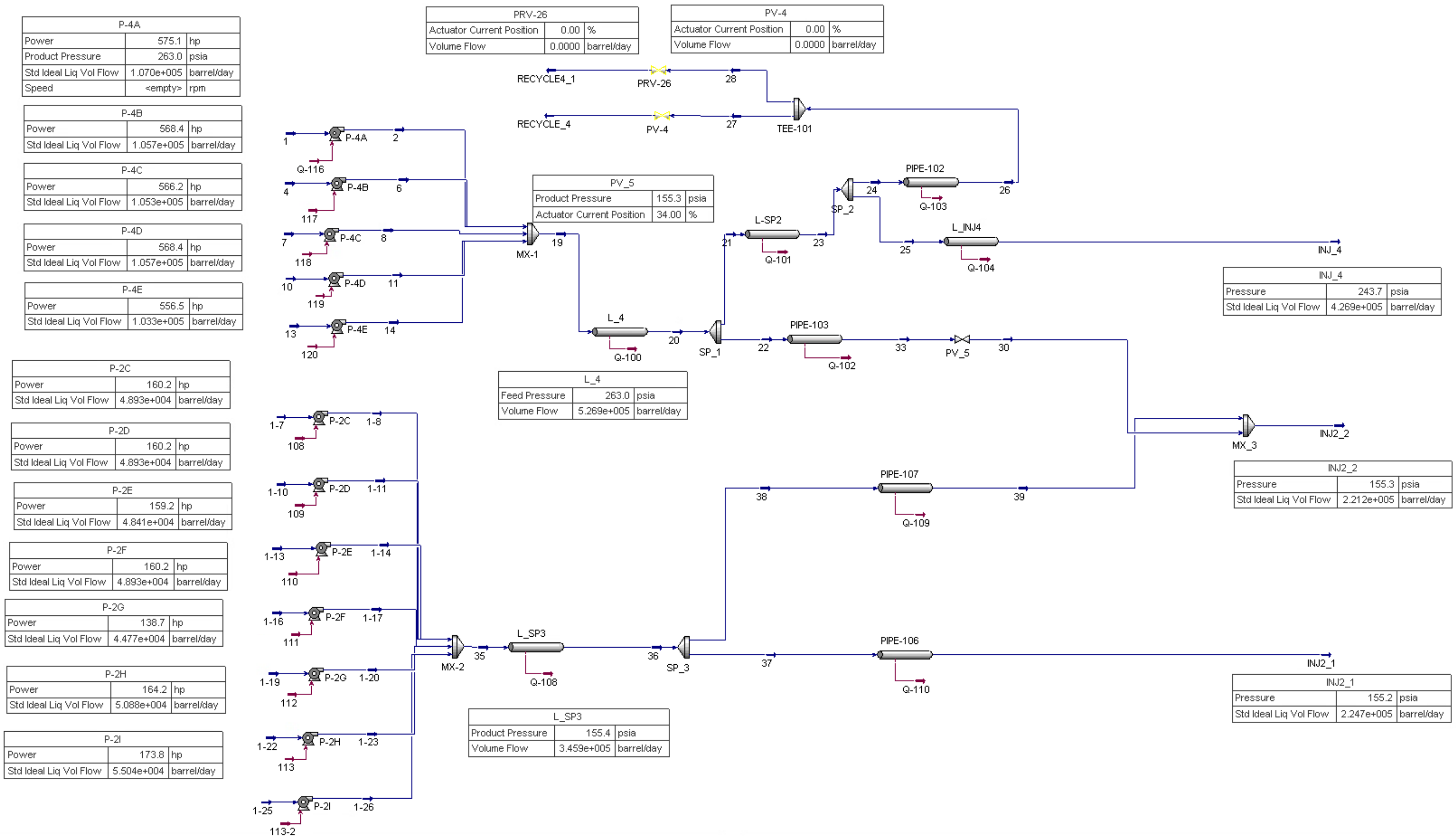
Material Stream

Material Streams													
		21	19	22	23	24	25	26	27	28	INJ_4	30	RECYCLE4_1
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.8	126.1
Pressure	psia	261.7	263.0	261.7	257.4	257.4	257.4	254.8	254.8	254.8	243.7	155.3	15.78
Molar Flow	lbmole/hr	3.454e+005	4.263e+005	8.092e+004	3.454e+005	0.0000	3.454e+005	0.0000	0.0000	0.0000	3.454e+005	8.092e+004	0.0000
Mass Flow	lb/hr	6.222e+006	7.680e+006	1.458e+006	6.222e+006	0.0000	6.222e+006	0.0000	0.0000	0.0000	6.222e+006	1.458e+006	0.0000
Liquid Volume Flow	barrel/day	4.269e+005	5.269e+005	1.000e+005	4.269e+005	0.0000	4.269e+005	0.0000	0.0000	0.0000	4.269e+005	1.000e+005	0.0000
Heat Flow	Btu/hr	-4.220e+010	-5.208e+010	-9.887e+009	-4.220e+010	0.0000	-4.220e+010	0.0000	0.0000	0.0000	-4.220e+010	-9.887e+009	0.0000
		RECYCLE_4	33	20	35	36	37	38	39	INJ2_2	INJ2_1	1	2
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	126.1	125.5	125.5	137.6	137.6	137.6	137.6	137.6	132.3	137.2	125.3	125.5
Pressure	psia	15.78	260.2	261.7	156.5	155.4	155.4	155.4	155.3	155.3	155.2	2.300	263.0
Molar Flow	lbmole/hr	0.0000	8.092e+004	4.263e+005	2.798e+005	2.798e+005	1.818e+005	9.806e+004	9.806e+004	1.790e+005	1.818e+005	8.656e+004	8.656e+004
Mass Flow	lb/hr	0.0000	1.458e+006	7.680e+006	5.041e+006	5.041e+006	3.275e+006	1.767e+006	1.767e+006	3.225e+006	3.275e+006	1.559e+006	1.559e+006
Liquid Volume Flow	barrel/day	0.0000	1.000e+005	5.269e+005	3.459e+005	3.459e+005	2.247e+005	1.212e+005	1.212e+005	2.212e+005	2.247e+005	1.070e+005	1.070e+005
Heat Flow	Btu/hr	0.0000	-9.887e+009	-5.208e+010	-3.412e+010	-3.412e+010	-2.217e+010	-1.196e+010	-1.196e+010	-2.185e+010	-2.217e+010	-1.058e+010	-1.058e+010
		4	6	10	11	1-7	1-8	1-13	1-14	1-19	1-20	1-10	1-11
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	125.3	125.5	125.3	125.5	137.5	137.6	137.5	137.6	137.5	137.6	137.5	137.6
Pressure	psia	2.300	263.0	2.300	263.0	2.700	156.5	2.700	156.5	2.700	156.5	2.700	156.5
Molar Flow	lbmole/hr	8.551e+004	8.551e+004	8.551e+004	8.551e+004	3.958e+004	3.958e+004	3.917e+004	3.917e+004	3.622e+004	3.622e+004	3.958e+004	3.958e+004
Mass Flow	lb/hr	1.540e+006	1.540e+006	1.540e+006	1.540e+006	7.131e+005	7.131e+005	7.056e+005	7.056e+005	6.526e+005	6.526e+005	7.131e+005	7.131e+005
Liquid Volume Flow	barrel/day	1.057e+005	1.057e+005	1.057e+005	1.057e+005	4.893e+004	4.893e+004	4.841e+004	4.841e+004	4.477e+004	4.477e+004	4.893e+004	4.893e+004
Heat Flow	Btu/hr	-1.045e+010	-1.045e+010	-1.045e+010	-1.045e+010	-4.828e+009	-4.827e+009	-4.777e+009	-4.776e+009	-4.418e+009	-4.417e+009	-4.828e+009	-4.827e+009
		1-16	1-17	1-22	1-23	1-25	1-26	13	14	7	8		
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
Temperature	F	137.5	137.6	137.5	137.6	137.5	137.6	125.3	125.5	125.3	125.5		
Pressure	psia	2.700	156.5	2.700	156.5	2.700	156.5	2.300	263.0	2.300	263.0		
Molar Flow	lbmole/hr	3.958e+004	3.958e+004	4.116e+004	4.116e+004	4.453e+004	4.453e+004	8.356e+004	8.356e+004	8.515e+004	8.515e+004		
Mass Flow	lb/hr	7.131e+005	7.131e+005	7.415e+005	7.415e+005	8.022e+005	8.022e+005	1.505e+006	1.505e+006	1.534e+006	1.534e+006		
Liquid Volume Flow	barrel/day	4.893e+004	4.893e+004	5.088e+004	5.088e+004	5.504e+004	5.504e+004	1.033e+005	1.033e+005	1.053e+005	1.053e+005		
Heat Flow	Btu/hr	-4.828e+009	-4.827e+009	-5.020e+009	-5.019e+009	-5.431e+009	-5.430e+009	-1.021e+010	-1.021e+010	-1.040e+010	-1.040e+010		

