CUMERI

Customised membranes for green and resilient industries

Sustainability pre-assessment

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PROJECT SUMMARY

This report is part of the deliverables from the project "CUMERI" which has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No. 101091812.

Increased energy and resource efficiency in industrial sectors is paramount to build a resilient and sustainable future. In this context, the CUMERI project will develop and demonstrate at technology readiness level (TRL) 7, advanced and customised membrane separation systems in two key industries: in the steel sector where H_2 will be recovered and CO_2 captured in one comprehensive system, and in the oil & gas industry where a multi-step liquid filtration system will enable base oil and additives recovery from used lubricant oil. To reach these goals, CUMERI gathers 16 partners (7 research organisations and 9 companies including 4 small and medium size companies) and will elaborate in 36 months three impactful membrane technologies: 1) Enhanced bio-based and recyclable polymer membranes for CO_2 permeation; 2) Stable and selective silicon carbide or silicon carbonitride (SiC/SiCN) membranes for H_2 recovery, for a better H_2 valorisation in the steel sector; 3) Grafted porous ceramic membranes for waste oil purification and additives recovery. All membrane systems will unlock greater energy efficiency and decreased emissions in their respective sectors. High separation performances together with increased chemical, mechanical and thermal stability will be demonstrated. Moreover, re-usage and recycling of membranes will be validated. Beyond these demonstrations, the project will generate novel insights on membrane separation including a variety of flexible solutions to help industry, the scientific community and policy makers accelerate the rollout of separation technologies. To maximise the impact of CUMERI, other promising separations will be screened and the transferability of results to other industries (refinery, pharmaceuticals, etc.) will be ensured. Through its activities, CUMERI will pave the way to decreased emissions in the industry, to the greater valorisation of valuable chemicals, and to more energy-efficient processes, promoting resilient and circular industrial value chains.

OBJECTIVE AND EXECUTIVE SUMMARY

CUMERI targets the development of customized membrane separation systems for liquid and gas treatment applications in two major industries. To evaluate the economic and environmental impacts of the proposed processes, Life Cycle Assessment (LCA) and Techno-economic Assessment (TEA) pre-analysis were conducted. This initial sustainability analysis relied on defining the value chains, collecting the needed data, and performing mass and energy balance calculations. The findings of these assessments will provide useful insights into the financial and environmental performances of the proposed membrane processes, which will guide partners throughout the future tasks.

1. INTRODUCTION

CUMERI aims to tackle the challenges of climate neutrality and industrial resilience, which are at the forefront of the objectives outlined in the European Green Deal. Customized membranes which are designed for specific applications offer a promising solution. This project focuses on two value chains: gas separation in the steel industry for H_2 recovery and CO_2 capture, and liquid treatment in the oil and gas (O&G) industry for base oil recovery from used lubricant oils (ULO). The recovery of H_2 in the steel industry is of particular interest as it is extensively used in steel-making production and comes with a high cost. By implementing ceramic and polymeric gas separation membranes, the CUMERI project aims to propose more energy-efficient processes, while also reducing CO_2 emissions through efficient CO_2 capture. This will promote resilient and circular industrial value chains by facilitating the recycling and reuse of valuable components. Furthermore, the utilization of different liquid filtration techniques in a multi-step approach in the CUMERI project targets the development of efficient methods for ULO recovery, thus contributing to sustainable practices in the oil and gas sector. Overall, the CUMERI project seeks to develop and implement customized membranes that can contribute to the objectives of the European Green Deal, including more resilient and circular industrial value chains, energy-efficient processes, and reduced emissions, while addressing the specific needs of the steel and oil/gas industries in terms of hydrogen and base oil/additives recovery, respectively.

2. METHODOLOGY

2.1 Techno-economic assessment

In general, the development of innovative technologies requires having a clear idea on the economic performance of the process. A techno-economic analysis (TEA) assists in optimizing the development of a process and identifying its most important parameters.

Using the methodology consistently will increase the likelihood of success when introducing innovative procedures to the market. A TEA considers the entire value chain and can be used during every technology readiness level (TRL). The procedure can be broken down into four distinct phases. First, a market study is conducted. Then, a simplified process flow diagram (PFD) and mass and energy balance are defined from a preliminary process design. This information is then directly integrated into a dynamic cost-benefit analysis (i.e., economic evaluation) in order to identify profitability. Lastly, a sensitivity analysis is carried out to evaluate the dependence of the economic performance of variations in key parameters. Due to the difficult and expensive step of information collection (especially for innovative technologies and processes), a TEA is carried out iteratively with a go/no-go decision after each iteration. A graphical representation of the TEA procedure is depicted in Figure 1. An in-depth description of the methodology can be found in (Van Dael, Kuppens et al. 2015).

To evaluate the financial viability of the considered processes (and thus their attractivity to investors), the economic analysis is coupled to the mass and energy balance calculations. The economic assessment must provide clear insights into the capital expenditures (CAPEX) and operational expenditures (OPEX) of the studied technology, which allow (when taken together) identifying the total production cost.

Furthermore, revenues must also be calculated. This information allows identifying several important economic parameters, such as the net present value (NPV), internal rate of return (IRR), payback period (PBP), and discounted payback period (DPBP).

Data relative to equipment costs are obtained from the project's partners and literature for a particular cost basis, which may be in terms of mass (e.g., volume, flowrate), energy (e.g., consumed power, installed electric capacity), or operating conditions (e.g., pressure, temperature). Often, these cost bases are different from the costs required for the analysis, hence the need for cost scaling.

One method to achieve this scaling is called the 'six-tenth rule', which is mostly employed for an order-of-magnitude estimation. This methodology correlates a certain process's fixed capital investment cost to that of a similar (already implemented) process with a known capacity. This is achieved by an exponential factor, called the scaling exponent, that relies on the nonlinear relationship that exists between a process's cost and capacity. The new cost of each equipment is calculated using equation (1). The investment costs for the processes' equipment, including good estimations for the costs of the membranes, were obtained from partners and literature.

$$Cost_{new} = Cost_{ref} \left(\frac{Basis_{new}}{Basis_{ref}}\right)^{scaling\ exponent} \quad (1)$$

When no equipment-specific value is available for the scaling exponent, it is accepted to assume a value of 0.6. Moreover, the installation costs for equipment may be included or not (bare unit prices). In the case where they are not included, an equipment-specific installation factor is considered.

