EPHYRA

Establishing European Production of Hydrogen from RenewAble energy and integration into an industrial environment

D2.2 Report on the internal use of electrolysis generated oxygen within MOH Refinery

WP2 – Industrial symbiosis: heat recovery, waste energy, O_2, water (sea water, wastewater)

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BACKGROUND AND DISCLAIMER

Project Background

EPHYRA project with the full title: "Establishing European Production of Hydrogen from RenewAble energy and integration into an industrial environment" was submitted in the call HORIZON-JTI-CLEANH2-2022-2, under the topic HORIZON-JTI-CLEANH2-2022-01-08 "Integration of multi-MW electrolysers in industrial applications". The project receives support by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research through the Grant Agreement No. 101112220.

Objective of Deliverable

The key objective of the Deliverable 2.2, titled *Report on the internal use of electrolysis generated oxygen within MOH Refinery,* is to develop and evaluate concepts for the utilization of co-produced oxygen from the Electrolyser within the Refinery. This deliverable includes a cost-benefit analysis of two selected oxygen enrichment applications in the Refinery units, identifying potential technical challenges and assessing their feasibility.

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Executive Summary

Deliverable D2.2 "*Report on the internal use of electrolysis generated oxygen within MOH Refinery*" is part of the Work Package 2 "*Industrial symbiosis: heat recovery, waste energy, O_2, water (sea water, wastewater)"* of the EPHYRA project and is the output of Task 2.2 "*Concept development for internal use of generated Oxygen from electrolyser*". The aim of the Deliverable is to develop concepts for internal use of generated Oxygen from Electrolyser.

Within the MOH Refinery, potential applications of the generated oxygen have been investigated. Two principal solutions have been identified and evaluated through a cost-benefit analysis: oxygen enrichment in the Claus Sulphur Recovery unit and the Fluid Catalytic Cracking (FCC) unit. Between these two options, the use of oxygen in the Claus unit emerged as the preferred solution as MOH Refinery has already implemented oxygen enrichment in its Claus unit using liquid oxygen supplied from third parties, and subsequent basic engineering for this application is ongoing. For the oxygen enrichment in the FCC unit, a desktop study is conducted within Task 2.2 to elucidate the potential benefits and challenges associated with this solution. The detailed examination aims to optimize the Refinery's operations by leveraging internally generated oxygen, thus reducing reliance on external suppliers and enhancing overall efficiency.

The MOH Refinery has already optimized its Claus unit with oxygen enrichment sourced from external suppliers. Consequently, the main benefit identified is the replacement of purchased oxygen with that produced by the Electrolyser, thereby eliminating third-party procurement costs. The costs associated with this solution, totaling approximately 2,116 k€, include the oxygen recovery system in the Electrolyser (including O_2 pipelines) and the purification unit. The cost-benefit analysis for oxygen enrichment in the Claus unit showed an annual saving stream ranging from 472 k€ to 3,845 k€ for the low and high rate scenario, respectively. Over a 20-year project lifespan, an exceptionally attractive benefit-cost ratio of 1.9 for the low rate and 15.5 for the high rate has been projected. In addition, the co-produced oxygen offers a cost-competitive advantage for the Electrolyser project, potentially reducing the Levelized Cost of Hydrogen (LCOH) up to approximately 0.94 €/kg (high-rate scenario) and increasing its IRR up to 12 percentage points (high-rate scenario).

Oxygen enrichment in Fluid Catalytic Cracking (FCC) units offers significant benefits for refinery operations, including improved efficiency, increased throughput, and enhanced product yields. This approach, which involves increasing oxygen concentration in the regenerator's air feed, enables more effective coke combustion, better catalyst regeneration, and compliance with environmental regulations. The study assessed these benefits through an in-depth cost-benefit analysis and scenarios related to oxygen supply from electrolysers, such as the EPHYRA project (30 MW), as well as the potential expansion of its capacity from 30 MW to 50 MW. Key Results in the case of directing the full supply of O_2 to the FCC unit:

- **Feed Rate Increase**: The most favorable scenario (50 MW electrolyser at full capacity, Case50c) demonstrated a feed rate increase of 6.66%, yielding a Net Present Value (NPV) of €75.43 million, a Benefit-Cost Ratio (BCR) of 1.147, and an Internal Rate of Return (IRR) of 213%.
- **Conversion Efficiency**: When optimizing conversion rates, the best case (50 MW electrolyser at full capacity, Case50c) achieved a gross conversion increase to 75.94%, with an NPV of €17.11 million, a BCR of 5.293, and an IRR of 57%.
- **Environmental and Economic Benefits**: O_2 enrichment reduces CO and NO_x emissions while enabling the FCC unit to process heavier feedstocks, aligning with environmental and operational goals.

Additionally, the utilization of "free" O_2 from electrolysers enhances economic feasibility and supports future refinery expansions, including sustainable aviation fuel production. While thermal management and equipment upgrades pose challenges, targeted solutions and advanced safety protocols ensure smooth integration of oxygen enrichment systems. These results underline oxygen enrichment as a highly promising strategy to enhance refinery operations, ensuring economic and environmental advantages while preparing refineries for future demands.

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ABBREVIATIONS

Abbreviation	Explanation
BCR	Benefit/Cost ratio
CBA	Cost-Benefit Analysis
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortization
FCC	Fluid Catalytic Cracking
HCO	Heavy Cycle Oil
IRR	Internal Rate of Return
LCO	Light Cycle Oil
LCOH	Levelized Cost of Hydrogen
MPC	Model Predictive Control
NPV	Net Present Value
ROI	Return Of Investment
tpa	tons per annum
tph	tons per hour
WACC	Weighted Average Cost of Capital

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1. Introduction

Deliverable D2.2 "*Report on the internal use of electrolysis generated oxygen within MOH Refinery*" is part of the Work Package 2 "*Industrial symbiosis: heat recovery, waste energy, O_2, water (sea water, wastewater)"* of the EPHYRA project and is the output of Task 2.2 "*Concept development for internal use of generated Oxygen from E*lectrolyser. The aim of the Deliverable D2.2 is to develop concepts for internal use of generated Oxygen from Electrolyser within the Refinery processes.

The 30 MW electrolysis system of the EPHYRA project will produce approximately 36,000 tpa of O_2 at full load. Typically, this oxygen is considered a waste stream and is vented into the atmosphere. However, under the concept of industrial symbiosis and circular economy, this by-product oxygen can be utilized in several processes within the Refinery, yielding benefits for both the units that utilize the oxygen and the Electrolyser project itself.

Within the MOH Refinery, potential applications of the generated oxygen have been investigated. Two principal solutions have been identified and evaluated through a cost-benefit analysis: oxygen enrichment in the Claus Sulphur Recovery unit and the Fluid Catalytic Cracking (FCC) unit. Between these two options, the use of oxygen in the Claus unit emerged as the preferred solution, and subsequent basic engineering is ongoing. For the application in the FCC unit, a desktop study accompanied by a preliminary cost benefit analysis is conducted within Task 2.2 to elucidate the potential benefits and challenges associated with this solution.

2. Supply of Oxygen via EPHYRA project

The Electrolysis unit produces 8 kg of oxygen for every 1 kg of hydrogen as oxygen is a by-product of the water electrolysis process. The produced oxygen is usually treated as waste stream and is vented to the atmosphere. However, in the framework of EPHYRA project potential internal uses of the waste oxygen are investigated and evaluated.

The 30 MW electrolysis system of the EPHYRA project can produce approximately **36,000** tonnes per annum of oxygen (O_2) at full operational capacity. The Electrolysis system will be designed with scalability to be able to be expanded to 50 MW capacity. With this future potential, oxygen production could increase to approximately 60,000 tonnes per annum. Full or partial recovery and utilization of the produced oxygen are being considered and assessed in the next Sections.

3. Potential uses of generated Oxygen within MOH Refinery

Within the industrial asset of the MOH refinery there are several potential users of the produced oxygen. This presents the opportunity to recover and re-use the by-product oxygen within the industrial site and this way improve the overall economics of the unit and further enhance the electrolytic hydrogen competitiveness quite significantly.

The key potential internal users comprise of:

- The Claus process of the Sulphur Recovery Units, where oxygen enrichment is used to expand and debottleneck the capacity of the unit, which is currently limiting the Refinery in some modes of operation.
- The regeneration reactor of the FCC process. The additional oxygen increases the coke-burning capacity of the regenerator and provides various benefits including capacity debottlenecking, cycle length, operability and yield advantages.
- The Hydrogen Production unit furnace (steam methane reforming units) to increase the concentration of the CO_2 off-gas and enhance the future Carbon Capture unit.

Furthermore, oxygen can also be considered for recovery and storage for external commercial applications i.e. hospitals, pharmaceutical industry etc. In other industrial sites oxygen can be used in a gasification process or in oxy-fuel combustion processes.

The most tangible and immediate opportunity for MOH refinery is the valorisation of oxygen in the Claus Sulphur Recovery unit (Section 4.1). The demand pressure for oxygen is low, hence the oxygen produced at higher pressure by the electrolyser unit is at sufficient pressure avoiding the need for an expensive compression system. The oxygen produced from the 30 MW electrolyser exceeds the oxygen demand of the Claus unit.

Additionally, the O_2 enrichment in the FCC unit is considered as an attractive solution of oxygen valorization, however, it entails certain challenges in the implementation. Within EPHYRA project, a desktop study accompanied by a preliminary cost-benefit analysis for O_2 enrichment in the regeneration reactor of the FCC process has been conducted and presented in Section 4.2.

For the oxygen valorization there is the need for additional investment, like oxygen purification unit, buffer vessel, pipeline infrastructure to transport the oxygen to the consumer unit(s), etc. These elements are taken under consideration in the cost-benefit analyses of the two applications, oxygen use in the Claus unit and FCC unit, which have been identified as the most promising solutions.

4. Design and cost benefit analysis of selected solutions

4.1 Oxygen Utilization in the Claus Unit

MOH Refinery has already implemented oxygen enrichment in its Claus unit, reaping the benefits of increased capacity and enhanced efficiency. Currently, the oxygen enrichment system of MOH Claus unit uses LOx vaporizer and the liquid oxygen is supplied from third parties.

The normal pressure at the battery limit of the Claus unit is approximately 3 barg based on the unit's design specifications, while the design pressure of the oxygen system at inlet Claus unit is around 5 barg. Purity of oxygen stream shall be higher than 99,9 % based on the study of the oxygen feeding in the Claus units. Therefore, the rest 0,1 % shall be the total impurities in the stream with the higher proportion being the water content. The hydrogen content shall be at 10 ppm max., while no KOH impurities are accepted for this type of service.