Pump, Valves and Products

Power consumption				
Object	Variable	Value	Units	Tag
P-2C	Power	160.2	hp	No Tag
P-2D	Power	160.2	hp	No Tag
P-2E	Power	159.2	hp	No Tag
P-2F	Power	160.2	hp	No Tag
P-2G	Power	138.7	hp	No Tag
P-2H	Power	164.2	hp	No Tag
P-2I	Power	173.8	hp	No Tag
P-4A	Power	575.1	hp	No Tag
P-4B	Power	568.4	hp	No Tag
P-4C	Power	566.2	hp	No Tag
P-4D	Power	568.4	hp	No Tag
P-4E	Power	556.5	hp	No Tag
INJ_4	Pressure	243.7	psia	No Tag
INJ_4	Std Ideal Liq Vol Flow	4.269e+005	barrel/day	No Tag
INJ2_2	Pressure	155.3	psia	No Tag
INJ2_2	Std Ideal Liq Vol Flow	2.212e+005	barrel/day	No Tag
INJ2_1	Pressure	155.2	psia	No Tag
INJ2_1	Std Ideal Liq Vol Flow	2.247e+005	barrel/day	No Tag
PV_5	Pressure Drop	104.8	psi	No Tag
PV_5	Actuator Current Position	34.00	%	No Tag
PV-4	Actuator Current Position	0.0000	%	No Tag
RECYCLE_4	Std Ideal Liq Vol Flow	0.0000	barrel/day	No Tag
PV_5	Resistance (Cv or K)	3081	USGPM(60F,1psi)	No Tag

Flowsheet on Aspen HYSYS



ANNEX C SCENARIO 1 AND 2 OPTMIZED ENERGY PER BARREL AND PROFIT

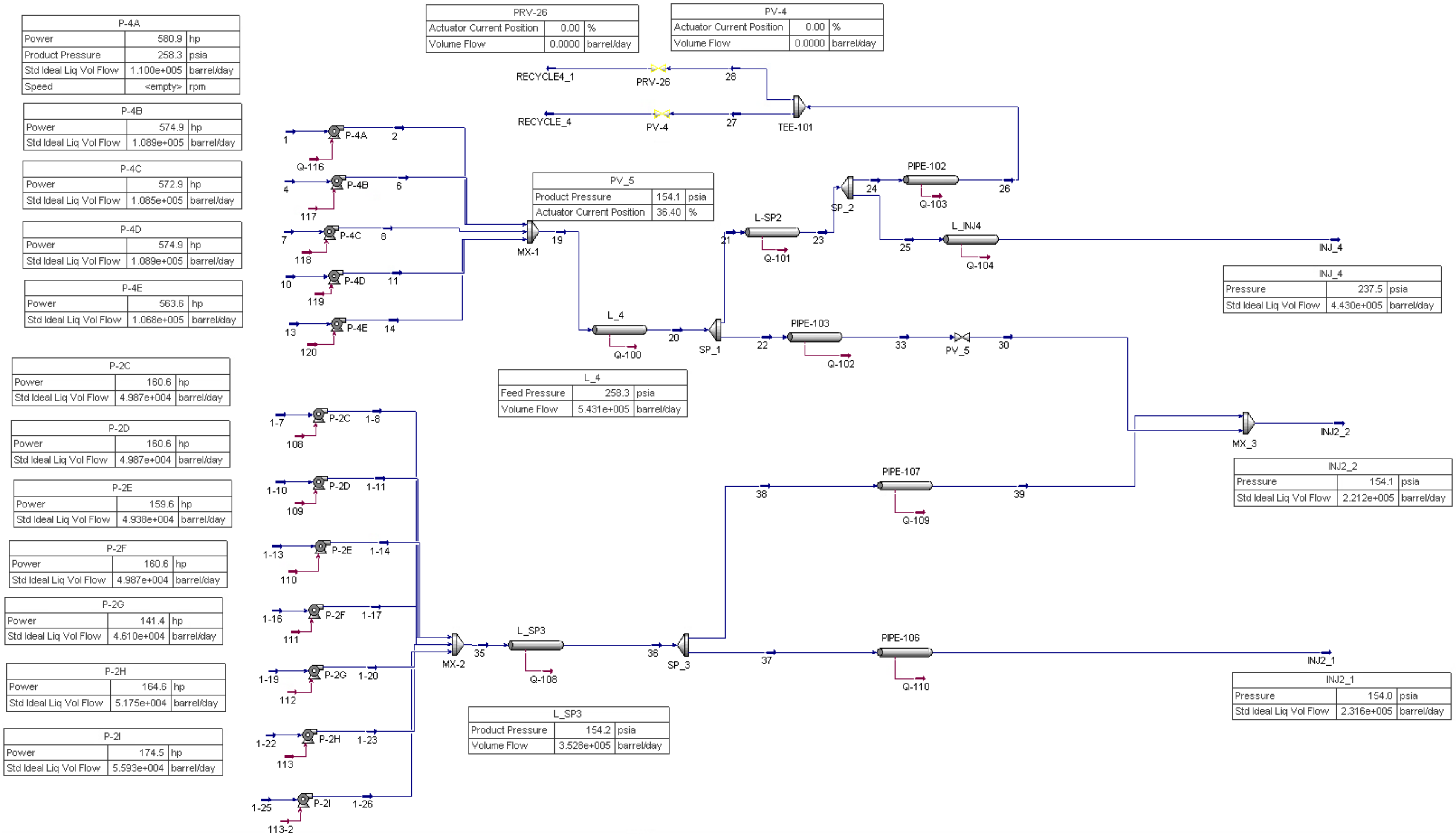
Material Stream

Material Streams													
		21	19	22	23	24	25	26	27	28	INJ_4	30	RECYCLE4_1
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.7	126.1
Pressure	psia	257.0	258.3	257.0	252.3	252.3	252.3	249.7	249.7	249.7	237.5	154.1	10.67
Molar Flow	lbmole/hr	3.584e+005	4.394e+005	8.092e+004	3.584e+005	0.0000	3.584e+005	0.0000	0.0000	0.0000	3.584e+005	8.092e+004	0.0000
Mass Flow	lb/hr	6.457e+006	7.915e+006	1.458e+006	6.457e+006	0.0000	6.457e+006	0.0000	0.0000	0.0000	6.457e+006	1.458e+006	0.0000
Liquid Volume Flow	barrel/day	4.430e+005	5.431e+005	1.000e+005	4.430e+005	0.0000	4.430e+005	0.0000	0.0000	0.0000	4.430e+005	1.000e+005	0.0000
Heat Flow	Btu/hr	-4.379e+010	-5.368e+010	-9.887e+009	-4.379e+010	-0.0000	-4.379e+010	-0.0000	-0.0000	-0.0000	-4.379e+010	-9.887e+009	-0.0000
		RECYCLE_4	33	20	35	36	37	38	39	INJ2_2	INJ2_1	1	2
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	126.1	125.5	125.5	137.6	137.6	137.6	137.6	137.6	132.2	137.2	125.3	125.5
Pressure	psia	10.67	255.4	257.0	155.3	154.2	154.2	154.2	154.1	154.1	154.0	2.300	258.3
Molar Flow	lbmole/hr	0.0000	8.092e+004	4.394e+005	2.854e+005	2.854e+005	1.873e+005	9.806e+004	9.806e+004	1.790e+005	1.873e+005	8.896e+004	8.896e+004
Mass Flow	lb/hr	0.0000	1.458e+006	7.915e+006	5.142e+006	5.142e+006	3.375e+006	1.767e+006	1.767e+006	3.225e+006	3.375e+006	1.603e+006	1.603e+006
Liquid Volume Flow	barrel/day	0.0000	1.000e+005	5.431e+005	3.528e+005	3.528e+005	2.316e+005	1.212e+005	1.212e+005	2.212e+005	2.316e+005	1.100e+005	1.100e+005
Heat Flow	Btu/hr	-0.0000	-9.887e+009	-5.368e+010	-3.480e+010	-3.480e+010	-2.285e+010	-1.196e+010	-1.196e+010	-2.185e+010	-2.285e+010	-1.087e+010	-1.087e+010
		4	6	10	11	1-7	1-8	1-13	1-14	1-19	1-20	1-10	1-11
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	125.3	125.5	125.3	125.5	137.5	137.6	137.5	137.6	137.5	137.6	137.5	137.6
Pressure	psia	2.300	258.3	2.300	258.3	2.700	155.3	2.700	155.3	2.700	155.3	2.700	155.3
Molar Flow	lbmole/hr	8.810e+004	8.810e+004	8.810e+004	8.810e+004	4.035e+004	4.035e+004	3.995e+004	3.995e+004	3.730e+004	3.730e+004	4.035e+004	4.035e+004
Mass Flow	lb/hr	1.587e+006	1.587e+006	1.587e+006	1.587e+006	7.268e+005	7.268e+005	7.197e+005	7.197e+005	6.719e+005	6.719e+005	7.268e+005	7.268e+005
Liquid Volume Flow	barrel/day	1.089e+005	1.089e+005	1.089e+005	1.089e+005	4.987e+004	4.987e+004	4.938e+004	4.938e+004	4.610e+004	4.610e+004	4.987e+004	4.987e+004
Heat Flow	Btu/hr	-1.076e+010	-1.076e+010	-1.076e+010	-1.076e+010	-4.920e+009	-4.920e+009	-4.872e+009	-4.872e+009	-4.549e+009	-4.548e+009	-4.920e+009	-4.920e+009
		1-16	1-17	1-22	1-23	1-25	1-26	13	14	7	8		
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
Temperature	F	137.5	137.6	137.5	137.6	137.5	137.6	125.3	125.5	125.3	125.5		
Pressure	psia	2.700	155.3	2.700	155.3	2.700	155.3	2.300	258.3	2.300	258.3		
Molar Flow	lbmole/hr	4.035e+004	4.035e+004	4.187e+004	4.187e+004	4.525e+004	4.525e+004	8.641e+004	8.641e+004	8.780e+004	8.780e+004		
Mass Flow	lb/hr	7.268e+005	7.268e+005	7.543e+005	7.543e+005	8.152e+005	8.152e+005	1.557e+006	1.557e+006	1.582e+006	1.582e+006		
Liquid Volume Flow	barrel/day	4.987e+004	4.987e+004	5.175e+004	5.175e+004	5.593e+004	5.593e+004	1.068e+005	1.068e+005	1.085e+005	1.085e+005		
Heat Flow	Btu/hr	-4.920e+009	-4.920e+009	-5.106e+009	-5.106e+009	-5.518e+009	-5.518e+009	-1.056e+010	-1.056e+010	-1.073e+010	-1.073e+010		