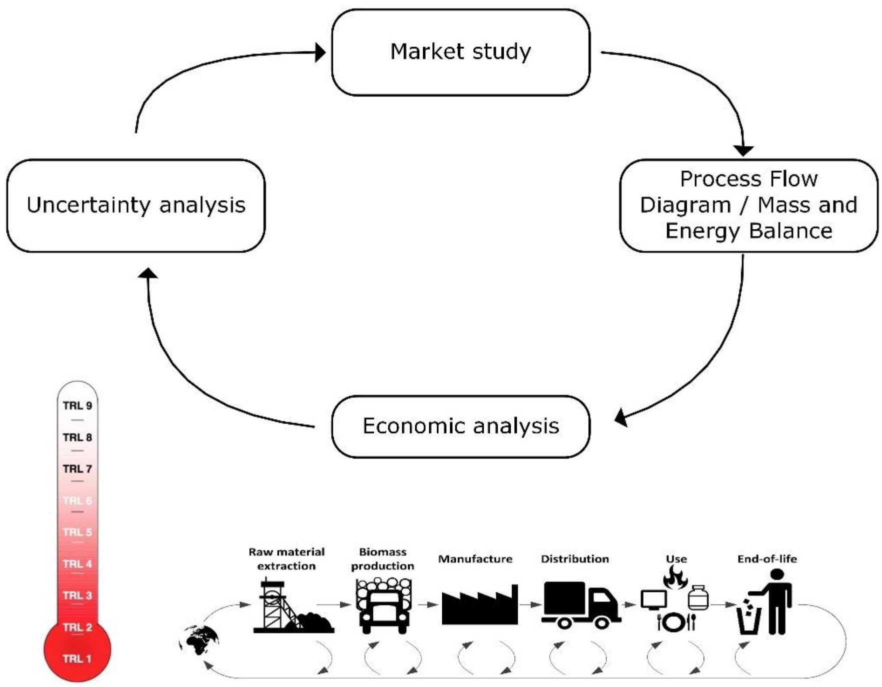

Figure 1. Techno-economic analysis (TEA)

An issue that could potentially be associated with this scaling method manifests in these estimates being based on historical cost data. Therefore, the calculated costs must be updated to current prices and economic conditions. The outdated prices can be modified using the Chemical Engineering Plant Cost Indices (CEPCI) following equation (2). It should be noted that this technique is accurate for time differences that do not exceed 10 years. Therefore, care must be taken with using this index otherwise.

$$Cost_{current\ year} = Cost_{ref} \times \left(\frac{CEPCI_{current\ year}}{CEPCI_{ref}}\right) \tag{2}$$

The capital costs are annualized using equation (3). The formula for the weighted average cost of capital (WACC) is described in equation (4). The WACC is the average cost of capital, considering the different sources of capital that a firm uses.

$$Annualized\ cost = \frac{Total\ capital\ cost\ over\ plant\ lifetime}{\frac{1-(1+WACC)^{-Plant\ lifetime}}{WACC}} \tag{3}$$

$$WACC = (Equity\ ratio \times Discount\ rate) + (Debt\ ratio \times (1 - Tax\ rate) \times Interest\ rate) \tag{4}$$

The NPV, which is calculated using equation (5), provides insights into the profitability of the technology, where T is the life span of the investment, CF_n is the difference between revenues and costs in year n, I_0 is the initial investment in year 0, and i the discount rate. A particular technology is said to be interesting when its NPV is positive (Levy and Sarnat 1994, Fiala, Pellizzi et al. 1997). The NPV compares the current amount of money invested in a project to the present value of the future cash receipts from the investment. Put differently, the invested money is compared to the future cash amounts after being discounted by a specified rate of return (i.e., discount rate). The NPV considers the investment today and the revenues and expenses from each year of the lifetime of a project. The riskier an investment, the higher the estimated discount rate must be. Typical discount rates are (i) 10% for cost improvement of conventional technologies, (ii) 15% for the expansion of conventional technologies, (iii) 20% for product development, and (iv) 30% for speculative venture (Mercken 2004). However, in most cases, a discount rate of 10-15% is used in combination with a life span of 10-15 years.

$$NPV = \sum_{n=1}^{T} \frac{CF_n}{(1+i)^n} - I_0 \tag{5}$$

Additional widely spread measures for evaluating whether an investment is economically viable or not are the DPBP and the IRR. The simple payback period is defined as the point in time when the initial investment is paid back by the net incoming cash flows. This metric does not, however, consider the time value of money. Therefore, the DPBP can be used to remedy this issue. The DPBP is calculated using equation (6), where *CF* is the difference between revenues and costs, i is the discount rate, and I_0 is the initial investment cost. It is worth noting that shorter DPBP values are a sign for more attractive investments. Moreover, the *IRR* is the discount rate at which the *NPV* value reaches zero. It thus associates the present value of the future cash flows of an investment with the initial investment. This allows knowing the effective interest rate being earned after taking into consideration the time periods when the various cash amounts are flowing in or out. An investor considered an *IRR* value to be attractive when it is higher than the return rate that can be generated in lower risk markets or investments (compared to the project), e.g., investing in safe, low-risk bonds or saving the investment money in a bank. Since the *IRR* is expressed as a percentage, it can only be used as a decision rule for selecting projects when there is only one alternative to a status quo and should certainly not be used to select one project from a group of mutually exclusive projects with different sizes (Boardman, Greenberg et al. 2006). Therefore, when presented with the choice of more than one technology or process (i.e., alternatives), one should prefer the *NPV* ranking over the *IRR* ranking (Lorie and Savage 1955).

$$DPBP = \frac{ln\left(\frac{CF}{CF - iI_0}\right)}{\ln(1+i)} \tag{6}$$

We selected the minimum selling price (MSP) of base oil (for the liquid line) and hydrogen (for the gas line) as the main performance indicator for this economic assessment. The MSP is calculated using equation (7).