Based on the above specifications for the oxygen use in the Claus unit, the waste oxygen of the Electrolyser is considered a great candidate, as it is delivered at high pressure (20 barg) and no expensive compression system is required. However, oxygen purification system is deemed necessary.

The following Sections provide a summary of the advantages and technical challenges associated with oxygen enrichment in the Claus units in general. Additionally, a cost-benefit analysis of the investment for the oxygen recovery and usage in the Claus unit at MOH Refinery has been conducted within Task 2.2 and is presented in Section 4.1.3.

4.1.1 Benefits

Advancements in oxygen enrichment have shown significant potential in enhancing the efficiency and capacity of the Claus process, thus allowing refineries to debottleneck operations and meet growing production demands. These findings are supported by various studies, including those by [1], [2]. Oxygen enrichment involves increasing the concentration of oxygen in the air feed to the Claus process. This enhancement addresses several operational challenges and brings a range of benefits:

- **Capacity expansion and debottlenecking:** One of the primary advantages of oxygen enrichment is the ability to expand and debottleneck the capacity of the Claus unit. By increasing the oxygen content, the reaction rate of H_2S oxidation is accelerated, thereby enhancing the throughput of the unit. This is particularly beneficial when capacity constraints are experienced in specific modes of operation, as it allows them to process higher volumes of feedstock without significant modifications to the existing infrastructure.

- **Improved combustion efficiency:** The enriched oxygen stream improves combustion efficiency within the thermal stage of the Claus process. This leads to a more complete oxidation of H_2S, reducing the likelihood of unreacted H_2S entering the catalytic stage. Consequently, the overall efficiency of sulphur recovery is increased, resulting in higher sulphur yields and lower emissions of sulphur compounds.
- **Reduction in tail gas emissions:** Enhanced combustion also contributes to a reduction in tail gas emissions. The presence of unreacted H_2S in the tail gas is minimized, which in turn decreases the load on tail gas treatment units. This not only improves the environmental performance of the Refinery but also reduces operational costs associated with tail gas treatment.

In addition, a project-specific advantage of the EPHYRA is the availability of "free" oxygen within the Refinery, as it will be produced as a by-product of the Electrolyser. This oxygen can be effectively utilized and supplied to the Claus unit replacing the liquid oxygen that is currently used and purchased by external suppliers.

Finally, the increased capacity and debottlenecking of the Claus unit will be also useful for the potential future expansion of the Refinery's operations with the addition of a new production unit for sustainable aviation fuels.

4.1.2 Technical Considerations for Oxygen Enrichment

While the benefits of oxygen enrichment are substantial, there are several technical considerations to account for during implementation:

- **Oxygen supply and purity:** The supply and purity of oxygen are critical factors in the successful deployment of oxygen enrichment. The oxygen produced by electrolyser units must meet the required purity standards to prevent contaminants from affecting the Claus process. Additionally, the pressure of the oxygen supply should be sufficient to integrate seamlessly with the existing unit without the need for costly compression systems. Both issues (purity and pressure) are resolved within the EPHYRA project as discussed in Section 4.1.3.
- **Safety measures:** Handling and storing enriched oxygen require stringent safety measures due to the increased risk of combustion. Adequate ventilation, leak detection systems, and fire suppression protocols must be in place to mitigate potential hazards. Personnel training and adherence to safety regulations are essential components of a safe operational environment.

4.1.3 Cost benefit analysis for oxygen enrichment

A comprehensive cost-benefit analysis is necessary to evaluate the economic feasibility of oxygen enrichment. Generally, the analysis should consider factors such as capital expenditure, operational savings, and the potential increase in sulphur recovery efficiency. Since O_2 enrichment is already implemented in the MOH Claus unit, we will focus on an incremental cost-benefit analysis by substituting the current oxygen supply source with oxygen produced by the Electrolyser. In this analysis, we assume oxygen enrichment only in the Claus unit (not in the FCC unit) thus we consider the full investment costs for the oxygen recovery system in the calculations.

For the oxygen utilization in the Refinery Claus unit a FEED study has been conducted based on the FEED study of the 30 MW electrolyser and the study indicated that an oxygen recovery system facility is required. The main equipment of the oxygen recovery system can be found in the Deliverable D1.1 *Technology validation* [3] of the EPHYRA project.

Additionally, it should be considered that in Claus unit 99.9% oxygen purity is the requested target purity according to the unit design. The balance 0.1% should be nitrogen or inert in any case. Regarding potential contaminants the following specifications should be met:

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- 10 ppmv max H2 content,
- no issues with water (as certain moisture already considered in the ambient air before mixing with O_2),
- other contaminants like residual salts shall be avoided.

The oxygen produced by the electrolyser has a purity of 98.5%, necessitating the implementation of an **oxygen purification system**. **A compression system** is **not** required, as the electrolyser operates at high pressure and the oxygen delivery pressure is 20 barg. (before any purification unit). During the distribution of oxygen via the pipeline from the electrolyser to the Claus unit (2-3 km), there will be a minor pressure reduction. However, the final pressure will remain significantly above the design specifications required by the Claus unit.

- The Claus unit currently uses 1.84 kta of oxygen (low usage, 47 days annually) based on 2023 data. The design capacity of the existing oxygen enrichment facility corresponds to O2 usage of 240 days annually leading to higher O2 volumes utilized[1]. It is crucial to note that the use of oxygen in the Claus unit depends on the sulphur content of the crude oil processed by the refinery, with the upper limit being the design capacity of the enrichment facility. Additionally, the high cost of oxygen supplied currently by an external vendor can be a limiting factor for high O2 usage. These constrains restricted oxygen enrichment in the Claus unit to just 47 days annually during 2023. Utilizing waste O2 from the Electrolyzer could help achieve the design usage levels, offering significant economic benefits, as detailed in the following sections. Consequently, we categorize the O2 use in the Claus unit into two scenarios: **low rate** and **high rate[2]**. The O_2 purification units are not included in the Electrolyser package. However, the electrolyser's vendor has proposed two potential solutions for our requirements:One single (1) unit of 1000 Nm^3/h O_2 (12 kta)
- One single (1) unit of 3000 Nm^3/h O_2 (36 kta)

The single unit of 1000 Nm^3/h is capable of partially recovering the oxygen, with any excess being vented. This unit meets the requirements for both the low and the high rate of the MOH Claus unit. Conversely, the single unit of 3000 Nm^3/h offers a purification capacity that accommodates the entire oxygen production at nominal capacity and maximum availability of the 30 MW Electrolyser. This capacity also allows for potential future utilization opportunities in other applications (e.g. O_2 use in the FCC unit).

For the cost-benefit analysis of the incremental investment for oxygen recovery and usage in the Claus unit, the single purification unit of 1000 Nm^3/h will be considered. Its cost is estimated at 259,000 € (based on a budgetary offer), plus installation costs. In the absence of a precise estimate for the installation costs, we apply a multiplier of two to the equipment costs to derive the total cost estimate. The cost of the oxygen recovery system (including recovery system and O_2 piping in existing pipe racks) is calculated to be 1,598,500 € (inclusive of construction costs) as per the FEED contractor's estimate. Consequently, the total costs for the Claus unit are estimated at **2,116,500 €**[3].

The MOH Refinery has already optimized its unit with oxygen enrichment (supplied by external suppliers), benefiting from increased capacity and other advantages. Substituting the oxygen purchased by external suppliers with the oxygen produced by the Electrolyser and avoiding its procurement cost has been identified as the main incremental saving stream for the Claus process due to the utilization of the waste electrolytic oxygen. The Refinery currently procures liquid oxygen under a signed contract at commercial price range depending on the supply volume. The cost of oxygen under the signed contract is considered as the economic benefit for the current analysis[4].

[1] The design capacity of the existing enrichment facility cannot be disclosed.
[2] Equal to the design usage.
[3] The actual costs will be available during the detailed engineering.
[4] The oxygen prices are sensitive data and cannot be disclosed.

The findings of the analysis for both low and high O_2 rate are summarized in Table 1. The benefit/cost ratio (BCR) shown in Table 1 is calculated assuming a discount rate equal to 10% (aligned with the project's WACC) and a project lifetime of 20 years, which corresponds to the lifetime of the Electrolyser project). The low-rate scenario has a payback period of 4.5 years, IRR=22% and a BCR of 1.9 for the oxygen recovery and usage in the Claus unit, indicating a positive net present value. The high-rate scenario exhibits a significantly shorter payback period of approximately 7 months, an exceptional high IRR=182% and a high BCR of around 15.5. As anticipated, the high-rate scenario offers considerably higher benefits due to the same investment cost but substantially greater saving streams, which are nearly 8 times higher than the low-rate scenario.

Table 1. Cost-benefit analysis for the low and high oxygen rate scenarios of the oxygen recovery unit.

Parameter	Low rate scenario	High rate scenario
Total Costs	**2.116.500 €**	**2.116.500 €**
O_2 recovery system	1.598.500 €	1.598.500 €
O_2 purification unit	518,000 €	518,000 €
Revenue streams (savings)	**471,859 €**	**3,844,920 €**
Payback period	**4.5 yrs**	**7 months**
IRR of O_2 recovery investment	**22%**	**182%**
BCR[5]	**1.9**	**15.5**

The oxygen utilization in other Refinery units can significantly enhance the financial viability of the Electrolyser project. When considered as a revenue stream, this can substantially reduce the Levelized Cost of Hydrogen (LCOH). Specifically, with the inclusion of oxygen revenues, the LCOH can decrease by 0.12 €/kg under the low-rate scenario (1.84 kta O2) and by 0.94 €/kg under the high-rate scenario (design usage)[6]. In addition, the IRR of the Electrolyser project can increase 1.9 under the low-rate scenario and 12 percentage points under the high-rate scenario. Table 2 summarizes the benefits of oxygen utilization on the Electrolyser business case.

Table 2. Impact of oxygen utilization in the Claus unit on the project LCOH and the Electrolyser business model for both low and high rate scenarios.

Parameter	Low rate scenario	High rate scenario
ΔLCOH	**-0.12 €/kg**	**-0.94 €/kg**
ΔEBITΔA	**471,859 €**	**3,844,920 €**
ΔIRR (of electrolyser business case)	**+1.9%**	**+12%**

Finally, in the theoretical scenario of a full recovery and utilization (36 kta O2), the oxygen revenue potential for the Electrolyser project could reach up to 17 million euros, assuming the oxygen pricing based on the signed contract as outlined in the previous paragraphs. This could result in a total LCOH reduction of 3.78 €/kg.