Pump, Valves and Products

Power consumption				
Object	Variable	Value	Units	Tag
P-2C	Power	160.6	hp	No Tag
P-2D	Power	160.6	hp	No Tag
P-2E	Power	159.6	hp	No Tag
P-2F	Power	160.6	hp	No Tag
P-2G	Power	141.4	hp	No Tag
P-2H	Power	164.6	hp	No Tag
P-2I	Power	174.5	hp	No Tag
P-4A	Power	580.9	hp	No Tag
P-4B	Power	574.9	hp	No Tag
P-4C	Power	572.9	hp	No Tag
P-4D	Power	574.9	hp	No Tag
P-4E	Power	563.6	hp	No Tag
INJ_4	Pressure	237.5	psia	No Tag
INJ_4	Std Ideal Liq Vol Flow	4.430e+005	barrel/day	No Tag
INJ2_2	Pressure	154.1	psia	No Tag
INJ2_2	Std Ideal Liq Vol Flow	2.212e+005	barrel/day	No Tag
INJ2_1	Pressure	154.0	psia	No Tag
INJ2_1	Std Ideal Liq Vol Flow	2.316e+005	barrel/day	No Tag
PV_5	Pressure Drop	101.3	psi	No Tag
PV_5	Actuator Current Position	36.40	%	No Tag
PV-4	Actuator Current Position	0.0000	%	No Tag
RECYCLE_4	Std Ideal Liq Vol Flow	0.0000	barrel/day	No Tag
PV_5	Resistance (Cv or K)	2732	USGPM(60F,1psi)	No Tag