$$MSP\ (€/kg) = \frac{\text{Annualized CAPEX } (€/yr) + \text{OPEX } (€/yr) - \text{Revenues coproducts } (€/yr)}{\text{Product } (kg/yr)} \quad (7)$$

2.2 Life cycle assessment

Life Cycle Assessment (LCA) is a tool to systematically assess the potential environmental impacts of a defined system, with the goal to quantify the associated impacts from cradle (raw material extraction) to grave (end of life or second life). LCA can have many uses including to support decision making, inform customers, identify environmental hotspots, and to assess improvement actions. Often LCA is used to compare against alternative systems performing the same function. To ensure that relevant and useful LCA is performed, it is essential to conduct LCA in accordance with the International Organization for Standards' ISO 14040 and 14044, as well as any accepted industry specific standards. LCA can be broken down into 4 phases, including Goal & Scope, Inventory, Impact Assessment, and Interpretation as shown in Figure 2 (ISO 14044, 2006).

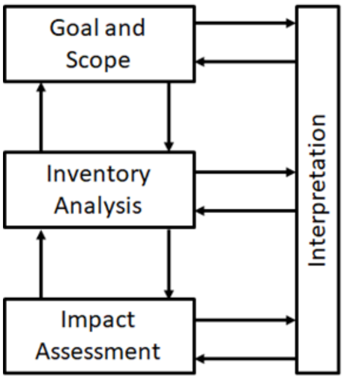

Figure 2. : Phases of an LCA adapted from ISO 14044, 2006

ISO 14044 describes these phases as follows (ISO 14044, 2006):

- The Goal & Scope definition includes the system boundary and level of detail. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA.
- The life cycle inventory (LCI) analysis is an inventory of input/output data regarding the system being studied. It involves the collection of the data necessary to meet the goals of the defined study.
- The life cycle impact assessment phase (LCIA) provides additional information to help assess a product system's LCI results to better understand their environmental significance.
- Finally, life cycle interpretation is when the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations, and decision-making in accordance with the goal and scope definition.

LCA is an iterative framework and interpretation occurs along the assessment process to refine the scope, data quality, or other assumptions as needed.

In the CUMERI project, a full LCA will be conducted in Work Package 6. For the current sustainability study, a screening LCA approach is used. This screening LCA attempts to capture as many system components as is currently feasible at the beginning of the research project.

Goal & Scope

The Goal of the screening LCA is to identify potential hotspots early in the research process. The initial scope of the LCA is gate to gate:

Liquid Line

- Scope: from when the collected ULO is received at the re-refining facility to when it leaves the facility as Base Oil (Class 2).
- Functional Unit: 100,000 tonnes ULO treated. This will likely be updated to Recovered Base Oil in the full assessment.

Gas Line

- Scope: from when the COG leaves the Coke Oven to the capture of CO_2 at the end of the treatment processes.
- Functional Unit: 144,000 tonnes COG treated

The stated Goals and Scopes will be reiterated and expanded when the full LCA is completed in Work Package 6.

The chosen impact methodology is ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H, including all 18 impact categories, and ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H, to inform the discussion (Huijbregts et al., 2016). The software for calculation is Simapro 9.3.0.3 using Ecoinvent 3.8 database.

Life Cycle Inventory

The Life Cycle Inventory data for both the Gas and Liquid separation lines are provided by the Techno-Economic Assessment. The TEA provided all values related to mass and energy balances, except for the impacts of membrane production and MEA used in the Gas Separation Benchmark. Assumptions from literature and expert opinion are used as proxies for these processes.

Environmental Impacts of Membrane Production

It is early in the CUMERI project to include membrane production environmental impacts. To estimate the magnitude of membrane production impacts, realistic proxies were used according to expert opinion on previous related work. These estimates will provide an initial understanding of the relative magnitude of membrane production impacts.

These proxies do not include all impact categories and have their own assumptions and scopes which may not align with the current study. This is recognized to be an uncertain parameter and is simply serving as a crude estimate until more data is available. The actual membrane production processes will be modelled fully in work package 6 of the CUMERI project.

3. CASE STUDY

3.1 Process Description

The main objective for CUMERI is to develop processes for liquid and gas separation using advanced and customized membranes in two key industries.

Liquid treatment line

Starting with the liquid treatment line, four options were investigated: a benchmark and three membrane processes. Concerning the benchmark process, it involved treating ULO using traditional re-refining methods to serve as a basis of comparison. The considered benchmark process begins by pumping ULO into a pre-treatment step. This initial step targets mainly the removal of water. Then, the ULO is pumped to a thin film vacuum distillation performed at high temperature (typically between 300 and 400°C) to remove impurities in the form of asphalt-like material. The heat required by the distillation is provided by combusting natural gas in a boiler. Finally, the ULO is treated in a hydrotreatment unit (which requires a constant stream of hydrogen gas) to reduce its sulphur content and, therefore, improve the quality of the recovered base oil from class I to class II. Hydrotreatment is not used in the already operating OSILUB re-refining plant (considered as benchmark in CUMERI), hence the results were presented for two cases (with and without hydrotreatment).

Regarding the membrane processes, three different options were considered. They were defined based on the level of pre-treatment that the ULO undergoes before reaching the membranes, and the details of the multi-step membrane process used. Typically, the membrane processes are envisioned to work at much lower temperature than the benchmark: between 100 and 150°C.

The products recovered from the ULO treatment processes are the same for all the considered options. The water from possible pre-treatment is incinerated off-site for energy generation (too dirty for water recovery), while the asphalt-like material is sold as substitute for bitumen roofing. As for the recovered base oil – with a yield of 70% compared to the incoming ULO mass, i.e., a base oil recovery of near 100% in all cases - it is reused as a virgin base oil in applications that match its quality. The process flow diagrams (PFDs) for the considered processes are shown in Figure 3.