4.2 Oxygen enrichment in FCC unit

The following Section provides a summary of the advantages (4.2.1) and technical challenges (4.2.2) associated with oxygen enrichment in the FCC unit in general. Additionally, a cost-benefit analysis for the FCC unit at MOH Refinery has been conducted within Task 2.2 and is presented in subsection 4.2.3.

[5] Similar as Value Investment Ratio (VIR)

[6] The LCOH without oxygen sales is calculated equal to 4.73 €/kg, while under the low rate oxygen sales is reduced to 4.61 €/kg and under the high rate to 3.79 €/kg. Please, keep in mind that the absolute value of the LCOH is not final yet, as certain actual costs, e.g. EPC costs, are not finalised.

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4.2.1 Benefits of Oxygen Enrichment in FCC unit

Fluid Catalytic Cracking (FCC) is a vital refining process used to convert heavy hydrocarbon fractions from crude oil, like vacuum gas oil, into valuable lighter products such as gasoline, diesel, and olefins. FCC is widely adopted in refineries to maximize the yield of high-demand fuels and petrochemicals from heavier feedstocks that are more challenging to refine.

The basic components of an FCC unit (Figure 1) are the reactor and riser, the catalyst regenerator and the fractionator. The process begins in the riser, where preheated feedstock is mixed with hot, regenerated catalyst. The heat from the catalyst vaporizes the feed, initiating cracking reactions as the mixture flows upwards. The reactor at the top of the riser separates the cracked product vapors from the spent catalyst. The catalyst, which becomes covered with coke, is guided into the regenerator, where air is introduced to burn off the coke and regenerate the catalyst's activity. The combustion of coke in the regenerator is essential as it provides the heat needed for the endothermic cracking reactions in the riser. Oxygen enrichment is sometimes used in the regenerator to increase the combustion rate, allowing more coke to be burned and potentially boosting throughput [5]. The cracked vapors, after the reactor, are sent to a fractionator where they are separated into different products based on boiling points, including gasoline, diesel, and gases such as propylene.

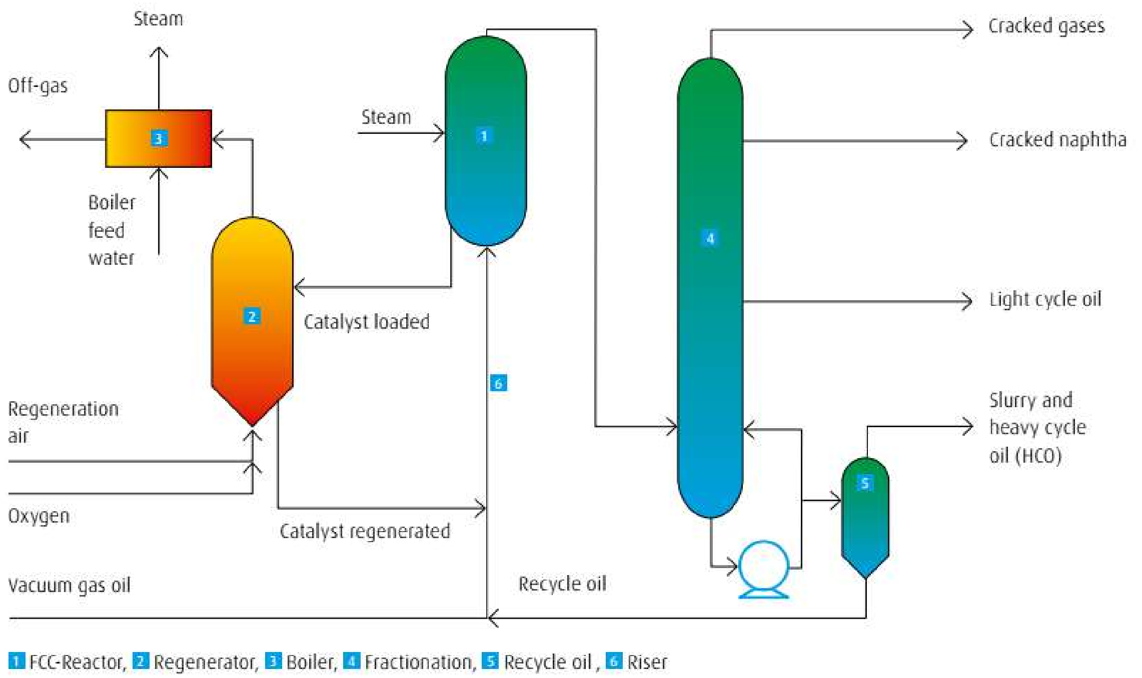

Figure 1. Main components and process flow of an FCC unit [6] [7]

The key parameters that affect the operation of the FCC unit, are temperatures and Catalyst-to-Oil Ratio. Higher temperatures and catalyst-to-oil ratios generally increase conversion but must be carefully managed to avoid over-cracking, which could reduce product yields. The regenerator conditions, also affect the operation. Since the regenerator operates under controlled temperatures and air flow to ensure adequate coke burn-off and catalyst regeneration, any adjustments to oxygen levels and airflow can impact the efficiency of regeneration and the amount of available heat. Finally, the composition of the feedstock quality affects the yield and quality of FCC products. Heavier feeds typically produce more coke, which in turn affects regeneration and catalyst activity.

In FCC units, the catalyst becomes covered in carbonaceous deposits or "coke" after cracking hydrocarbons. Regenerating this catalyst involves burning off the coke, typically in the presence of air, which is primarily

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nitrogen (~78%) and oxygen (~21%). Oxygen-enriched air (increasing oxygen to 23-30%) accelerates the coke combustion reaction:

$$C + O_2 \rightarrow CO_2 + HEAT$$

With higher oxygen levels, the coke combustion is more complete and rapid, reducing carbon monoxide (CO) formation. Enhanced combustion efficiency results in higher heat generation, which benefits reaction kinetics but poses thermal challenges both in the equipment such as increased thermal stress and overheating and also in the process itself, like disruption of the heat balance and accelerated catalyst deactivation.

The thermodynamic principle governing the effect of oxygen enrichment in FCC units is based on the combustion enthalpy of carbon. When oxygen concentration is increased, the rate of coke oxidation accelerates, resulting in **Higher Catalyst Regeneration Temperatures** and **Enhanced Coke-Burning Rates**. The kinetic rate $r = k[O_2][C]$ shows direct proportionality to oxygen concentration, with elevated O_2 levels intensifying the reaction and allowing more coke to be burned per cycle but also higher temperatures. This can help maintain catalyst activity by minimizing residual coke, enhancing process efficiency.

FCC units are often designed with operational flexibility to adjust to market demands, maximizing gasoline production, for example, when prices are high. Advanced control techniques, such as Model Predictive Control (MPC), are increasingly used to optimize these operating variables, balancing reactor and regenerator conditions to maximize yield, energy efficiency, and process stability.

Utilizing oxygen in FCC units has gained attention as an option to enhance efficiency, particularly in terms of capacity, processing flexibility, and emissions reduction. Oxygen enrichment specifically improves the regeneration process, which is a critical phase in FCC where spent catalyst is regenerated by burning off accumulated coke. Here's a comprehensive breakdown of the advantages, challenges, and practical considerations of implementing oxygen enrichment in FCC units, including some notable case studies:

- **Enhanced Regenerator Efficiency**: In a typical FCC unit, air is used as the source of oxygen to burn off coke from the catalyst. However, when oxygen enrichment is applied, the oxygen content in the combustion air is increased. This allows for more efficient and faster combustion of the coke, which enhances the regenerator's capacity. The improved coke-burning efficiency leads to better heat management and allows the regenerator to handle higher coke loads.

- **Increased Unit Capacity**: By enriching the air with oxygen, refineries can increase the throughput of the FCC unit without making significant hardware changes. This is because higher oxygen levels allow more coke to be burned off, regenerating the catalyst faster and supporting a higher feed rate. This is particularly beneficial when refineries are processing heavier crudes that tend to produce more coke. This allows the FCC unit to handle higher throughput, increasing capacity by up to 40%, especially in cases where the air blower capacity is a limiting factor. For example, oxygen levels can be increased to around 23-28%, with some systems even reaching the mid-30% range, supporting higher throughput without requiring a larger regenerator.

- **Reduced Air Blower Demand**: In FCC units, the air blower is used to supply air to the regenerator. O_2 enrichment reduces the amount of air required to achieve the same oxygen partial pressure, allowing the air blower to operate more efficiently. This reduces energy consumption and overall operational costs. Moreover, air blowers often limit FCC performance. With O_2 enrichment, refineries can circumvent this constraint and increase coke burning rates, allowing for higher processing rates.
- **Improved Catalyst Regeneration**: A higher oxygen concentration ensures more complete combustion of the coke, which can reduce the amount of unburned carbon and improve the activity

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of the regenerated catalyst. This leads to better catalytic performance in the riser, where the cracking reactions take place.

- **Increased Regenerator Temperature**: Increased oxygen levels can raise the temperature of the regenerator, enhancing combustion and thermal efficiency. However, careful control is needed to avoid overheating, which could damage the catalyst or regenerator equipment.
- **Environmental Benefits**: Oxygen enrichment can lead to more efficient combustion of coke, potentially reducing the production of pollutants such as carbon monoxide (CO) and nitrogen oxides (NO_x). A more efficient combustion process can lower emissions and help refineries meet environmental regulations.
- **Operational Flexibility**: It allows refiners to maintain or even increase FCC capacity during periods of high ambient temperatures, which can affect air blower performance. The flexibility in adjusting oxygen levels helps in managing seasonal or operational variations. Oxygen enrichment serves as an alternative to traditional methods like hydrocracking heavier FCC unit feeds, thus supporting continuous, flexible operations.
- **Energy Efficiency**: Oxygen enrichment reduces the amount of nitrogen introduced into the system, lowering the gas velocity and minimizing losses. This leads to fewer erosive effects on equipment, such as cyclones, and reduces catalyst wear, ultimately extending the time between maintenance shutdowns.
- **Improved Yields**: Higher oxygen levels improve coke combustion, leading to better conversion rates and higher yields of desirable products, such as gasoline and light hydrocarbon fractions. This also helps handle heavier feedstocks more effectively by ensuring adequate carbon burn-off. Oxygen enrichment can improve the conversion of feedstocks into valuable products like light cycle oil (LCO) and liquefied petroleum gas (LPG). For instance, specific studies have shown an LCO increase from about 10% to 18% when enriching to around 23% oxygen.
- **Improved Catalyst Lifespan**: The process reduces the erosion of cyclones used in catalyst separation, thereby improving overall catalyst handling and lifespan.