Flowsheet on Aspen HYSYS



ANNEX D SCENARIO 1 OPTMIZED ENERGY

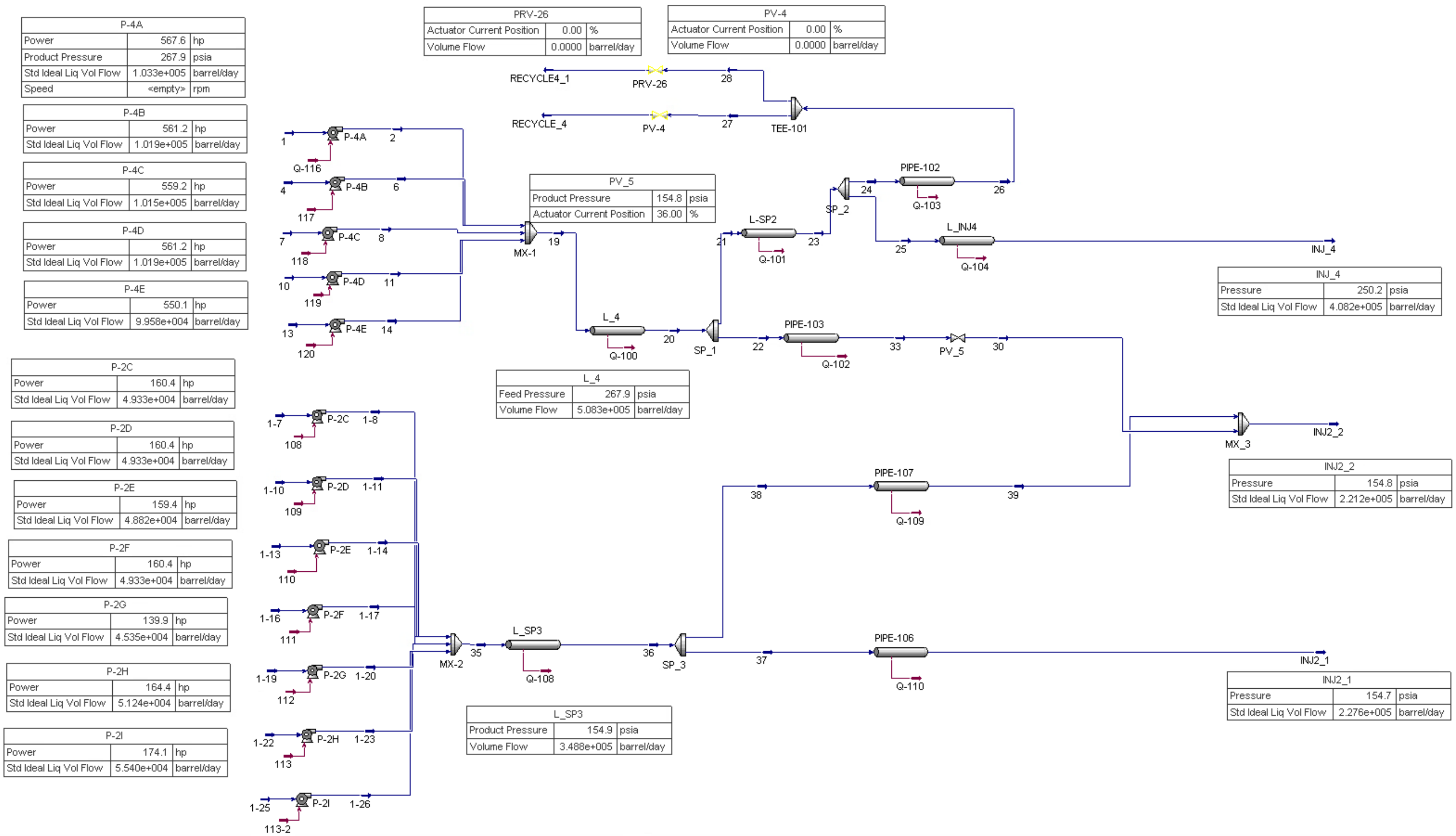
Material Stream

Material Streams													
		21	19	22	23	24	25	26	27	28	INJ_4	30	RECYCLE4_1
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.8	126.2
Pressure	psia	266.7	267.9	266.7	262.8	262.8	262.8	260.1	260.1	260.1	250.2	154.8	21.14
Molar Flow	lbmole/hr	3.303e+005	4.112e+005	8.092e+004	3.303e+005	0.0000	3.303e+005	0.0000	0.0000	0.0000	3.303e+005	8.092e+004	0.0000
Mass Flow	lb/hr	5.950e+006	7.408e+006	1.458e+006	5.950e+006	0.0000	5.950e+006	0.0000	0.0000	0.0000	5.950e+006	1.458e+006	0.0000
Liquid Volume Flow	barrel/day	4.082e+005	5.083e+005	1.000e+005	4.082e+005	0.0000	4.082e+005	0.0000	0.0000	0.0000	4.082e+005	1.000e+005	0.0000
Heat Flow	Btu/hr	-4.035e+010	-5.024e+010	-9.887e+009	-4.035e+010	-0.0000	-4.035e+010	-0.0000	-0.0000	-0.0000	-4.035e+010	-9.887e+009	-0.0000
		RECYCLE_4	33	20	35	36	37	38	39	INJ2_2	INJ2_1	1	2
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	126.2	125.5	125.5	137.6	137.6	137.6	137.6	137.6	132.3	137.2	125.3	125.5
Pressure	psia	21.14	265.1	266.7	156.0	154.9	154.9	154.9	154.8	154.8	154.7	2.300	267.9
Molar Flow	lbmole/hr	0.0000	8.092e+004	4.112e+005	2.822e+005	2.822e+005	1.841e+005	9.806e+004	9.806e+004	1.790e+005	1.841e+005	8.356e+004	8.356e+004
Mass Flow	lb/hr	0.0000	1.458e+006	7.408e+006	5.084e+006	5.084e+006	3.317e+006	1.767e+006	1.767e+006	3.225e+006	3.317e+006	1.505e+006	1.505e+006
Liquid Volume Flow	barrel/day	0.0000	1.000e+005	5.083e+005	3.488e+005	3.488e+005	2.276e+005	1.212e+005	1.212e+005	2.212e+005	2.276e+005	1.033e+005	1.033e+005
Heat Flow	Btu/hr	-0.0000	-9.887e+009	-5.024e+010	-3.441e+010	-3.441e+010	-2.245e+010	-1.196e+010	-1.196e+010	-2.185e+010	-2.245e+010	-1.021e+010	-1.021e+010
		4	6	10	11	1-7	1-8	1-13	1-14	1-19	1-20	1-10	1-11
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	125.3	125.5	125.3	125.5	137.5	137.6	137.5	137.6	137.5	137.6	137.5	137.6
Pressure	psia	2.300	267.9	2.300	267.9	2.700	156.0	2.700	156.0	2.700	156.0	2.700	156.0
Molar Flow	lbmole/hr	8.248e+004	8.248e+004	8.248e+004	8.248e+004	3.991e+004	3.991e+004	3.950e+004	3.950e+004	3.669e+004	3.669e+004	3.991e+004	3.991e+004
Mass Flow	lb/hr	1.486e+006	1.486e+006	1.486e+006	1.486e+006	7.189e+005	7.189e+005	7.116e+005	7.116e+005	6.609e+005	6.609e+005	7.189e+005	7.189e+005
Liquid Volume Flow	barrel/day	1.019e+005	1.019e+005	1.019e+005	1.019e+005	4.933e+004	4.933e+004	4.882e+004	4.882e+004	4.535e+004	4.535e+004	4.933e+004	4.933e+004
Heat Flow	Btu/hr	-1.008e+010	-1.008e+010	-1.008e+010	-1.008e+010	-4.867e+009	-4.866e+009	-4.817e+009	-4.817e+009	-4.474e+009	-4.474e+009	-4.867e+009	-4.866e+009
		1-16	1-17	1-22	1-23	1-25	1-26	13	14	7	8		
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
Temperature	F	137.5	137.6	137.5	137.6	137.5	137.6	125.3	125.5	125.3	125.5		
Pressure	psia	2.700	156.0	2.700	156.0	2.700	156.0	2.300	267.9	2.300	267.9		
Molar Flow	lbmole/hr	3.991e+004	3.991e+004	4.146e+004	4.146e+004	4.482e+004	4.482e+004	8.057e+004	8.057e+004	8.212e+004	8.212e+004		
Mass Flow	lb/hr	7.189e+005	7.189e+005	7.469e+005	7.469e+005	8.075e+005	8.075e+005	1.451e+006	1.451e+006	1.479e+006	1.479e+006		
Liquid Volume Flow	barrel/day	4.933e+004	4.933e+004	5.124e+004	5.124e+004	5.540e+004	5.540e+004	9.958e+004	9.958e+004	1.015e+005	1.015e+005		
Heat Flow	Btu/hr	-4.867e+009	-4.866e+009	-5.056e+009	-5.056e+009	-5.467e+009	-5.466e+009	-9.845e+009	-9.843e+009	-1.003e+010	-1.003e+010		

Pump, Valves and Products

Power consumption				
Object	Variable	Value	Units	Tag
P-2C	Power	160.4	hp	No Tag
P-2D	Power	160.4	hp	No Tag
P-2E	Power	159.4	hp	No Tag
P-2F	Power	160.4	hp	No Tag
P-2G	Power	139.9	hp	No Tag
P-2H	Power	164.4	hp	No Tag
P-2I	Power	174.1	hp	No Tag
P-4A	Power	567.6	hp	No Tag
P-4B	Power	561.2	hp	No Tag
P-4C	Power	559.2	hp	No Tag
P-4D	Power	561.2	hp	No Tag
P-4E	Power	550.1	hp	No Tag
INJ_4	Pressure	250.2	psia	No Tag
INJ_4	Std Ideal Liq Vol Flow	4.082e+005	barrel/day	No Tag
INJ2_2	Pressure	154.8	psia	No Tag
INJ2_2	Std Ideal Liq Vol Flow	2.212e+005	barrel/day	No Tag
INJ2_1	Pressure	154.7	psia	No Tag
INJ2_1	Std Ideal Liq Vol Flow	2.276e+005	barrel/day	No Tag
PV_5	Pressure Drop	110.4	psi	No Tag
PV_5	Actuator Current Position	36.00	%	No Tag
PV-4	Actuator Current Position	0.0000	%	No Tag
RECYCLE_4	Std Ideal Liq Vol Flow	0.0000	barrel/day	No Tag
PV_5	Resistance (Cv or K)	2675	USGPM(60F,1psi)	No Tag