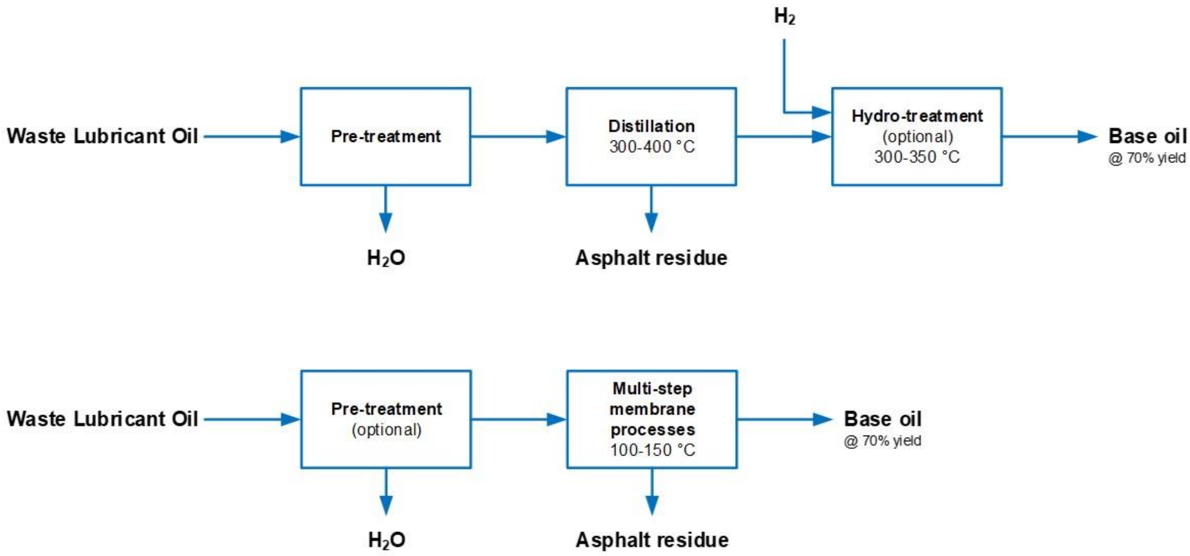

Figure 3. Process flow diagrams for (top) the benchmark process, (bottom) membrane alternative

Gas separation line

Regarding the gas separation line, two scenarios were evaluated: a benchmark and a membrane process. Regarding the benchmark process, it involved treating coke oven gas using a traditional flue-gas treatment process. After proper cleaning, the coke oven gas is introduced to a pressure swing adsorption (PSA) unit, which is responsible for H_2 separation. Thereafter, the coke oven gas is heated and introduced into an oxycombustion unit. The dehumidified flue gas is introduced to a Monoethanolamine scrubbing (MEA) unit for CO_2 capture. A similar process was considered for CUMERI, apart from two main aspects: *i)* using SiC/SiCN membranes instead of PSA and *ii)* using PEBA membranes instead of MEA. Thanks to the high thermal and chemical robustness of the SiC/SiCN membrane, the membrane process would not require a cooling step prior to this step. This also removes the need for heating the coke oven gas before the oxycombustion. The PEBA membranes work at typical conditions for polymeric gas separation membranes. The PFDs for the considered processes for the gas separation line are shown in Figure 4.

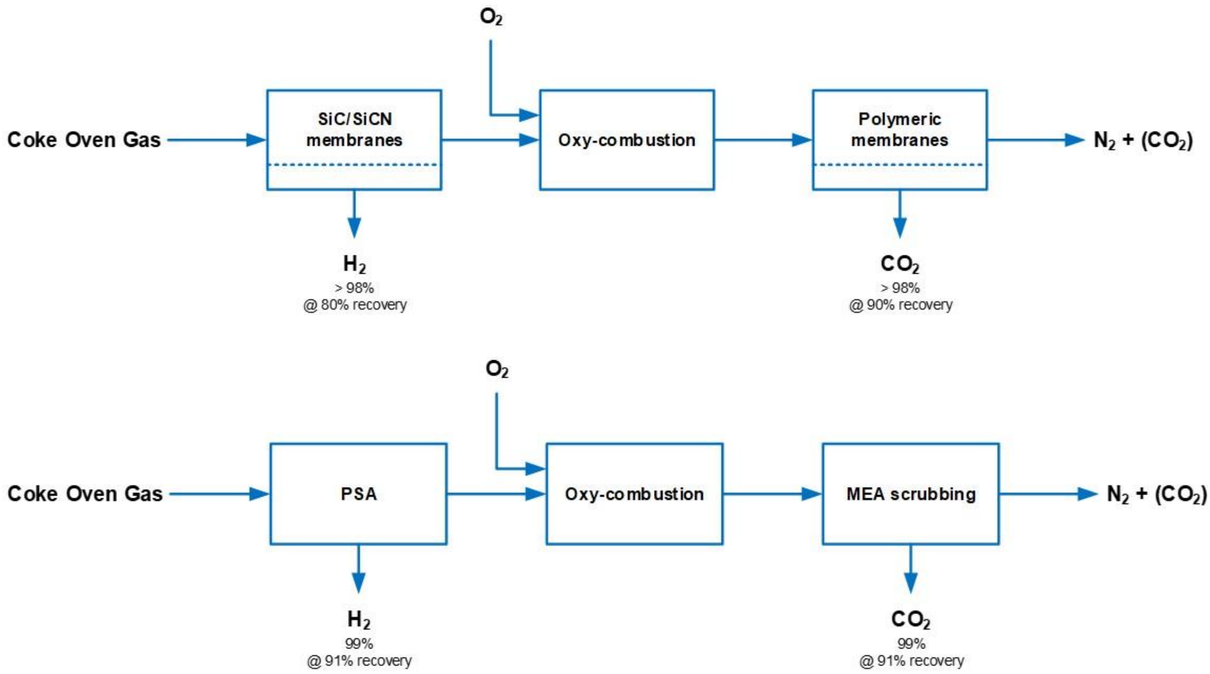

Figure 4. Process flow diagrams for (bottom) the benchmark process and (top) the membrane alternative

3.2 Mass and Energy Balance

In this section, we provide the detailed mass and energy balances for the liquid and gas lines, including the main data and assumptions.