Several industry leaders like Praxair and Linde have implemented oxygen enrichment systems in FCC units, showing practical success. Praxair has implemented oxygen enrichment across over 20 FCC units, with most systems reaching oxygen levels between 23-28%. Notable benefits included increased LCO production, better feedstock flexibility, and improved regenerator performance. In one instance, LCO production improved by approximately 8%, while operating at stable coke-on-catalyst levels. This suggests oxygen enrichment may also aid in maintaining product stability by balancing out coke formation rates.

In summary, oxygen enrichment in FCC units presents a valuable option for refineries aiming to increase capacity, efficiency, and environmental compliance. However, it involves technical challenges, including managing higher temperatures and navigating regulatory requirements. Refineries considering oxygen enrichment should evaluate their existing systems' capabilities, particularly air blowers and cooling systems, to ensure a smooth transition.

In addition, a project-specific advantage of the EPHYRA is the availability of "free" oxygen within the Refinery, as it will be produced as a by-product of the Electrolyser. This oxygen can be effectively utilized and supplied to the FCC unit.

4.2.2 Technical Considerations and Challenges for Oxygen Enrichment in FCC unit

However, some challenges rise, and considerations have to be taken. While oxygen enrichment can improve FCC performance, additional capital and operational costs (Section 4.2.3) have to be considered for oxygen supply and for additional precise control systems installation. Furthermore, greater importance must be given to:

- **Thermal Management**: High temperatures necessitate additional equipment (catalyst coolers) and safety protocols, impacting operational costs. A significant challenge with oxygen enrichment is controlling the regenerator's temperature. High oxygen levels can cause an increase in combustion temperatures, potentially leading to damage. This is often managed by using catalyst coolers, though adding these coolers can increase operational costs.

- **Equipment and Safety Concerns**: Enriching oxygen in an FCC unit often requires an upgrade to air blowers and cooling systems, adding to the initial capital investment. Additionally, higher oxygen levels mean more stringent safety measures, including robust hazard and operability (HAZOP) studies to ensure safe operations
- **Regulatory Constraints**: Increasing oxygen levels can require additional permitting, as it may affect emission levels and permissible coke-burning rates. Ensuring compliance with these regulations can delay implementation and add to the complexity of integrating oxygen enrichment systems into existing FCC units
- **Increased Maintenance**: Frequent inspections of air blowers, regenerators, and cooling units are essential to maintain operational integrity under enriched oxygen conditions.
- **Metal Fatigue and Oxidation**: With increased oxygen, the environment becomes more oxidizing, heightening the potential for corrosion and thermal stress in reactor internals and piping. High-temperature alloys or corrosion-resistant linings are recommended to mitigate these effects.
- **Impacts on Catalyst Integrity**: Higher temperatures can cause sintering, where catalyst particles aggregate and lose surface area. Newer catalysts are often designed to withstand these conditions, but older or standard catalysts may suffer activity losses due to thermal degradation.

Several techniques are employed to introduce oxygen into the FCC unit, ranging from liquid oxygen systems to on-site oxygen production facilities, depending on the refinery's infrastructure. The effectiveness of oxygen enrichment has been demonstrated in various tests and commercial applications, showing significant improvements in FCC unit performance without requiring extensive capital investment for unit upgrades.

Emerging technologies in oxygen enrichment focus on fine-tuning oxygen injection rates and locations within the regenerator to minimize hotspots. Advances in high-stability catalyst formulations also aim to improve FCC resilience to higher temperatures, allowing oxygen enrichment to be used more broadly and safely across different FCC configurations.

In summary, oxygen enrichment in FCC units offers substantial benefits, but it requires precise control and consideration of equipment durability, catalyst stability, and environmental impacts.

4.2.3 Cost benefit analysis for oxygen enrichment

This report examines two scenarios for O_2 production. In the first scenario, the installed 30 MW electrolyser from the EPHYRA project is considered, while the second scenario explores an additional 20 MW extension, bringing the total capacity to 50 MW. The electrolysers in the two scenarios will operate across three modes: Minimum capacity (56% for the 30MW, 33% for the 50MW), Optimal capacity (67%), and Maximum capacity (100%).

Initially, a portion of the O_2 produced by each system is designated for the MOH's CLAUS unit, with any surplus directed to the FCC unit. The CLAUS unit's actual operational oxygen requirement is 0.21 tph, though it is designed for a higher capacity[7]. This study bases calculations on the design requirement. The following table provides details on each scenario, including total O_2 production on each operating mode, surplus O_2 available for the FCC unit, and calculated O_2 enrichment. For enrichment calculations, the total air feed rate to the regenerator remains constant at 165,8 tph. This means that when O_2 is used, the total air blower feed is reduced accordingly. A case where the entire amount of the produced O_2 is used by the FCC unit is also examined. The respective final O_2 content in that case is shown also in Table 3.

[7] The design capacity of the existing enrichment facility cannot be disclosed.

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Table 3. Case studies and available O_2 final content to FCC

Total Air Feed (Air+O_2) (tph)	165,8					
		O_2 to CLAUS and FCC			O_2 only to FCC	
	O_2 production (tph)	O_2 for FCC (tph)	Air blower feed	O_2 final content	Air blower feed	O_2 final content
30 MW Capacity factor (%)						
Minimum capacity factor 56% (Case30a)	2,40	1,29	164,51	**21,62%**	163,40	**22,14%**
Optimum capacity factor 67% (Case30b)	2,89	1,79	164,01	**21,85%**	162,91	**22,38%**
Maximum capacity factor 100% (Case30c)	4,32	3,21	162,59	**22,53%**	161,48	**23,06%**
50 MW Capacity factor (%)						
Minimum capacity factor 33% (Case50a)	2,40	1,29	164,51	**21,62%**	163,40	**22,14%**
Optimum capacity factor 67% (Case50b)	4,82	3,72	162,08	**22,77%**	160,98	**23,30%**
Maximum capacity factor 100% (Case50c)	7,20	6,09	159,71	**23,90%**	158,60	**24,43%**

In order to perform the preliminary cost benefit analysis, a base case is used, where the FCC operates without O_2 enrichment, and it is compared against two other cases resulting from the O_2 enrichment. The two additional scenarios are based on Figure 2 found in literature [6], and the concept that increasing the O_2 content at the air inlet of the FCC's regenerator, can result in: 1) either the ability to process higher feed rates with similar conversion ratios, or 2) the ability to process similar feed rates but with higher conversion rates.

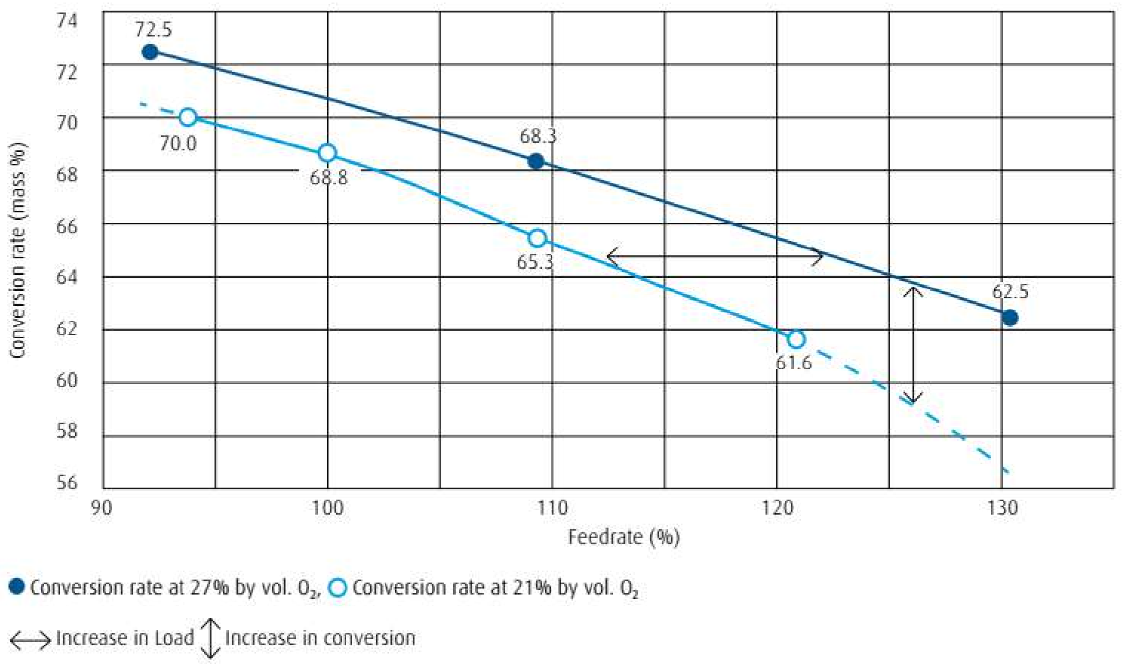

Figure 2. Increased conversion efficiency and capacity resulting from O_2 enrichment in the regeneration process (27% by vol. O_2). Experimental results of a laboratory unit [6]

As such, this analysis examines two scenarios of the FCC operation, with the percentage of O_2 enrichment calculated in Table 3. In the first scenario, the feed rate adjustment is assessed while keeping the conversion rate of the process constant. Conversely, the second scenario explores changes in the conversion rate while maintaining a constant feed rate. This approach helps evaluate the operational impacts of varying O_2 levels on both feed rate and conversion efficiency, giving insights into optimal operation strategies under enriched O_2 conditions.

Chart transformation

To align Figure 2 with MOH's FCC operations, a quadratic transformation was applied to map both curves, adjusting the chart so that a 100% feed rate corresponds to a 74.53% conversion rate at 21% O_2, consistent with MOH's baseline operation. Additionally, another quadratic transformation was employed to represent varying O_2 levels between the 21% and 27% curves. Figure 3 illustrates this mapping process, along with additional intermediate curves to depict various O_2 enrichment levels.