Flowsheet on Aspen HYSYS



ANNEX E SCENARIO 2 OPTMIZED ENERGY

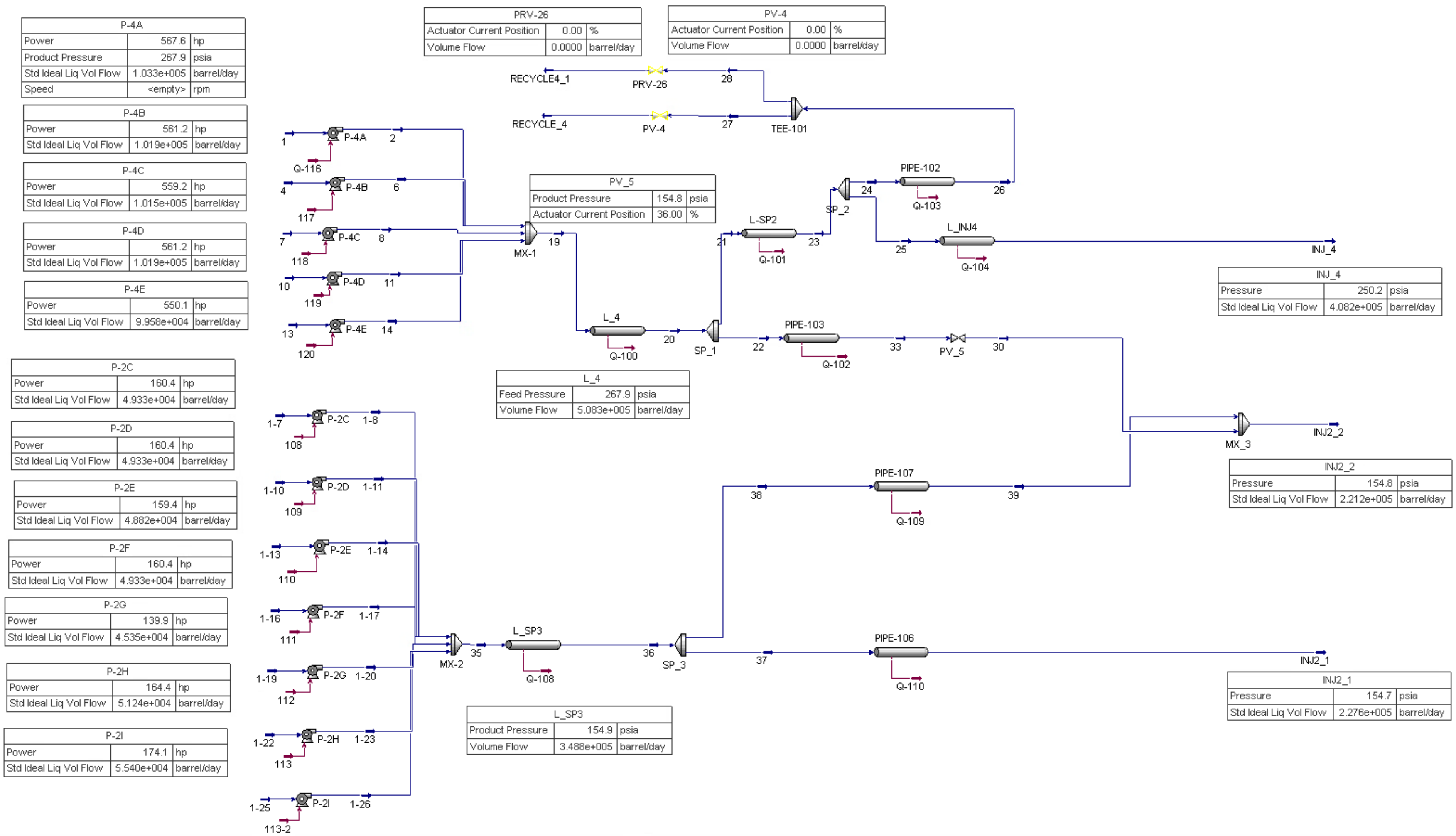
Material Stream

Material Streams													
		21	19	22	23	24	25	26	27	28	INJ_4	30	RECYCLE4_1
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.5	125.8	126.2
Pressure	psia	266.7	267.9	266.7	262.8	262.8	262.8	260.1	260.1	260.1	250.2	154.8	21.14
Molar Flow	lbmole/hr	3.303e+005	4.112e+005	8.092e+004	3.303e+005	0.0000	3.303e+005	0.0000	0.0000	0.0000	3.303e+005	8.092e+004	0.0000
Mass Flow	lb/hr	5.950e+006	7.408e+006	1.458e+006	5.950e+006	0.0000	5.950e+006	0.0000	0.0000	0.0000	5.950e+006	1.458e+006	0.0000
Liquid Volume Flow	barrel/day	4.082e+005	5.083e+005	1.000e+005	4.082e+005	0.0000	4.082e+005	0.0000	0.0000	0.0000	4.082e+005	1.000e+005	0.0000
Heat Flow	Btu/hr	-4.035e+010	-5.024e+010	-9.887e+009	-4.035e+010	-0.0000	-4.035e+010	-0.0000	-0.0000	-0.0000	-4.035e+010	-9.887e+009	-0.0000
		RECYCLE_4	33	20	35	36	37	38	39	INJ2_2	INJ2_1	1	2
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	126.2	125.5	125.5	137.6	137.6	137.6	137.6	137.6	132.3	137.2	125.3	125.5
Pressure	psia	21.14	265.1	266.7	156.0	154.9	154.9	154.9	154.8	154.8	154.7	2.300	267.9
Molar Flow	lbmole/hr	0.0000	8.092e+004	4.112e+005	2.822e+005	2.822e+005	1.841e+005	9.806e+004	9.806e+004	1.790e+005	1.841e+005	8.356e+004	8.356e+004
Mass Flow	lb/hr	0.0000	1.458e+006	7.408e+006	5.084e+006	5.084e+006	3.317e+006	1.767e+006	1.767e+006	3.225e+006	3.317e+006	1.505e+006	1.505e+006
Liquid Volume Flow	barrel/day	0.0000	1.000e+005	5.083e+005	3.488e+005	3.488e+005	2.276e+005	1.212e+005	1.212e+005	2.212e+005	2.276e+005	1.033e+005	1.033e+005
Heat Flow	Btu/hr	-0.0000	-9.887e+009	-5.024e+010	-3.441e+010	-3.441e+010	-2.245e+010	-1.196e+010	-1.196e+010	-2.185e+010	-2.245e+010	-1.021e+010	-1.021e+010
		4	6	10	11	1-7	1-8	1-13	1-14	1-19	1-20	1-10	1-11
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	125.3	125.5	125.3	125.5	137.5	137.6	137.5	137.6	137.5	137.6	137.5	137.6
Pressure	psia	2.300	267.9	2.300	267.9	2.700	156.0	2.700	156.0	2.700	156.0	2.700	156.0
Molar Flow	lbmole/hr	8.248e+004	8.248e+004	8.248e+004	8.248e+004	3.991e+004	3.991e+004	3.950e+004	3.950e+004	3.669e+004	3.669e+004	3.991e+004	3.991e+004
Mass Flow	lb/hr	1.486e+006	1.486e+006	1.486e+006	1.486e+006	7.189e+005	7.189e+005	7.116e+005	7.116e+005	6.609e+005	6.609e+005	7.189e+005	7.189e+005
Liquid Volume Flow	barrel/day	1.019e+005	1.019e+005	1.019e+005	1.019e+005	4.933e+004	4.933e+004	4.882e+004	4.882e+004	4.535e+004	4.535e+004	4.933e+004	4.933e+004
Heat Flow	Btu/hr	-1.008e+010	-1.008e+010	-1.008e+010	-1.008e+010	-4.867e+009	-4.866e+009	-4.817e+009	-4.817e+009	-4.474e+009	-4.474e+009	-4.867e+009	-4.866e+009
		1-16	1-17	1-22	1-23	1-25	1-26	13	14	7	8		
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
Temperature	F	137.5	137.6	137.5	137.6	137.5	137.6	125.3	125.5	125.3	125.5		
Pressure	psia	2.700	156.0	2.700	156.0	2.700	156.0	2.300	267.9	2.300	267.9		
Molar Flow	lbmole/hr	3.991e+004	3.991e+004	4.146e+004	4.146e+004	4.482e+004	4.482e+004	8.057e+004	8.057e+004	8.212e+004	8.212e+004		
Mass Flow	lb/hr	7.189e+005	7.189e+005	7.469e+005	7.469e+005	8.075e+005	8.075e+005	1.451e+006	1.451e+006	1.479e+006	1.479e+006		
Liquid Volume Flow	barrel/day	4.933e+004	4.933e+004	5.124e+004	5.124e+004	5.540e+004	5.540e+004	9.958e+004	9.958e+004	1.015e+005	1.015e+005		
Heat Flow	Btu/hr	-4.867e+009	-4.866e+009	-5.056e+009	-5.056e+009	-5.467e+009	-5.466e+009	-9.845e+009	-9.843e+009	-1.003e+010	-1.003e+010		

Pump, Valves and Products

Power consumption				
Object	Variable	Value	Units	Tag
P-2C	Power	160.4	hp	No Tag
P-2D	Power	160.4	hp	No Tag
P-2E	Power	159.4	hp	No Tag
P-2F	Power	160.4	hp	No Tag
P-2G	Power	139.9	hp	No Tag
P-2H	Power	164.4	hp	No Tag
P-2I	Power	174.1	hp	No Tag
P-4A	Power	567.6	hp	No Tag
P-4B	Power	561.2	hp	No Tag
P-4C	Power	559.2	hp	No Tag
P-4D	Power	561.2	hp	No Tag
P-4E	Power	550.1	hp	No Tag
INJ_4	Pressure	250.2	psia	No Tag
INJ_4	Std Ideal Liq Vol Flow	4.082e+005	barrel/day	No Tag
INJ2_2	Pressure	154.8	psia	No Tag
INJ2_2	Std Ideal Liq Vol Flow	2.212e+005	barrel/day	No Tag
INJ2_1	Pressure	154.7	psia	No Tag
INJ2_1	Std Ideal Liq Vol Flow	2.276e+005	barrel/day	No Tag
PV_5	Pressure Drop	110.4	psi	No Tag
PV_5	Actuator Current Position	36.00	%	No Tag
PV-4	Actuator Current Position	0.0000	%	No Tag
RECYCLE_4	Std Ideal Liq Vol Flow	0.0000	barrel/day	No Tag
PV_5	Resistance (Cv or K)	2675	USGPM(60F,1psi)	No Tag