Liquid treatment line

The benchmark case is based on the large-scale plant operated by OSILUB (ULO treatment capacity of about 120 kt/yr). In this plant, ULO is treated at a flowrate of 15 ton/hr. Mass and energy data of the different steps were provided by OSILUB. As mentioned earlier, the oil obtained at the end of the process is considered as a class I oil due to its high sulphur content, thus a hydrotreatment step was also evaluated. Typical hydrogen, electricity and heat use of this step were taken from literature (Emam and Shoaib, 2013; Lau et al., 2022). (Oliveira and Schure, 2020). The electricity needed in the benchmark case was considered to be purchased, while the required heat was assumed to be produced onsite using a natural gas boiler.

Keeping a similar treatment capacity to the benchmark, the three membrane processes and the required heat exchangers were sized. Mass balances were defined based on the assumed performance for each membrane step.

Gas separation line

The evaluated gas separation processes (benchmark and membrane process) were modelled using Aspen plus. The coke oven gas treatment capacity was based on the typical amount treated by ERDEMIR (36 kNm^3/hr). In the benchmark process, the coke oven gas is cooled and introduced into the PSA unit for H_2 separation (recovery rate of 91%) (Portha et al., 2021). Nevertheless, for the membrane process, the coke oven gas is directly introduced to the SiC/SiCN membrane (H_2 recovery rate of 80%). The coke oven gas is then burned in the oxycombustion unit to generate steam. Thereafter, the flue gas of the oxycombustion is cooled and dehumidified. The last step used for CO_2 capture is different for the considered processes: for the benchmark, MEA is used (capture rate of 91%), while for the membrane process, a PEBA membrane is employed (capture rate of 90%).

In addition to the above process parameters, some assumptions specific to the LCA must be made. As mentioned previously, the membrane production impacts are included by realistic proxies. To fairly compare to the benchmark case, the production impacts of MEA are also included in the LCA inventory (Singh et al., 2011, IPCC, 2005).

3.3 Economic Assessment

The assumptions used for estimating the capital costs and the operating and maintenance (O&M) costs are given in Table 1. The money values are presented in 2023 euros using the chemical engineering plant cost index (CEPCI = 802.6) (Maxwell, 2023). The economic lifetime for the liquid treatment process (25 years) was based on the benchmark plant at OSIL. However, since there is no actual benchmark (in operation) for the gas separation process, its economic lifetime (20 years) was based on literature (Portha et al., 2021). To account for expenses associated with start-up, civil works, engineering, procurement and construction, electrical assembly and wiring, buildings and structures, and contingencies, the equipment purchase costs are multiplied by installation factors. Furthermore, the variable O&M costs for the electricity, heat, water, oxygen, and solvent were estimated based on the unit prices given in Table 1.

Table 1. General capital (CAPEX) and operational (OPEX) expenditures assumptions

Item	Unit	Value	Source
Lifetime	yr	25 (Liquid line) 20 (Gas line)	(OSIL) (Portha et al., 2021)
Base year	-	2023	-
Insurance	% CAPEX	1%	(Peters et al., 2004)
Operating hours	hr/yr	8,000	(OSIL; VITO)
Labour wage rate	€/hr	30	(OSIL)

Electricity price	€/MWh	180	(Eurostat, 2022)
Heat price	€/MWh	112.5	(Eurostat, 2022)
Steam price	€/ton	18	(Aspen data)
Hydrogen price	€/kg	2	(Oni et al., 2022)

3.4 Sensitivity Analysis

Since the values used for the calculations were uncertain, a sensitivity analysis was performed. For the most part, the used values were provided by partners, collected from literature, or determined through simulations. The values are therefore deterministic rather than stochastic. The sensitivity analysis investigates the impacts of several parameters (both technical and economic) on the financial performance of the considered processes in more detail. An overview of the parameters included in the sensitivity analysis is presented in Table 2.

Table 2. Sensitivity parameters for the liquid- and gas-based value chains

Treatment line	Parameter
Liquid treatment	Base oil recovery rate (wt.%)
	membrane purchase prices (€/m^2)
	Membrane lifetime (yr)
	Membranes fluxes (kg/hr/m^2)
	Cleaning frequency (yr^{-1})
	Membrane temperature (°C)
	ULO purchase cost (€/ton)
	Heat cost (€/MWh)
Gas separation	H_2 recovery rate (%)
	CO_2 capture rate (%)
	COG treatment capacity (kg/s)
	COG purchase cost (€/ton)
	Membrane lifetime (yr)
	SiC/SiCN membrane price (€/m^2)
	CO_2 tax (€/ton_{CO_2})

4. RESULTS AND DISCUSSION

4.1 Market study

Used lubricant oils are generated as a by-product of various industrial and transportation activities. These oils are contaminated with impurities, such as dust, fuel, water, exhaust gases, coolant, acids, and metallic particles, which can adversely affect the performance of the lubricant and harm the environment if not properly treated (Raţiu et al., 2021). According to a report by Chemical Market Forecast, the European lubricants market was valued at $36 billion in 2020 and is projected to reach $38.7 billion by 2029. In Europe, there is a growing demand for efficient and sustainable technologies for used lubricant oil treatment to minimize environmental pollution and conserve natural resources (GEIR, 2016; Pinheiro et al., 2021). Thus, the European Union (EU) has implemented stringent regulations to promote the proper collection, transportation, and treatment of used lubricant oils (Pinheiro et al., 2021). The EU Waste Framework Directive (2008/98/EC) establishes a waste hierarchy that prioritizes waste prevention, recycling, and recovery over disposal. In addition, the EU End-of-Waste (EoW) criteria for used lubricant oils provide guidelines for determining when these oils cease to be classified as waste and can be used as a product or raw material without further treatment. These regulations have created a favorable environment for the growth of the used lubricant oil treatment market in Europe, as companies are required to comply with these regulations to minimize their environmental impact (Kupareva et al., 2013).

Coke oven gas (COG) is a by-product of the steel industry, and the annual EU COG production is in the range of 8.4 BNm^3 (Eurofer, 2022). COG is a usually used for energy recovery but separating the large portions of H_2 and CO_2 from the COG before energy recovery could provide a new source of value (Portha et al., 2021). Whether it is profitable will depend on the future market prices of energy vs hydrogen and CO_2. A recent report by the Joint Research Commission shows that the EU steel industry is mainly focused on the use of hydrogen to decarbonise the industry (Somers, 2022). The Global hydrogen market for all purposes is expected to grow from 90Mt/yr hydrogen in 2022 to over 300 MT/yr by 2050 (DNV, 2023). Recovered hydrogen from the COG could be sold into this growing market or reused directly by the steel producer to directly reduce iron. As for the reduction or capture of carbon dioxide from the flue gas, it will continue to be driven by government regulation until a market develops for captured CO_2.