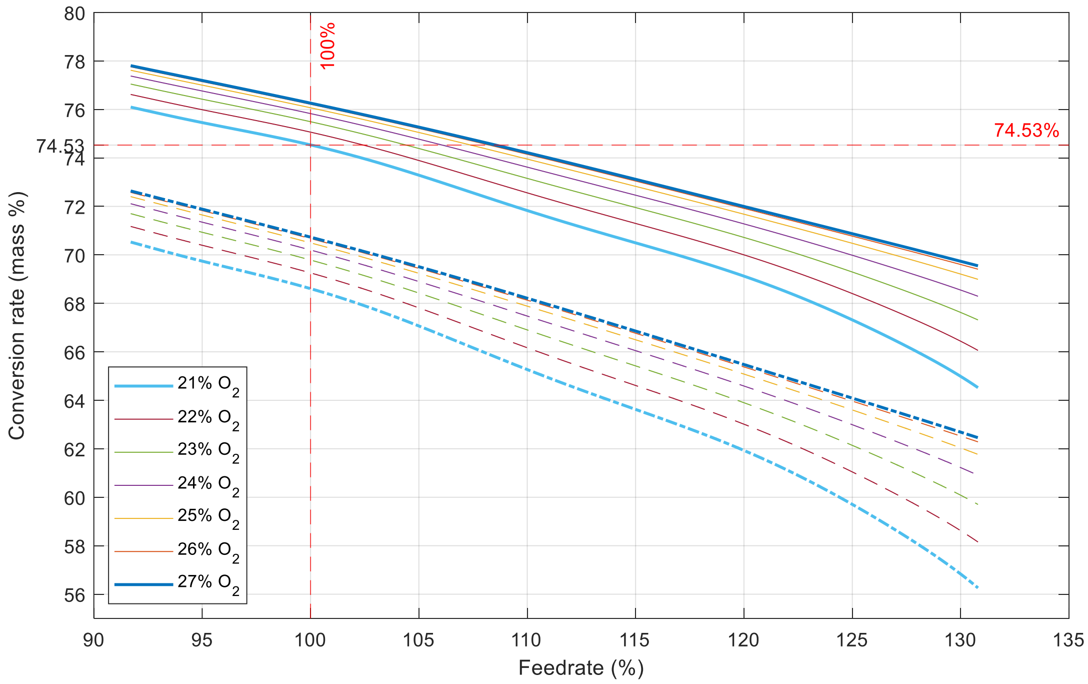

Figure 3 A quadratic transformation of Linde's chart to fit MOH's FCC operation and a quadratic distribution of different levels of O_2 between 21% and 27%

Increasing feed rate with constant conversion: Adjustments and operation

In the first scenario, the goal is to use O_2 enrichment to increase the feed rate keeping the conversion steady. The process taking place is as follows. Starting from the base operating conditions, which are constrained by air availability, gaseous O_2 is introduced into the regenerator. Simultaneously, the FCC feed rate is increased to consume excess O_2 which then produces more coke. As the feed rate rises, reactor temperature is maintained by boosting the catalyst circulation rate. This leads to a higher dense bed temperature in the regenerator, which decreases the catalyst-to-oil ratio and lowers conversion compared to the base case. To counteract this, feed preheat is reduced and catalyst circulation is further increased to maintain reactor temperature [8].

All these adjustments are balanced when the CO_2/CO ratio, excess O_2, and reactor temperature align with the base case, resulting in nearly the same dense bed temperature, gas velocity, and feed conversion as before. The increase in feed rate is approximately proportional to the additional O_2 available for coke combustion. Ultimately, capacity limits are typically dictated by product recovery, particularly the wet gas compressor.

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Increasing conversion with constant feed rate: Adjustments and operation

In this scenario, the goal is to increase conversion by increasing the catalyst-to-oil ratio at the optimal reactor temperature while keeping the feed rate constant. Starting from the base operating conditions, gaseous O_2 is added to the regenerator, and feed preheat is reduced. Simultaneously, catalyst circulation is increased to regulate the reactor temperature, which leads to a decrease in the regenerator temperature. As the reactor temperature and catalyst-to-oil ratio rise, both coke yield and conversion improve.

As more coke is burned, the CO_2/CO ratio, excess O_2, and reactor temperature stabilize to values similar to the base case, maintaining nominally the same regenerator temperature and gas velocity. This results in increased conversion at a constant feed rate. The increase in coke yield is almost proportional to the additional available O_2, with conversion being directly related to coke yield. Ultimately, the limiting factors for conversion, due to the maximization of the catalyst-to-oil ratio, are typically product recovery (particularly the capacity of the wet gas compressor) or the minimum feed preheat temperature, which could lead to high regenerator temperatures [8].

Analysis

To analyze the two scenarios, the O_2 enrichment levels derived from Table 3, where applied to the adjusted chart. Figure 4 illustrates the conversion-feed curves for the O_2 derived from the 30MW electrolyser and the respective calculated changes on feed rate and conversion. Similarly, Figure 5 illustrates the results for the 50MW electrolyser.

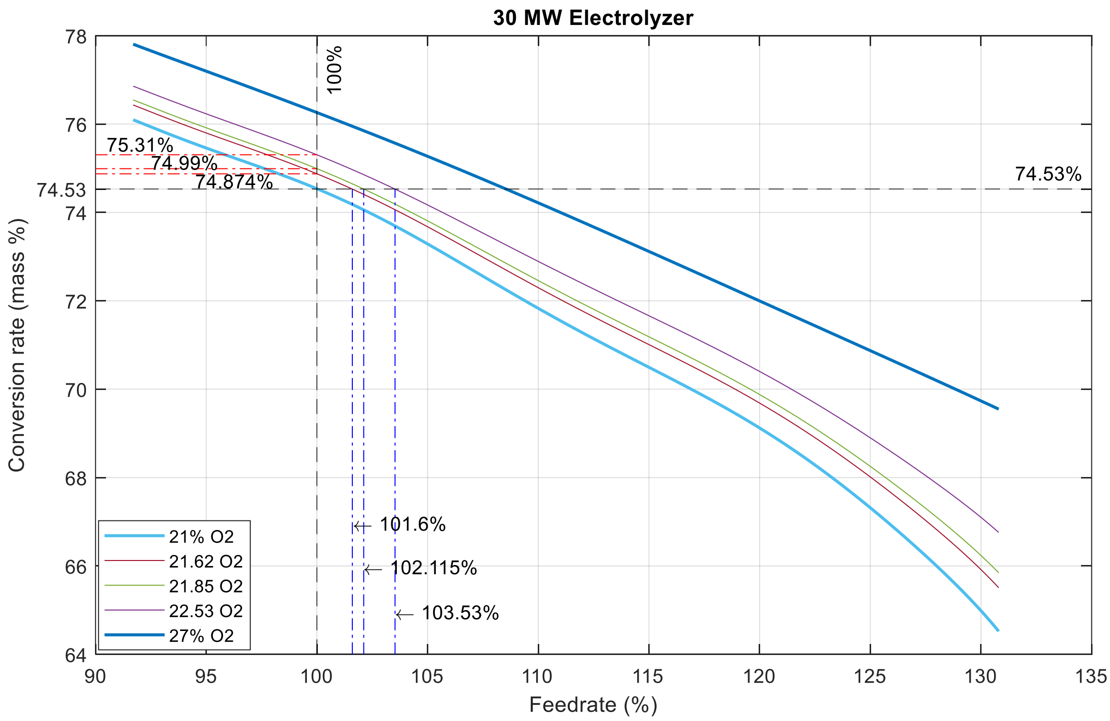

Figure 4. Possible changes on feed rate or conversion on FCC unit according to O_2 enrichment resulting from the available O_2 from the three operational cases of the 30MW Electrolyser

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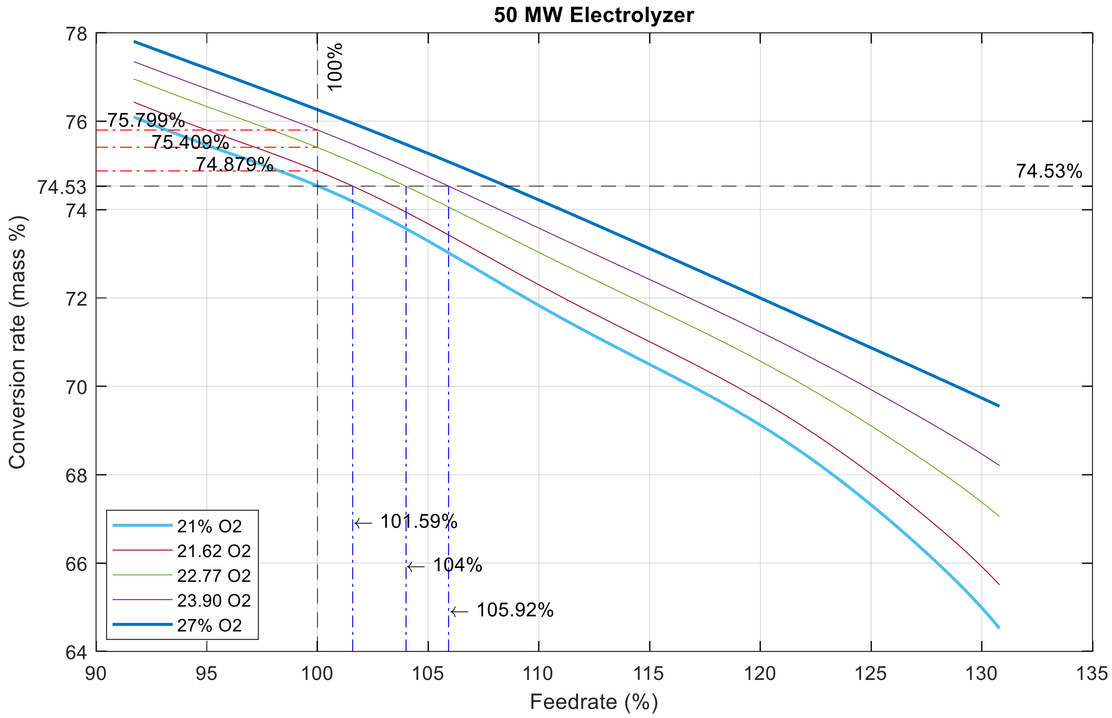

Figure 5. Possible changes on feed rate or conversion on FCC unit according to O_2 enrichment resulting from the available O_2 from the three operational cases of the 50MW Electrolyser

To summarize the results of the two scenarios examined, Table 4 presents the calculated conversion rate and feed rate changes for the respective O_2 enrichments in both electrolyser cases (30 MW and 50 MW), derived from the curves shown in Figure 4 and Figure 5.