Flowsheet on Aspen HYSY



ANNEX F SCENARIO 3 INITIAL CONDITIONS

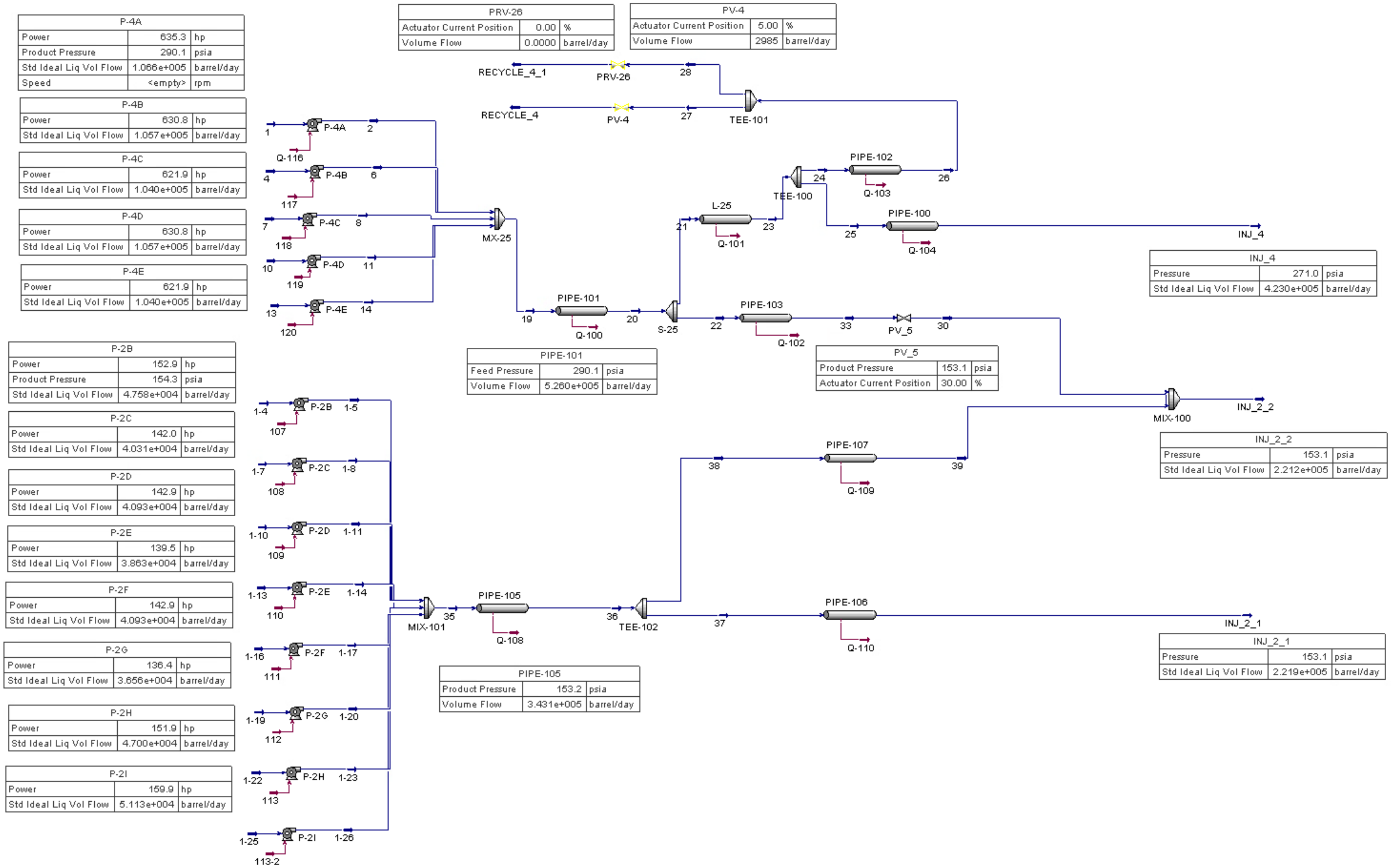
Material Stream

Material Streams													
		21	19	22	23	24	25	26	27	28	INJ_4	30	RECYCLE_4_1
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	130.9	130.9	130.9	130.9	130.9	130.9	130.9	130.9	130.9	130.9	131.3	131.6
Pressure	psia	288.8	290.1	288.8	284.5	284.5	284.5	281.9	281.9	281.9	271.0	153.1	25.50
Molar Flow	lbmole/hr	3.447e+005	4.256e+005	8.092e+004	3.447e+005	2415	3.422e+005	2415	2415	0.0000	3.422e+005	8.092e+004	0.0000
Mass Flow	lb/hr	6.209e+006	7.667e+006	1.458e+006	6.209e+006	4.351e+004	6.165e+006	4.351e+004	4.351e+004	0.0000	6.165e+006	1.458e+006	0.0000
Liquid Volume Flow	barrel/day	4.260e+005	5.260e+005	1.000e+005	4.260e+005	2985	4.230e+005	2985	2985	0.0000	4.230e+005	1.000e+005	0.0000
Heat Flow	Btu/hr	-4.207e+010	-5.195e+010	-9.878e+009	-4.207e+010	-2.948e+008	-4.178e+010	-2.948e+008	-2.948e+008	0.0000	-4.178e+010	-9.878e+009	0.0000
		RECYCLE_4	33	20	35	36	37	38	39	INJ_2_2	INJ_2_1	1	2
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	131.6	130.9	130.9	107.1	107.1	107.1	107.1	107.1	118.0	106.7	130.7	130.9
Pressure	psia	16.60	287.3	288.8	154.3	153.2	153.2	153.2	153.1	153.1	153.1	3.000	290.1
Molar Flow	lbmole/hr	2415	8.092e+004	4.256e+005	2.776e+005	2.776e+005	1.795e+005	9.806e+004	9.806e+004	1.790e+005	1.795e+005	8.625e+004	8.625e+004
Mass Flow	lb/hr	4.351e+004	1.458e+006	7.667e+006	5.000e+006	5.000e+006	3.234e+006	1.767e+006	1.767e+006	3.225e+006	3.234e+006	1.554e+006	1.554e+006
Liquid Volume Flow	barrel/day	2985	1.000e+005	5.260e+005	3.431e+005	3.431e+005	2.219e+005	1.212e+005	1.212e+005	2.212e+005	2.219e+005	1.066e+005	1.066e+005
Heat Flow	Btu/hr	-2.948e+008	-9.878e+009	-5.195e+010	-3.401e+010	-3.401e+010	-2.199e+010	-1.202e+010	-1.202e+010	-2.189e+010	-2.200e+010	-1.053e+010	-1.053e+010
		4	6	10	11	1-7	1-8	1-13	1-14	1-19	1-20	1-10	1-11
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	130.7	130.9	130.7	130.9	107.0	107.2	107.0	107.2	107.0	107.2	107.0	107.1
Pressure	psia	3.000	290.1	3.000	290.1	3.000	154.3	3.000	154.3	3.000	154.3	3.000	154.3
Molar Flow	lbmole/hr	8.554e+004	8.554e+004	8.554e+004	8.554e+004	3.262e+004	3.262e+004	3.126e+004	3.126e+004	2.958e+004	2.958e+004	3.311e+004	3.311e+004
Mass Flow	lb/hr	1.541e+006	1.541e+006	1.541e+006	1.541e+006	5.876e+005	5.876e+005	5.631e+005	5.631e+005	5.329e+005	5.329e+005	5.965e+005	5.965e+005
Liquid Volume Flow	barrel/day	1.057e+005	1.057e+005	1.057e+005	1.057e+005	4.031e+004	4.031e+004	3.863e+004	3.863e+004	3.656e+004	3.656e+004	4.093e+004	4.093e+004
Heat Flow	Btu/hr	-1.044e+010	-1.044e+010	-1.044e+010	-1.044e+010	-3.997e+009	-3.996e+009	-3.830e+009	-3.830e+009	-3.625e+009	-3.625e+009	-4.057e+009	-4.057e+009
		1-16	1-17	1-4	1-5	1-22	1-23	1-25	1-26	13	14	7	8
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	107.0	107.1	107.0	107.1	107.0	107.1	107.0	107.1	130.7	130.9	130.7	130.9
Pressure	psia	3.000	154.3	3.000	154.3	3.000	154.3	3.000	154.3	3.000	290.1	3.000	290.1
Molar Flow	lbmole/hr	3.311e+004	3.311e+004	3.850e+004	3.850e+004	3.803e+004	3.803e+004	4.137e+004	4.137e+004	8.412e+004	8.412e+004	8.412e+004	8.412e+004
Mass Flow	lb/hr	5.965e+005	5.965e+005	6.935e+005	6.935e+005	6.851e+005	6.851e+005	7.453e+005	7.453e+005	1.516e+006	1.516e+006	1.516e+006	1.516e+006
Liquid Volume Flow	barrel/day	4.093e+004	4.093e+004	4.758e+004	4.758e+004	4.700e+004	4.700e+004	5.113e+004	5.113e+004	1.040e+005	1.040e+005	1.040e+005	1.040e+005
Heat Flow	Btu/hr	-4.057e+009	-4.057e+009	-4.717e+009	-4.717e+009	-4.660e+009	-4.660e+009	-5.069e+009	-5.069e+009	-1.027e+010	-1.027e+010	-1.027e+010	-1.027e+010

Pump, Valves and Products

Power consumption				
Object	Variable	Value	Units	Tag
P-2B	Power	152.9	hp	No Tag
P-2C	Power	142.0	hp	No Tag
P-2D	Power	142.9	hp	No Tag
P-2E	Power	139.5	hp	No Tag
P-2F	Power	142.9	hp	No Tag
P-2G	Power	136.4	hp	No Tag
P-2H	Power	151.9	hp	No Tag
P-2I	Power	159.9	hp	No Tag
P-4A	Power	635.3	hp	No Tag
P-4B	Power	630.8	hp	No Tag
P-4C	Power	621.9	hp	No Tag
P-4D	Power	630.8	hp	No Tag
P-4E	Power	621.9	hp	No Tag
INJ_4	Pressure	271.0	psia	No Tag
INJ_4	Std Ideal Liq Vol Flow	4.230e+005	barrel/day	No Tag
INJ_2_2	Pressure	153.1	psia	No Tag
INJ_2_2	Std Ideal Liq Vol Flow	2.212e+005	barrel/day	No Tag
INJ_2_1	Pressure	153.1	psia	No Tag
INJ_2_1	Std Ideal Liq Vol Flow	2.219e+005	barrel/day	No Tag
RECYCLE_4	Std Ideal Liq Vol Flow	2985	barrel/day	No Tag
PV-4	Actuator Current Position	5.000	%	No Tag
PV_5	Actuator Current Position	30.00	%	No Tag
PV_5	Pressure Drop	134.1	psi	No Tag
PV_5	Resistance (Cv or K)	3673	USGPM(60F,1psi)	No Tag