4.2 TEA results

In this section, the findings relative to the techno-economic assessment of the considered processes are described. First, the results for the benchmark cases (for both the liquid and gas lines) are briefly presented and commented. Then, the findings for the membrane processes are detailed and discussed.

Liquid treatment line

Mass and energy balances

The mass and energy balances for the benchmark case were mostly provided by OSILUB, where the traditional process for ULO re-refining is used. The process treats about 15 ton/hr of ULO and results in a flow of base oil (class I) of 10.2 ton/hr. This is where the actual process used by OSILUB ends. In the CUMERI model, we also investigated the inclusion of a hydrotreatment step.

Regarding the membrane processes, three types of multi-step membrane processes were considered to recover base oil from ULO. As mentioned previously, the difference between these processes manifests in the level of pretreatment and the detailed sequence of filtration steps. For all the membrane processes, a similar ULO treatment capacity to the benchmark was considered (15 ton/hr). All processes result in a flowrate of base oil of 10.17 ton/hr.

Economic assessment

In the baseline benchmark process, the hydrotreatment is not considered. For the benchmark, it can be concluded that the pre-treatment equipment and the distillation tower account for the largest part of the CAPEX while the boilers only contribute by about 10%. For the membrane alternatives, the membranes and the optional pre-treatment equipment make up the bulk of the CAPEX. If no pre-treatment is necessary, the total CAPEX will be significantly lower (~50%).

Moreover, for all of the considered processes, findings show that the ULO purchase contributes the most to the OPEX, with an average share of 64%, followed by natural gas/heat purchase (15% on average), and personnel wages (9% on average). It is important to note that the membrane processes consume less energy compared to the benchmark (up to ≈72%), which translates into cheaper energy expenditures. These energy-costs savings are one of the benefits associated with adopting the membranes processes instead of (energy intensive) traditional ULO re-refining processes. It is also interesting to keep in mind that a higher level of ULO pretreatment results in higher operating expenses for the membrane processes.

The main contribution to the base oil recovery cost (for the membrane processes) comes from ULO purchase (61% on average), followed by equipment replacement (15% on average), heating (13% on average), and labour (9% on average). The large contribution of the replacement costs comes from the assumption that the membranes need to be replaced each time their lifetime is elapsed, which is relatively short compared to the processes' lifetime (3 years vs. 25 years).Due to the low contribution of the capital investment to the base oil recovery cost, we report that there is room for using higher cost (more advanced) membranes that could have better fluxes and longer lifetimes.

In addition to the main product (base oil), the asphalt-like by-product (about 20% of the total yield) also has an economic value. Though not significant, the revenue obtained by selling the by-products could offset a fraction of the base oil recovery costs. The product revenues generated by selling at the baseline prices were calculated. In all cases the revenue of the by-product constitutes only about 6% of the total revenues

Sensitivity analysis

In this section, the impacts of several key parameters (both technical and economic) on the base oil recovery cost are evaluated. Regarding the technical input parameters, the most significant cost drivers are the membranes' lifetime (yr), flux (kg/s/m²), temperature (°C), and cleaning frequency (yr^{-1}), in addition to the base oil recovery rate (wt.%). As for the economic input parameters, it is the ULO purchase price (€/ton), heating costs (€/MWh), labour expenses (€/yr), membranes purchase price (€/m²), and base oil and asphalt-like material selling prices (€/ton) that mainly influence the cost.

Starting with the base oil recovery rate, it was varied from 20 to 100%. This range captures the worst- and best-case scenarios for base oil recovery. Findings show that the recovery cost of the base oil is highly sensitive to variations in its recovery rate and is preferentially above 90% to reach the same value as for the benchmark case (under baseline assumptions).

Furthermore, the lifetimes of the membranes were varied from 1 to 9 years. This range allows evaluating a wide distribution of membrane lifetimes, which is in line with typical values reported in literature for ceramic membranes (Dilaver et al., 2023). The base oil recovery cost is very sensitive to variations in the lifetimes of membranes when they are lower than 5 years. For membrane lifetimes longer than 5 years, the decrease in the recovery price seems less significant.

Moreover, regarding the fluxes of the ceramic membranes, they were varied from 5 to 60 kg/hr/m². This range includes a wide spectrum of operating conditions for ceramic membranes, from a very restricted to an open flow. We report that the flux has a moderate impact on the base oil recovery cost for values between 5 and 15 kg/hr/m². However, variation in flux values, when they are higher than 15 kg/hr/m², have nearly no effects on the base oil recovery cost in the current model.

Concerning the effects of the membranes' temperature and cleaning frequency, varying the membranes' operating temperatures or their cleaning frequencies does not induce a significant change in the financial performance of the processes. However, in this analysis, we did keep the membrane flux constant when changing the temperature. This is most likely not a realistic situation, and this interdependency will be included in Work Package 6, when also more membrane performance data is available.

Additionally, the purchase prices of membranes were varied across a wide spectrum (400-4000 €/m²) that includes the typical prices for ceramic membranes (Dilaver et al., 2023). Such a broad range was selected to reflect the typical high variability associated with membrane prices. Findings show that also this parameter does not have a significant impact on the economic performance of the membrane processes under the current assumptions made.

Moreover, the ULO purchase price, the heating cost, and the labour expenses were respectively varied from 75 to 300 €/ton, 64 to 160 €/MWh, and 1.5 to 6.2 M€/yr. Results indicate that the financial performance of the processes has a relatively high dependence on the ULO purchase price, as a 25% decrease in the latter has the potential to reduce the base oil recovery cost by 13%. The processes' economic performance is less sensitive to variations in the heating and labour expenses.