Table 4. Feed rate and conversion change derived from the adjusted chart for the respective O_2 enrichment

	O_2 Usage (kta)	O_2 Enrichment (%)	Conversion % (with fixed feed rate 100%)	Feed rate% (with fixed conversion 74,53%)
Base Case	-	21%	74,53%	100,00%
Case30a	10,76	21,62%	74,87%	101,60%
Case30b	14,87	21,85%	74,99%	102,12%
Case30c	26,73	22,53%	75,31%	103,53%
Case50a	10,75	21,62%	74,87%	101,60%
Case50b	30,92	22,77%	75,41%	104,00%
Case50c	50,69	23,90%	75,80%	105,92%

Cost benefit analysis

The Cost-Benefit Analysis (CBA) spans a twenty-year period, evaluating costs and benefits over time by calculating their present values. By applying a 10% discount rate, future values are converted to their current equivalents, allowing for meaningful comparisons of cash flows that occur at different times. This discounting reflects the time value of money, the concept that a Euro today can be invested to yield returns, and thus, is worth more than the same amount received in the future. Using present values enables the CBA to support informed decisions about initiatives with long-term costs and benefits. Using a discount rate r, the Discounted Costs at year t (DC_t) are calculated as:

$$DC_t = \frac{C_t}{(1+r)^t}$$

and the Discounted Benefits at year *t* (DB_t) are calculated as:

$$DB_t = \frac{B_t}{(1+r)^t}$$

where C_t: Costs in year *t*

B_t: Benefits in year *t*

r: discount rate

CBA uses two primary metrics, the Benefit-Cost Ratio (BCR) and Net Present Value (NPV), to evaluate the economic feasibility of an action. The Benefit-Cost Ratio is calculated by dividing the present value of the action's benefits by the present value of its costs, providing a measure of Return Of Investment (ROI). A BCR greater than 1 suggests that the benefits exceed the costs, indicating a potentially viable investment.

Net Present Value, on the other hand, measures the difference between the present value of benefits and the present value of costs. If NPV is positive, the action is generally favorable, showing that the expected benefits surpass the costs. For a given discount rate *r*, a positive NPV and a BCR greater than 1 both signal that an action's benefits outweigh its costs, supporting decision-making based on economic justification. Together, BCR and NPV are crucial for assessing whether an investment or project is likely to yield a positive economic outcome.

Net Present Value and Benefit-Cost ratio are calculated for a period of T years, from the following relationships, given a discount ratio r:

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t}$$

$$BCR = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} \Bigg/ \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

where *T* is the number of years in the analysis period.

Another metric used in this analysis is EBITDA. EBITDA stands for Earnings Before Interest, Taxes, Depreciation, and Amortization. It's a financial metric used to assess a company's operational profitability by focusing on earnings from core business operations, excluding the effects of interest, taxes, and non-cash accounting items like depreciation and amortization. The formula to calculate EBITDA is:

$$EBITDA = Revenue - Operating\ Expenses\ (excluding\ interest,\ taxes,\ depreciation,\ and\ amortization)$$

More specifically, this analysis calculates Δ_{EBITDA}, which is the differential EBITDA from the base case.

Finally, the Internal Rate of Return (IRR) is also calculated. IRR is a financial metric used to evaluate the profitability of an investment or project. Specifically, the IRR is the discount rate at which the NPV of all cash flows (both incoming and outgoing) from a particular investment or project becomes zero. In simpler terms, IRR represents the annualized effective compounded return rate that makes the present value of the expected future cash inflows equal to the initial investment. Therefore, IRR results from the parameter *r* in NPV formula setting NPV equal to zero.

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CAPEX

The capital investment for O_2 enrichment includes the installation of an O_2 purification unit and an O_2 recovery system. Since a purification unit will be installed for O_2 enrichment in the Claus unit, and to accommodate the O_2 requirements for the FCC unit, an increase in the capacity of the FCC unit will incur an additional cost of 385.000€ for the unit itself. The final system will be capable of purifying 3.000 Nm^3/h (36 kta). This figure represents the equipment procurement cost only, while another 385.000€ is estimated for the installation. The O_2 recovery system will be shared between the Claus and FCC units, with its estimated cost accounting for nearly two-thirds of the total, amounting to 586.700€ for equipment and installation. An additional 479.000€ (representing two-thirds of the total cost) will be required for installing 3 km of 3" O_2 piping on existing pipe racks. Finally, an injection skid needs to be procured and installed at the output of the air blower in order to mix the pure O_2 with the air. For the 30MW electrolyser, the maximum amount of O_2 delivered to the FCC is 3,21 tph, and the CAPEX for the corresponding injection skid is estimated at 92.348€. On the other hand, for the 50MW electrolyser, the CAPEX is estimated at 175.139€, since the O_2 flow is now 6,09 tph. Therefore, the total capital investment for the FCC unit is estimated at 1.928.015€ for the 30MW electrolyser, while for the 50MW electrolyser is estimated at 2.010.806€.

Change in feed rate with constant conversion

In the scenario where conversion is kept constant and O_2 enrichment only affects the feed rate, Table 4 presents the total increase in feed. It is assumed that the enrichment does not affect the quality of the products (i.e., the percentage content), so the total product price depends solely on the amount of fresh feed. In all cases, the price of feed per ton is assumed to be the same.

The following tables present the results of the preliminary CBA. Table 5 displays the differential EBITDA and NPV between each case and the base case and the corresponding BCR and IRR, resulting from the feed rate changes of Table 4. A ranking of the cases indicates that Case50c is the most favorable, as anticipated.

Table 5. NPV, BCR and ranking results of the CBA for the feed rate change case

Case	Δ_{EBITDA}	NPV	BCR	IRR	NPV Rank out of 6	BCR Rank out of 6
Case30a	+1.971.056 €	+16.535.385 €	1,137	102%	5	5
Case30b	+2.665.794 €	+23.041.551 €	1,142	139%	4	4
Case30c	+4.435.534 €	+39.615.024 €	1,147	231%	3	3
Case50a	+1.971.056 €	+16.456.734 €	1,136	98%	6	6
Case50b	+5.026.324 €	+45.069.079 €	1,148	251%	2	2
Case50c	+7.526.329 €	+68.481.419 €	1,151	376%	1	1

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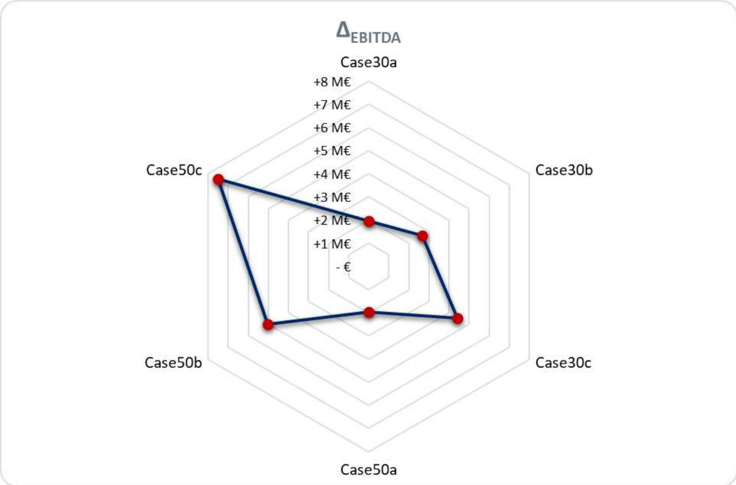

Figure 6 Radar of Δ_{EBITDA} for O_2 enrichment with feed rate change

Sensitivity analysis in the case of constant conversion

In this study, a Cost-Benefit Sensitivity Analysis complements the primary Cost-Benefit Analysis by assessing outcomes under varied assumptions. Specifically, this analysis examines the Δ_{EBITDA}, NPV, BCR and IRR, in scenarios involving 10% increase and decrease in costs and benefits in order to evaluate and understand the impact of potential fluctuations. The study also includes extreme scenarios: a worst-case scenario with a 5% increase in costs and a 5% decrease in benefits, and a best-case scenario with a 5% decrease in costs and a 5% increase in benefits, to provide a range of possible outcomes.

Table 6 and Table 7 present the analysis results for a ±10% change in costs and benefits, respectively. The findings indicate that, even with a 10% increase in costs or a 10% decrease in benefits, O_2 enrichment still generates a profit, even at these lower levels. When comparing these two scenarios (percentage changes in costs and benefits), it appears that the project is more profitable when costs are increased by 10% than when benefits are reduced by 10%.

Table 6. Effect on the metrics of a ±10% change in costs, for the feed rate change case

	Costs +10%				Costs -10%			
Case	Δ_{EBITDA}	NPV	BCR	IRR	Δ_{EBITDA}	NPV	BCR	IRR
Case30a	+512.395 €	+4.484.046 €	1,034	37%	+3.429.717 €	+28.586.724 €	1,264	168%
Case30b	+760.793 €	+6.810.272 €	1,038	50%	+4.570.796 €	+39.272.831 €	1,269	228%
Case30c	+1.393.548 €	+12.735.978 €	1,043	82%	+7.477.520 €	+66.494.070 €	1,275	379%
Case50a	+504.530 €	+4.397.530 €	1,033	35%	+3.437.582 €	+28.515.937 €	1,263	162%
Case50b	+1.596.915 €	+14.627.635 €	1,044	90%	+8.455.733 €	+75.510.522 €	1,276	412%
Case50c	+2.490.771 €	+22.998.522 €	1,046	134%	+12.561.886 €	+113.964.317 €	1,278	617%

Table 7. Effect on the metrics of a ±10% change in benefits for the feed rate change case

	Benefits +10%				Benefits -10%			
Case	Δ_{EBITDA}	NPV	BCR	IRR	Δ_{EBITDA}	NPV	BCR	IRR
Case30a	+3.434.483 €	+30.240.262 €	1,251	179%	+507.629 €	+2.830.508 €	1,023	26%
Case30b	+4.645.035 €	+41.576.986 €	1,256	242%	+686.553 €	+4.506.117 €	1,028	36%
Case30c	+7.728.733 €	+70.455.572 €	1,262	402%	+1.142.335 €	+8.774.476 €	1,033	59%
Case50a	+3.434.483 €	+30.161.611 €	1,250	172%	+507.629 €	+2.751.857 €	1,023	25%

Case50b	+8.758.161 €	+80.017.430 €	1,263	437%	+1.294.488 €	+10.120.727 €	1,033	65%
Case50c	+13.114.315 €	+120.812.459 €	1,266	655%	+1.938.343 €	+16.150.380 €	1,036	97%

Table 8 presents the metrics for both the worst and best-case scenarios. Over a 20-year analysis period, even the worst-case scenario results in a profitable investment for all cases, where the NPVs for all cases become positive in the 4th year of operation.