Flowsheet on Aspen HYSYS



ANNEX G SCENARIO 3 OPTIMIZED ENERGY PER BARREL

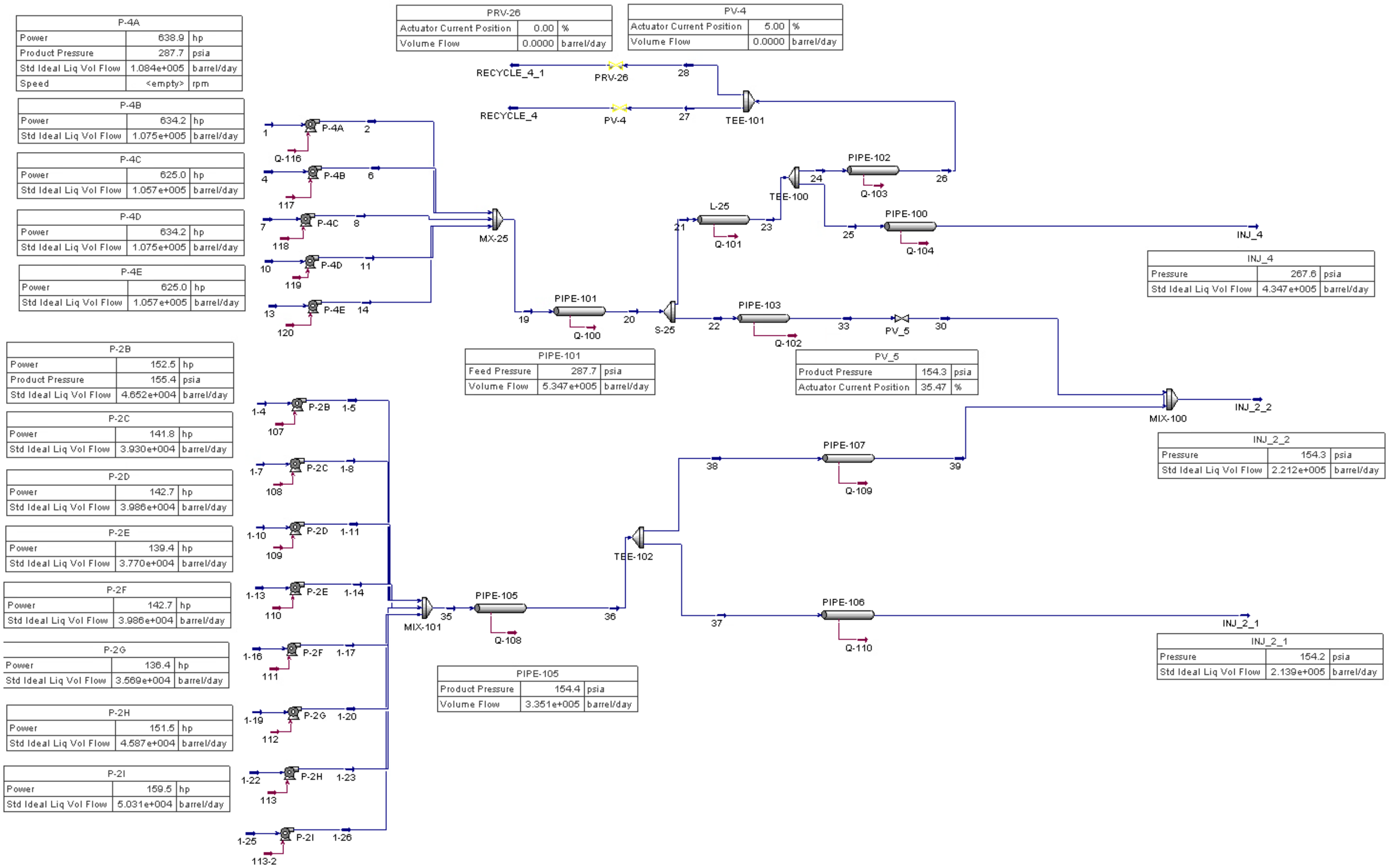
Material Stream

Material Streams													
		21	19	22	23	24	25	26	27	28	INJ_4	30	RECYCLE_4_1
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	130.9	130.9	130.9	130.9	130.9	130.9	130.9	130.9	130.9	130.9	131.3	131.6
Pressure	psia	286.4	287.7	286.4	281.9	281.9	281.9	279.3	279.3	279.3	267.6	154.3	22.88
Molar Flow	lbmole/hr	3.517e+005	4.326e+005	8.092e+004	3.517e+005	0.0000	3.517e+005	0.0000	0.0000	0.0000	3.517e+005	8.092e+004	0.0000
Mass Flow	lb/hr	6.336e+006	7.794e+006	1.458e+006	6.336e+006	0.0000	6.336e+006	0.0000	0.0000	0.0000	6.336e+006	1.458e+006	0.0000
Liquid Volume Flow	barrel/day	4.347e+005	5.347e+005	1.000e+005	4.347e+005	0.0000	4.347e+005	0.0000	0.0000	0.0000	4.347e+005	1.000e+005	0.0000
Heat Flow	Btu/hr	-4.293e+010	-5.281e+010	-9.878e+009	-4.293e+010	-0.0000	-4.293e+010	-0.0000	-0.0000	-0.0000	-4.293e+010	-9.878e+009	-0.0000
		RECYCLE_4	33	20	35	36	37	38	39	INJ_2_2	INJ_2_1	1	2
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	131.6	130.9	130.9	107.1	107.1	107.1	107.1	107.1	118.0	106.7	130.7	130.9
Pressure	psia	13.98	284.8	286.4	155.4	154.4	154.4	154.4	154.3	154.3	154.2	3.000	287.7
Molar Flow	lbmole/hr	0.0000	8.092e+004	4.326e+005	2.711e+005	2.711e+005	1.730e+005	9.806e+004	9.806e+004	1.790e+005	1.730e+005	8.768e+004	8.768e+004
Mass Flow	lb/hr	0.0000	1.458e+006	7.794e+006	4.884e+006	4.884e+006	3.118e+006	1.767e+006	1.767e+006	3.225e+006	3.118e+006	1.580e+006	1.580e+006
Liquid Volume Flow	barrel/day	0.0000	1.000e+005	5.347e+005	3.351e+005	3.351e+005	2.139e+005	1.212e+005	1.212e+005	2.212e+005	2.139e+005	1.084e+005	1.084e+005
Heat Flow	Btu/hr	-0.0000	-9.878e+009	-5.281e+010	-3.322e+010	-3.322e+010	-2.120e+010	-1.202e+010	-1.202e+010	-2.189e+010	-2.120e+010	-1.071e+010	-1.070e+010
		4	6	10	11	1-7	1-8	1-13	1-14	1-19	1-20	1-10	1-11
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	130.7	130.9	130.7	130.9	107.0	107.2	107.0	107.2	107.0	107.2	107.0	107.2
Pressure	psia	3.000	287.7	3.000	287.7	3.000	155.4	3.000	155.4	3.000	155.4	3.000	155.4
Molar Flow	lbmole/hr	8.696e+004	8.696e+004	8.696e+004	8.696e+004	3.179e+004	3.179e+004	3.050e+004	3.050e+004	2.888e+004	2.888e+004	3.225e+004	3.225e+004
Mass Flow	lb/hr	1.567e+006	1.567e+006	1.567e+006	1.567e+006	5.728e+005	5.728e+005	5.495e+005	5.495e+005	5.202e+005	5.202e+005	5.809e+005	5.809e+005
Liquid Volume Flow	barrel/day	1.075e+005	1.075e+005	1.075e+005	1.075e+005	3.930e+004	3.930e+004	3.770e+004	3.770e+004	3.569e+004	3.569e+004	3.986e+004	3.986e+004
Heat Flow	Btu/hr	-1.062e+010	-1.061e+010	-1.062e+010	-1.061e+010	-3.896e+009	-3.896e+009	-3.738e+009	-3.737e+009	-3.539e+009	-3.538e+009	-3.952e+009	-3.951e+009
		1-16	1-17	1-4	1-5	1-22	1-23	1-25	1-26	13	14	7	8
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	107.0	107.2	107.0	107.1	107.0	107.1	107.0	107.1	130.7	130.9	130.7	130.9
Pressure	psia	3.000	155.4	3.000	155.4	3.000	155.4	3.000	155.4	3.000	287.7	3.000	287.7
Molar Flow	lbmole/hr	3.225e+004	3.225e+004	3.764e+004	3.764e+004	3.711e+004	3.711e+004	4.070e+004	4.070e+004	8.552e+004	8.552e+004	8.552e+004	8.552e+004
Mass Flow	lb/hr	5.809e+005	5.809e+005	6.780e+005	6.780e+005	6.686e+005	6.686e+005	7.332e+005	7.332e+005	1.541e+006	1.541e+006	1.541e+006	1.541e+006
Liquid Volume Flow	barrel/day	3.986e+004	3.986e+004	4.652e+004	4.652e+004	4.587e+004	4.587e+004	5.031e+004	5.031e+004	1.057e+005	1.057e+005	1.057e+005	1.057e+005
Heat Flow	Btu/hr	-3.952e+009	-3.951e+009	-4.612e+009	-4.611e+009	-4.548e+009	-4.547e+009	-4.987e+009	-4.987e+009	-1.044e+010	-1.044e+010	-1.044e+010	-1.044e+010