In all analysed cases, keeping the level of pre-treatment in the membrane process minimal, gives the best economic performance. And if no pre-treatment is needed, the membrane process is more economic than the benchmark process, in most of the analysed parameter conditions.

Gas separation line

Mass and energy balances

The mass and energy balances for the gas separation line scenarios were mostly obtained through Aspen plus simulations. The gas separation process is considered to treat 5 kg/s of coke oven gas. For the benchmark process, a stream of 0.53 kg/s of H_2 is generated in the PSA unit and the MEA unit results in capturing 9.3 kg/s of CO_2.

Regarding the membrane process, the coke oven gas is introduced to the SiC/SiCN membrane. A stream of 0.47 kg/s of H_2 is separated. After the oxycombustion the PEBA membranes capture 7.3 kg/s of CO_2.

Economic assessment

Findings confirm that the membrane process would require much less capital investment (by about 57%) compared to a traditional coke oven gas treatment process. This is mainly attributed to the much lower cost of the SiC/SiCN and PEBA membranes compared to the MEA and PSA (by more than 96% and 99%, respectively). For the benchmark, the MEA unit makes up most of the CAPEX (38%), followed by the PSA unit (23%). Regarding the membrane process, the compressors and gas cleaning unit take up about 82% of the CAPEX, whereas the membranes, and other equipment have a minor contribution (18%). We mention that due to the small contributions of the membranes' capital investments, it is likely that there will be room for using higher cost (and consequently more advanced) membranes that could have a better performance.

Moreover, results indicate that the major contribution to the benchmark process' OPEX comes from the site maintenance (41%), followed by the purchase of oxygen (16%), purchase of electricity (14%), and equipment repair (8%). Regarding the membrane process, the purchase of electricity and oxygen and the equipment maintenance make up the bulk of the OPEX (76%), followed by labour costs (6%), and cooling water purchase (5%). These results indicate that using the SiC/SiCN membrane (instead of PSA) and the PEBA membrane (instead of MEA) results in 25% less operating expenditures. It is important to mention that the costs associated with electricity purchase for the membrane process are higher by 43% compared to the benchmark. This is a result of the extra equipment (i.e., compressor and vacuum pump) needed for the membrane process.

Regarding the membrane process, the main contribution comes from investment (32%), followed by electricity purchase (29%), oxygen purchase (19%), and site maintenance (19%). Regarding revenues, they were lower by 9% for the membrane process compared to the benchmark. This is due to the lower hydrogen separation rate of the SiC/SiCN membrane compared to the PSA, which results in lower quantities of H_2 available for sale. This can be remedied by improving the H_2 separation rate of the SiC/SiCN membranes, which is within the objectives of CUMERI. In addition to H_2 (considered as the main product), the generated steam also has an economic value. The sale of steam contributes, on average, by 38% to the total revenues of both the benchmark and the membrane process.

Sensitivity analysis

In this section, we evaluated the effects of several key parameters (both technical and economic) on the hydrogen recovery cost for two processes, i.e., the benchmark (representative of the traditional COG treatment practices) and the membrane process. From a technical standpoint, the cost is mainly influenced by the hydrogen recovery and CO_2 capture rates (%), and membranes' lifetime (yr). From an economic perspective, the most important cost drivers are the coke oven gas purchase price (€/ton) and the SiC/SiCN membrane purchase price (€/m²).

The H_2 recovery and CO_2 capture rates were both varied from 60 to 100%. This range captures the worst- and best-case scenarios, as well as the ranges that are targeted in CUMERI (>80% for H_2 recovery and >90% for CO_2 capture). Findings show that the hydrogen recovery cost is more sensitive to the H_2 recovery rate compared to the CO_2 capture rateThis indicates that more efforts may have to be directed towards the development and improvement of the SiC/SiCN membranes.

Concerning the membranes' lifetime, it was varied from 1 to 15 years. The selected range includes the typical values for membranes lifetimes as well as CUMERI targets (>7-10 years for SiC/SiCN membranes and >15 years for PEBA membranes). The hydrogen recovery cost is highly sensitive to variations in the lifetimes of membranes when they are shorter than 4 years. Nonetheless, for membrane lifetimes longer than 4 years, the decrease in the recovery price is minor.

Moreover, we evaluated the case where the coke oven gas would not be freely available (similar to the need for purchasing ULO in the liquid treatment line). This corresponds to imposing a price on coke oven gas purchase, which was varied from 0 to 80 €/ton (Li and Cheng, 2020). The results indicate that there is a relatively moderate impact of the coke oven gas price on the hydrogen recovery cost.

Furthermore, since the CO_2 capture is less than 100%, some CO_2 gas is expected to be released to the atmosphere. Therefore, a carbon tax value was assigned and varied from 0 to 100 €/ton. We concluded that the hydrogen recovery cost is sensitive to variations in the CO_2 tax, as having to pay as little as 50 €/ton would result in relatively higher H_2 recovery cost (by 3%).

Additionally, the purchase prices of the considered membranes were varied across broad ranges (50-1850 €/m² for SiC/SiCN membranes and 20-200 €/m² for PEBA membranes) (FluidCELL, 2018; Lin, 2019). These wide spectrums were adopted in an attempt to capture the significant variability of membrane prices. Results indicate that this parameter does not have a noticeable impact on the financial performance of the membrane process. This is probably due to the low contribution of the membranes to the total investment costs as shown previously. These findings are particularly interesting since they confirm the possibility of using more expensive (therefore more performant) membranes.

Finally, the coke oven gas treatment capacity of the membrane process was varied from 10^{-3} to 10 kg/s (7.3 Nm^3/hr to 73.4 kNm^3/hr). This range includes the expected COG treatment capacity of the pilot system (10 Nm^3/hr) as well as the total production at ERDEMIR (36 kNm^3/hr), which (the latter) was taken as the baseline (5 kg/s). Results show that the hydrogen recovery cost decreases steeply as the COG treatment capacity is increased, which holds true until about 0.03 kg/s. As the scale of the process is increased, the hydrogen recovery cost drops down significantly and can reach competitive values of less than 3 €/kg at 5 kg/s.