Table 8. Extreme scenarios for the feed rate change case. Worst Case and Best Case

	Worst Case Scenario				Best Case Scenario			
Case	Δ_{EBITDA}	NPV	BCR	IRR	Δ_{EBITDA}	NPV	BCR	IRR
Case30a	+510.012 €	+3.657.277 €	1,029	31%	+3.432.100 €	+29.413.493 €	1,257	173%
Case30b	+723.673 €	+5.658.194 €	1,033	43%	+4.607.915 €	+40.424.908 €	1,262	235%
Case30c	+1.267.942 €	+10.755.227 €	1,038	71%	+7.603.126 €	+68.474.821 €	1,268	390%
Case50a	+506.079 €	+3.574.693 €	1,028	30%	+3.436.033 €	+29.338.774 €	1,256	167%
Case50b	+1.445.702 €	+12.374.181 €	1,039	77%	+8.606.947 €	+77.763.976 €	1,269	425%
Case50c	+2.214.557 €	+19.574.451 €	1,041	116%	+12.838.100 €	+117.388.388 €	1,272	636%

Finally, Table 9 shows how the metrics are affected when the investment costs are increased 50% or 100%.

Table 9. Metrics when the investment costs are increased

	50% increase of Investment cost				100% increase of Investment cost			
Case	Δ_{EBITDA}	NPV	BCR	IRR	Δ_{EBITDA}	NPV	BCR	IRR
Case30a	+1.971.056 €	+15.573.686 €	1,128	68%	+1.971.056 €	+14.611.988 €	1,119	51%
Case30b	+2.665.794 €	+22.079.853 €	1,135	92%	+2.665.794 €	+21.118.154 €	1,129	69%
Case30c	+4.435.534 €	+38.653.325 €	1,143	154%	+4.435.534 €	+37.691.627 €	1,139	115%
Case50a	+1.971.056 €	+15.455.709 €	1,127	66%	+1.971.056 €	+14.454.685 €	1,118	49%
Case50b	+5.026.324 €	+44.068.054 €	1,144	167%	+5.026.324 €	+43.067.030 €	1,141	126%
Case50c	+7.526.329 €	+67.480.395 €	1,148	251%	+7.526.329 €	+66.479.371 €	1,146	188%

Change in conversion with constant feed rate

In this scenario, the feed rate is kept constant, and O_2 enrichment only affects the conversion. Table 4 presents the conversion changes derived from Figure 4 and Figure 5, based on the O_2 enrichment levels.

Conversion is a measure of the degree to which feedstock is cracked into lighter products and coke during processing in the FCC. It is defined as 100 percent minus the volume percent yield of LCO and HCO. Therefore, as conversion increases, the yield of lighter products rises, while the production of LCO and HCO decreases. This, in turn, impacts the final product profit, as the estimated profit for each product varies.

For this case, the feedstock price is the same for every O_2 enrichment case and the same as the previous case. Table 10 presents the calculated products content percentage changes over the base case, for each one of the O_2 enrichment cases. This was determined based on the final conversion of each case and the product content of the base case.

Table 10. Product content according to conversion cases and respective product prices

Product		Case30a	Case30b	Case30c	Case50a	Case50b	Case50c
Total dry gas		+0,52%	+0,52%	+1,04%	+0,52%	+1,04%	+1,56%
	C3	+0,79%	+0,79%	+1,57%	+0,79%	+1,57%	+2,36%

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Product		Case30a	Case30b	Case30c	Case50a	Case50b	Case50c
Total LPG	C3=	+0,36%	+0,54%	+1,08%	+0,36%	+1,08%	+1,62%
	iC4	+0,58%	+0,58%	+1,17%	+0,58%	+1,17%	+1,75%
	nC4	+0,00%	+0,00%	+0,88%	+0,00%	+0,88%	+0,88%
	i-Butene	+0,49%	+0,49%	+0,98%	+0,49%	+0,98%	+1,47%
	nC4 olefins	+0,41%	+0,62%	+1,03%	+0,41%	+1,03%	+1,64%
Light Naptha (C5)		+0,43%	+0,58%	+1,01%	+0,43%	+1,13%	+1,65%
Side-cut Naptha		+0,43%	+0,64%	+1,00%	+0,43%	+1,15%	+1,65%
LCO		- 1,22%	- 1,71%	- 2,87%	- 1,22%	- 3,23%	- 4,82%
HCO-MCB		- 1,32%	- 1,76%	- 2,98%	- 1,32%	- 3,31%	- 4,85%
Coke		+0,35%	+0,53%	+0,89%	+0,35%	+1,06%	+1,60%
Gross Conversion %		74,85%	74,97%	75,27%	74,85%	75,37%	75,76%

The following tables present the results of the CBA for the conversion change case. Table 11 displays the values of the metrics, resulting from the feed rate changes of Table 4. A ranking of the cases indicates that Case50c is the most favorable, also for this case.

Table 11. NPV, BCR and ranking results of the CBA for the conversion change case

Case	Δ_{EBITDA}	NPV	BCR	IRR	NPV Rank out of 6	BCR Rank out of 6
Case30a	+534.028 €	+3.077.734 €	2,600	28%	5	5
Case30b	+724.952 €	+4.865.716 €	3,530	38%	4	4
Case30c	+1.214.819 €	+9.453.283 €	5,915	63%	3	3
Case50a	+534.028 €	+2.999.083 €	2,498	26%	6	6
Case50b	+1.376.193 €	+10.885.884 €	6,437	69%	2	2
Case50c	+2.018.076 €	+16.897.072 €	9,440	101%	1	1

Figure 7 Radar of Δ_{EBITDA} for O_2 enrichment with conversion change

Sensitivity analysis in the case of constant feed rate

Table 12 and Table 13 illustrate the impact on the metrics when costs and benefits are adjusted by ±10%. The results indicate that, for the 20-year analysis, even with a 10% increase in costs or a 10% decrease in benefits, the metrics are positive.

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Table 12. Effect on the NPV and BCR of a ±10% change in costs for the conversion change case

	Costs +10%				Costs -10%			
Case	ΔEBITDA	NPV	BCR	IRR	ΔEBITDA	NPV	BCR	IRR
Case30a	+341.688 €	+2.885.394 €	2,364	28%	+726.368 €	+3.270.074 €	2,889	28%
Case30b	+532.612 €	+4.673.377 €	3,209	38%	+917.291 €	+5.058.056 €	3,922	38%
Case30c	+1.022.479 €	+9.260.943 €	5,377	63%	+1.407.158 €	+9.645.623 €	6,572	63%
Case50a	+333.823 €	+2.798.878 €	2,271	26%	+734.233 €	+3.199.288 €	2,776	26%
Case50b	+1.175.988 €	+10.685.679 €	5,852	69%	+1.576.397 €	+11.086.089 €	7,153	69%
Case50c	+1.817.871 €	+16.696.867 €	8,582	101%	+2.218.281 €	+17.097.277 €	10,489	101%

Table 13. Effect on the NPV and BCR of a ±10% change in benefits for the conversion change case

	Benefits +10%				Benefits -10%			
Case	ΔEBITDA	NPV	BCR	IRR	ΔEBITDA	NPV	BCR	IRR
Case30a	+587.431 €	+3.577.847 €	2,860	30%	+480.625 €	+2.577.621 €	2,340	25%
Case30b	+797.447 €	+5.544.628 €	3,883	41%	+652.456 €	+4.186.805 €	3,177	34%
Case30c	+1.336.301 €	+10.590.951 €	6,506	69%	+1.093.337 €	+8.315.615 €	5,323	57%
Case50a	+587.431 €	+3.499.196 €	2,748	29%	+480.625 €	+2.498.970 €	2,248	24%
Case50b	+1.513.812 €	+12.174.678 €	7,081	76%	+1.238.573 €	+9.597.091 €	5,794	62%
Case50c	+2.219.884 €	+18.786.984 €	10,384	111%	+1.816.268 €	+15.007.160 €	8,496	91%

In the O_2 enrichment scenario with conversion change and constant feed, the worst-case analysis shows positive metrics for all cases (Table 14).

Table 14. Extreme scenarios for the conversion change case. Worst Case and Best Case

	Worst Case Scenario				Best Case Scenario			
Case	ΔEBITDA	NPV	BCR	IRR	ΔEBITDA	NPV	BCR	IRR
Case30a	+411.157 €	+2.731.507 €	2,353	26%	+656.899 €	+3.423.960 €	2,874	29%
Case30b	+592.534 €	+4.430.091 €	3,194	36%	+857.369 €	+5.301.342 €	3,901	40%
Case30c	+1.057.908 €	+8.788.279 €	5,352	60%	+1.371.730 €	+10.118.287 €	6,538	66%
Case50a	+407.224 €	+2.648.924 €	2,260	25%	+660.832 €	+3.349.242 €	2,761	28%
Case50b	+1.207.280 €	+10.141.385 €	5,824	65%	+1.545.105 €	+11.630.383 €	7,115	72%
Case50c	+1.817.070 €	+15.852.014 €	8,541	96%	+2.219.082 €	+17.942.131 €	10,434	106%

Finally, for this case also, a scenario with an increment of the investment costs is examined. In this case, the costs are increased by 25% and 50%, and the results are presented in Table 15.

Table 15. Increase of investment costs by 25% and 50%, for the conversion change case

	25% Investment cost increase				50% Investment cost increase			
Case	ΔEBITDA	NPV	BCR	IRR	ΔEBITDA	NPV	BCR	IRR
Case30a	+534.028 €	+2.596.885 €	2,080	22%	+534.028 €	+2.116.035 €	1,733	18%
Case30b	+724.952 €	+4.384.867 €	2,824	30%	+724.952 €	+3.904.018 €	2,353	25%

Case30c	+1.214.819 €	+8.972.434 €	4,732	51%	+1.214.819 €	+8.491.584 €	3,943	42%
Case50a	+534.028 €	+2.498.571 €	1,998	21%	+534.028 €	+1.998.058 €	1,665	17%
Case50b	+1.376.193 €	+10.385.372 €	5,150	55%	+1.376.193 €	+9.884.860 €	4,292	46%
Case50c	+2.018.076 €	+16.396.560 €	7,552	81%	+2.018.076 €	+15.896.048 €	6,293	67%

Directing the full supply of O_2 to the FCC unit

The final scenario analyzed in this study involves directing the entire output of the produced O_2 to the FCC unit. In this case, the investment costs for processing the O_2 differ between the two electrolysers. The 30MW electrolyser produces 35.945 tons per annum (tpa) of O_2, and the 3.000 Nm³/h (36 kta) purification unit capacity is sufficient for purification. Since all the O_2 produced is allocated to the FCC unit (with none diverted elsewhere), all associated investment costs, including those for purification, the O_2 recovery unit, and piping, are accounted for in this case. Additionally, the injection skid must have a capacity of 4,32 tph for this case, which means its total cost will be now 124.190€.