Pump, Valves and Products

Power consumption				
Object	Variable	Value	Units	Tag
P-2B	Power	152.5	hp	No Tag
P-2C	Power	141.8	hp	No Tag
P-2D	Power	142.7	hp	No Tag
P-2E	Power	139.4	hp	No Tag
P-2F	Power	142.7	hp	No Tag
P-2G	Power	136.4	hp	No Tag
P-2H	Power	151.5	hp	No Tag
P-2I	Power	159.5	hp	No Tag
P-4A	Power	638.9	hp	No Tag
P-4B	Power	634.2	hp	No Tag
P-4C	Power	625.0	hp	No Tag
P-4D	Power	634.2	hp	No Tag
P-4E	Power	625.0	hp	No Tag
INJ_4	Pressure	267.6	psia	No Tag
INJ_4	Std Ideal Liq Vol Flow	4.347e+005	barrel/day	No Tag
INJ_2_2	Pressure	154.3	psia	No Tag
INJ_2_2	Std Ideal Liq Vol Flow	2.212e+005	barrel/day	No Tag
INJ_2_1	Pressure	154.2	psia	No Tag
INJ_2_1	Std Ideal Liq Vol Flow	2.139e+005	barrel/day	No Tag
RECYCLE_4	Std Ideal Liq Vol Flow	0.0000	barrel/day	No Tag
PV-4	Actuator Current Position	5.000	%	No Tag
PV_5	Actuator Current Position	35.47	%	No Tag
PV_5	Pressure Drop	130.5	psi	No Tag
PV_5	Resistance (Cv or K)	2532	USGPM(60F,1psi)	No Tag

Flowsheet on Aspen HYSYS



ANNEX H SCENARIO 3 OPTIMIZED PROFIT

Material Stream

Material Streams													
		21	19	22	23	24	25	26	27	28	INJ_4	30	RECYCLE_4_1
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	130.9	130.9	130.9	130.9	130.9	130.9	130.9	130.9	130.9	130.9	131.2	131.6
Pressure	psia	275.0	276.5	275.0	269.7	269.7	269.7	267.1	267.1	267.1	252.9	155.8	10.70
Molar Flow	lbmole/hr	3.813e+005	4.622e+005	8.092e+004	3.813e+005	0.0000	3.813e+005	0.0000	0.0000	0.0000	3.813e+005	8.092e+004	0.0000
Mass Flow	lb/hr	6.869e+006	8.327e+006	1.458e+006	6.869e+006	0.0000	6.869e+006	0.0000	0.0000	0.0000	6.869e+006	1.458e+006	0.0000
Liquid Volume Flow	barrel/day	4.713e+005	5.713e+005	1.000e+005	4.713e+005	0.0000	4.713e+005	0.0000	0.0000	0.0000	4.713e+005	1.000e+005	0.0000
Heat Flow	Btu/hr	-4.655e+010	-5.642e+010	-9.878e+009	-4.655e+010	-0.0000	-4.655e+010	-0.0000	-0.0000	-0.0000	-4.655e+010	-9.878e+009	-0.0000
		RECYCLE_4	33	20	35	36	37	38	39	INJ_2_2	INJ_2_1	1	2
Vapour Fraction		0.0092	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	122.7	130.9	130.9	107.1	107.1	107.1	107.1	107.1	118.0	106.7	130.7	130.9
Pressure	psia	1.804	273.4	275.0	153.9	152.9	152.9	152.9	152.8	152.8	152.7	3.000	276.5
Molar Flow	lbmole/hr	0.0000	8.092e+004	4.622e+005	2.756e+005	2.756e+005	1.776e+005	9.806e+004	9.806e+004	1.790e+005	1.776e+005	9.330e+004	9.330e+004
Mass Flow	lb/hr	0.0000	1.458e+006	8.327e+006	4.966e+006	4.966e+006	3.199e+006	1.767e+006	1.767e+006	3.225e+006	3.199e+006	1.681e+006	1.681e+006
Liquid Volume Flow	barrel/day	0.0000	1.000e+005	5.713e+005	3.407e+005	3.407e+005	2.195e+005	1.212e+005	1.212e+005	2.212e+005	2.195e+005	1.153e+005	1.153e+005
Heat Flow	Btu/hr	-0.0000	-9.878e+009	-5.642e+010	-3.378e+010	-3.378e+010	-2.176e+010	-1.202e+010	-1.202e+010	-2.189e+010	-2.176e+010	-1.139e+010	-1.139e+010
		4	6	10	11	1-7	1-8	1-13	1-14	1-19	1-20	1-10	1-11
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	130.7	130.9	130.7	130.9	107.0	107.2	107.0	107.2	107.0	107.2	107.0	107.1
Pressure	psia	3.000	276.5	3.000	276.5	3.000	153.9	3.000	153.9	3.000	153.9	3.000	153.9
Molar Flow	lbmole/hr	9.278e+004	9.278e+004	9.278e+004	9.278e+004	2.863e+004	2.863e+004	3.154e+004	3.154e+004	2.984e+004	2.984e+004	3.345e+004	3.345e+004
Mass Flow	lb/hr	1.671e+006	1.671e+006	1.671e+006	1.671e+006	5.158e+005	5.158e+005	5.682e+005	5.682e+005	5.376e+005	5.376e+005	6.026e+005	6.026e+005
Liquid Volume Flow	barrel/day	1.147e+005	1.147e+005	1.147e+005	1.147e+005	3.539e+004	3.539e+004	3.898e+004	3.898e+004	3.689e+004	3.689e+004	4.135e+004	4.135e+004
Heat Flow	Btu/hr	-1.133e+010	-1.133e+010	-1.133e+010	-1.133e+010	-3.509e+009	-3.508e+009	-3.865e+009	-3.864e+009	-3.657e+009	-3.657e+009	-4.099e+009	-4.099e+009
		1-16	1-17	1-4	1-5	1-22	1-23	1-25	1-26	13	14	7	8
Vapour Fraction		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Temperature	F	107.0	107.1	107.0	107.1	107.0	107.1	107.0	107.1	130.7	130.9	130.7	130.9
Pressure	psia	3.000	153.9	3.000	153.9	3.000	153.9	3.000	153.9	3.000	276.5	3.000	276.5
Molar Flow	lbmole/hr	3.345e+004	3.345e+004	3.879e+004	3.879e+004	3.833e+004	3.833e+004	4.161e+004	4.161e+004	9.169e+004	9.169e+004	9.169e+004	9.169e+004
Mass Flow	lb/hr	6.026e+005	6.026e+005	6.988e+005	6.988e+005	6.906e+005	6.906e+005	7.496e+005	7.496e+005	1.652e+006	1.652e+006	1.652e+006	1.652e+006
Liquid Volume Flow	barrel/day	4.135e+004	4.135e+004	4.794e+004	4.794e+004	4.738e+004	4.738e+004	5.143e+004	5.143e+004	1.133e+005	1.133e+005	1.133e+005	1.133e+005
Heat Flow	Btu/hr	-4.099e+009	-4.099e+009	-4.753e+009	-4.753e+009	-4.697e+009	-4.697e+009	-5.099e+009	-5.098e+009	-1.119e+010	-1.119e+010	-1.119e+010	-1.119e+010

Pump, Valves and Products

Power consumption				
Object	Variable	Value	Units	Tag
P-2B	Power	153.1	hp	No Tag
P-2a	Power	134.2	hp	No Tag
P-2D	Power	143.1	hp	No Tag
P-2E	Power	139.6	hp	No Tag
P-2F	Power	143.1	hp	No Tag
P-2G	Power	136.4	hp	No Tag
P-2H	Power	152.1	hp	No Tag
P-2I	Power	160.0	hp	No Tag
P-4A	Power	653.3	hp	No Tag
P-4B	Power	649.3	hp	No Tag
P-4C	Power	641.1	hp	No Tag
P-4D	Power	649.3	hp	No Tag
P-4E	Power	641.1	hp	No Tag
INJ_4	Pressure	252.9	psia	No Tag
INJ_4	Std Ideal Liq Vol Flow	4.713e+005	barrel/day	No Tag
INJ_2_2	Pressure	152.8	psia	No Tag
INJ_2_2	Std Ideal Liq Vol Flow	2.212e+005	barrel/day	No Tag
INJ_2_1	Pressure	152.7	psia	No Tag
INJ_2_1	Std Ideal Liq Vol Flow	2.195e+005	barrel/day	No Tag
RECYCLE_4	Std Ideal Liq Vol Flow	0.0000	barrel/day	No Tag
PV-4	Actuator Current Position	5.000	%	No Tag
PV_5	Actuator Current Position	36.40	%	No Tag
PV_5	Pressure Drop	117.7	psi	No Tag
PV_5	Resistance (Cv or K)	2538	USGPM(60F,1psi)	No Tag

Flowsheet on Aspen HYSYS