In contrast, the 50MW electrolyser produces 59.907 tpa of O_2, requiring an additional 2.000 Nm³/h (24 kta) of purification capacity. Therefore, the total investment cost includes the same costs as for the 30MW electrolyser, plus the additional cost for the extra purification capacity, and the cost for the respective injection skid.

As a result, the total investment cost for the 30MW electrolyser, is estimated at 3.010.690€, while for the 50MW electrolyser, it is estimated at 3.996.480 €.

Table 16, presents the results of the O_2 enrichment resulting from the usage of the entire amount of the produced O_2, and the respective conversion and feed rate changes as they are calculated from the respective diagrams (similar to Figure 4 and Figure 5).

Table 16. Full O_2 enrichment and the respective conversion and feed rate changes

	O_2 Usage (kta)	O_2 Enrichment (%)	Conversion % (with fixed feed 100%)	Feed % (with fixed conversion 74,53%)
Base Case	-	21%	74,53%	100,00%
Case30a	19,97	22,14%	75,13%	102,74%
Case30b	24,09	22,38%	75,24%	103,22%
Case30c	35,92	23,06%	75,52%	104,55%
Case50a	19,97	22,14%	75,13%	102,74%
Case50b	40,12	23,30%	75,60%	104,94%
Case50c	59,92	24,43%	75,94%	106,66%

The results of the CBA analysis for this case are presented on the following tables. Table 17, presents the resulted metrics when full O_2 enrichment is used with constant conversion and changing in the feed rate.

Table 17. Metrics with full O_2 enrichment and change in feed rate

Case	Δ_{EBITDA}	NPV	BCR	IRR	NPV Rank out of 6	BCR Rank out of 6
Case30a	+3.473.690 €	+29.526.351 €	1,139	116%	5	5
Case30b	+4.078.954 €	+35.194.602 €	1,142	136%	4	4
Case30c	+5.684.220 €	+50.227.789 €	1,146	189%	3	2
Case50a	+3.473.690 €	+28.544.700 €	1,134	87%	6	6

Case50b	+6.243.432 €	+54.483.109 €	1,144	157%	2	3
Case50c	+8.480.278 €	+75.430.993 €	1,147	213%	1	1

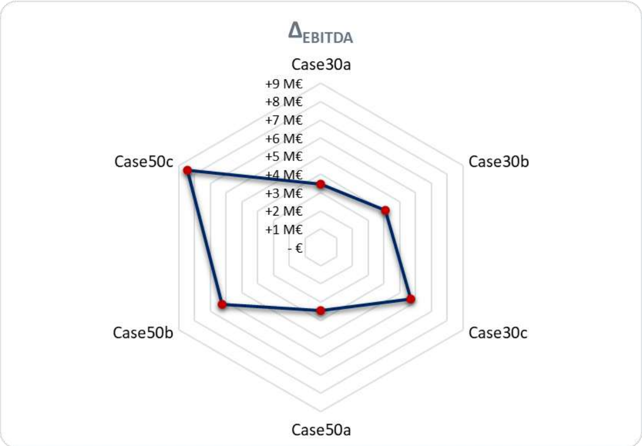

Figure 8. Radar of Δ_{EBITDA} for full O_2 enrichment with feed rate change

In the case of constant feed rate and change in conversion, Table 18 shows the percentage change of the products content over the initial content.

Table 18. Percentage change of products content over the initial content

Product		Case30a	Case30b	Case30c	Case50a	Case50b	Case50c
Total dry gas		+0,78%	+1,04%	+1,30%	+0,78%	+1,30%	+1,82%
Total LPG	C3	+0,79%	+1,57%	+1,57%	+0,79%	+1,57%	+2,36%
	C3=	+0,72%	+0,90%	+1,26%	+0,72%	+1,44%	+1,80%
	iC4	+0,88%	+0,88%	+1,46%	+0,88%	+1,46%	+2,05%
	nC4	+0,00%	+0,88%	+0,88%	+0,00%	+0,88%	+1,77%
	i-Butene	+0,49%	+0,98%	+0,98%	+0,49%	+0,98%	+1,47%
	nC4 olefins	+0,82%	+0,82%	+1,23%	+0,82%	+1,23%	+1,85%
Light Naptha (C5)		+0,76%	+0,92%	+1,28%	+0,76%	+1,37%	+1,83%
Side-cut Naptha		+0,79%	+0,93%	+1,29%	+0,79%	+1,43%	+1,86%
LCO		- 2,26%	- 2,62%	- 3,72%	- 2,26%	- 4,02%	- 5,37%
HCO-MCB		- 2,32%	- 2,65%	- 3,75%	- 2,32%	- 4,08%	- 5,40%
Coke		+0,71%	+0,89%	+1,24%	+0,71%	+1,42%	+1,77%
Gross Conversion %		75,11%	75,21%	75,48%	75,11%	75,56%	75,90%

Finally, Table 19 shows the metrics of the CBA analysis when using the full amount of the produced O_2 and changing the conversion in the FCC unit.

Table 19. Metrics with full O_2 enrichment and change in conversion

Case	Δ_{EBITDA}	NPV	BCR	IRR	NPV Rank out of 6	BCR Rank out of 6
Case30a	+947.723 €	+5.870.870 €	2,954	31%	5	5
Case30b	+1.113.529 €	+7.423.632 €	3,471	37%	4	4
Case30c	+1.560.057 €	+11.605.328 €	4,863	52%	3	2
Case50a	+947.723 €	+4.889.218 €	2,227	23%	6	6

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Case50b	+1.696.313 €	+11.899.709 €	3,985	43%	2	3
Case50c	+2.252.831 €	+17.111.455 €	5,293	57%	1	1

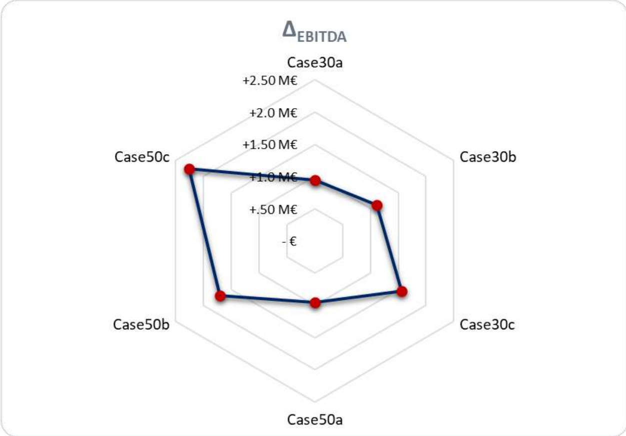

Figure 9 Radar of Δ_{EBITDA} for full O_2 enrichment with conversion change

5. Conclusions

In the framework of Task 2.2, titled *Concept Development for Internal Use of Generated Oxygen from Electrolyser,* within EPHYRA Work Package 2, various concepts for the internal utilization of the generated oxygen within the Refinery have been developed. Deliverable D2.2, "Report on the Internal Use of Electrolysis Generated Oxygen within MOH Refinery", investigates the potential uses of waste oxygen generated by the Electrolyser in the Refinery's processes. A cost-benefit analysis has been performed on two selected solutions identified as most promising: the use of oxygen in the Claus Sulphur Recovery unit to enhance efficiency, increase capacity, and debottleneck operations, and the oxygen enrichment in the FCC unit with similar benefits. The analysis aims to optimize the Refinery's operations by leveraging internally generated oxygen, thus reducing reliance on external suppliers and enhancing overall efficiency.

The most tangible and immediate solution moving forward with detailed engineering is the utilization of oxygen in the Claus unit, whereas for the utilization in the FCC unit, only a desktop study and a preliminary cost-benefit analysis has been conducted. The costs for the Claus unit case study include the oxygen recovery system costs (including oxygen pipelines) and the purification unit with a capacity necessary to meet the Claus unit demands. For the FCC case study, the recovery system costs (based on oxygen usage) and all other relevant costs specific to the FCC application have been considered, including the additional purification capacity and the oxygen injection skid.

The cost-benefit analysis revealed that the utilization of waste oxygen in the Claus unit presents an attractive solution. Specifically, the payback period for the investment of the oxygen recovery and usage in the Claus unit is approximately 7 months with a Benefit-Cost Ratio (BCR) of around 15.5 and IRR=182% for the design rate scenario for the Claus unit project. For the low-rate scenario based on actual refinery data from the period 2023 (1.84 kta O_2 use), the payback period extends to 4.5 years with a BCR of 1.9 and IRR=22% for the incremental investment.

In addition to the operational benefits of oxygen enrichment in the Claus unit, the use of the waste oxygen offers a cost-competitive advantage for the Electrolysis plant, potentially reducing the Levelized Cost of Hydrogen (LCOH) by approximately 0.12 €/kg for the low-rate scenario, 0.94 €/kg for the high-rate scenario, and 3.78 €/kg for full oxygen utilization (36 kta O2 use). Furthermore, if the revenue from oxygen is

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incorporated into the Electrolyser's business plan, the IRR could increase 1.88 percentage points and 12 percentage points for the low and high-rate scenario, respectively.

Oxygen enrichment in FCC units demonstrates substantial potential to enhance refinery performance, supported by detailed cost-benefit analysis results. The integration of oxygen-enriched air improves coke combustion efficiency, leading to higher throughput, better product yields, and reduced environmental impact. Key findings from the analysis include:

- **Feed Rate Increase**: In scenarios focusing on throughput, the most favorable case (50 MW electrolyser at full capacity, Case50c) achieved a feed rate increase of 6.45%, resulting in a Net Present Value (NPV) increment of €75.43 million, a Benefit-Cost Ratio (BCR) of 1.147, and an Internal Rate of Return (IRR) of 213%.
- **Conversion Efficiency**: In scenarios optimizing conversion, the best case (50 MW electrolyser at full capacity, Case50c) yielded a gross conversion increase to 75.90% with an NPV increment of €17.11 million, a BCR of 5.293, and an IRR of 57%.

The findings confirm that oxygen enrichment allows FCC units to handle heavier feedstocks effectively while maintaining high efficiency. Leveraging surplus oxygen from electrolysers, as in the EPHYRA project, further enhances the economic feasibility of the process. While challenges such as thermal management, equipment upgrades, and regulatory considerations exist, these can be mitigated through targeted investments and safety measures. The most favorable outcomes underline oxygen enrichment as a robust pathway to improve refinery capacity, product yields, and sustainability, positioning refineries for future expansion and compliance with stricter environmental standards.

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