4.3 LCA results

In this section, the findings related to the initial life cycle assessment of the processes are described. The results are presented at both the ReCiPe Midpoint and ReCiPe Endpoint level. The Endpoint level results are provided to provide additional context for discussion and should be interpreted with caution. It is noted that endpoint aggregation is not a requirement of ISO 14044 (ISO 14044, 2006).

A contribution analysis is performed for the Impact Category Global Warming Potential to understand the main contributing processes in both the Gas and Liquid Separation Systems.

Both the Liquid Separation Line and the Gas Separation line results in the coproduction of marketable goods other than the Functional Unit (Liquid coproducts= Asphalt; Gas coproducts= Hydrogen, Steam). Accounting for these coproducts is the only fair way to compare these systems, as they have the potential to replace the same amount of conventionally produced goods.

The ISO 14044 standard is clear that allocation should be avoided wherever possible (ISO 14044, 2006). Allocation occurs when a single process has multiple co-products, and the impacts of the process are divided between the co-products based on a defined relationship. The ISO standard states allocation should be avoided by either; dividing a larger process into smaller subprocesses or expanding the product system to include the additional functions related to the coproduct. The second choice, system expansion, is usually interpreted in two ways: system expansion and substitution. System expansion actually expands upon the functional unit to include the function of the coproducts. Substitution reduced the multifunctional system by subtracting the avoided burdens related to the co-products. (Heijungs et al., 2021). Whether these burdens are added (system expansions) or subtracted (substitution) is theoretically the same but changes how the results are presented and potentially interpreted. An amendment to ISO 14044 in 2020 refined the term system expansion to be in line with the second option, substitution (Heijungs et al., 2021).

For the present study, one scenario of the LCA includes the second option, substitution. This assumes that any coproducts can be used as a direct substitute for the conventionally produced product (Asphalt separated from Liquid Line directly replaces the production of Asphalt), such that the avoided impacts are subtracted from our system. This is an important assumption which will be revisited when the full LCA is completed. To ensure it does not skew insights for the present study, substitution is included in only one scenario. It should be noted that the three membrane systems produce similar amounts of coproducts so substitution should affect them to a similar extent. Caution should be taken when comparing the results to other systems that may have different or no coproducts.

The Baseline results presented below do not include substitution. They present overall system impacts for the defined functional units.

Liquid treatment line

The liquid separation system has 6 different systems to compare across all impact categories. These include the benchmark system with and without hydrotreatment (resulting in Class 2 and Class 1 oil respectively), the three membrane alternatives also used for the TEA and a Virgin Lubricating Oil production process from the Ecoinvent Database. Including a benchmark without Hydrotreatment can provide insight into the additional step of Hydrotreatment, while Including virgin lubricating oil production provides additional perspective. These systems will be presented with Baseline Assumptions, a Substitution scenario, and a sensitivity check for membrane lifetime and electricity source.

All midpoint impacts

It is difficult to present the results for all impact categories in a succinct but meaningful way as the impact category results span a range of magnitudes. The following results have been normalized to the maximum value within each impact category, such that the relative impacts can be displayed in one image.

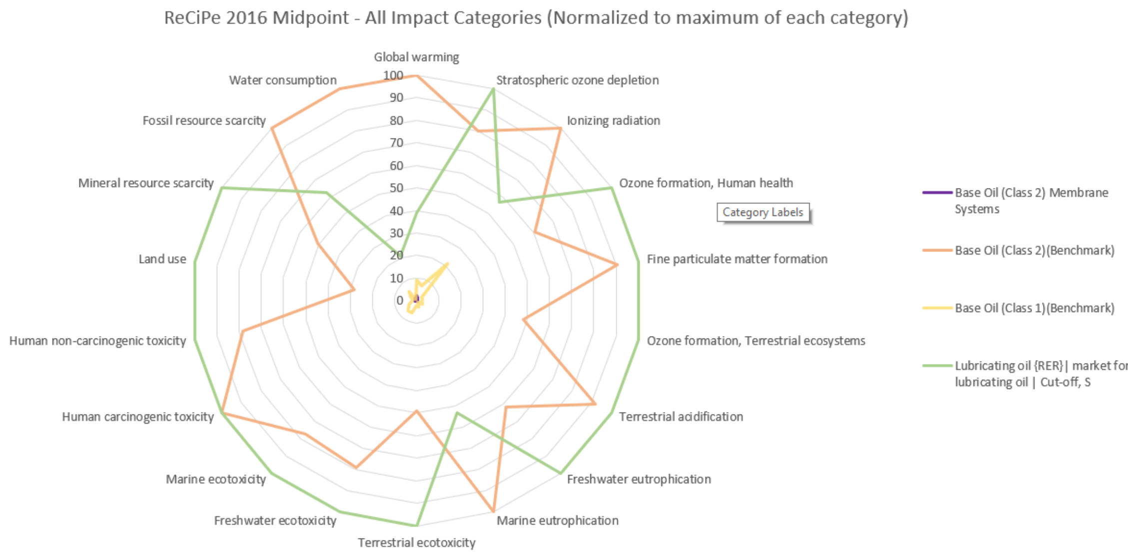

Figure 5. Liquid Separation Baseline LCA Midpoint Results

Figure 5 shows that even at the baseline assumptions, the Membrane alternatives are likely to be significantly better across all impact categories. The Benchmark case with Hydrotreatment (class 2) and the Lubricating Oil production system within Ecoinvent have the highest impacts across all impact categories. The low relative impact of the Benchmark without Hydrotreatment (Class 1) shows that most impacts of the benchmark can be attributed to the Hydrotreatment process.

A more detailed analysis showed that the membrane results are clearly lower when the level of pre-treatment is decreased.

Midpoint: Substitution of coproducts scenario

As mentioned earlier, a scenario for investigating the effect of substituting coproducts is performed. Substitution may become an important consideration in the full LCA work if the functional unit is revised to be recovered base oil to allow a fair comparison with alternative products. This scenario assumes that coproducts can directly replace their conventionally produced alternatives. The system then subtracts the impacts of producing the coproducts in the conventional system to account for their value. This should then allow for a fairer comparison of producing 1 kg base oil from the membrane system to 1 kg of base oil from an entirely different system, regardless of coproducts.

This analysis shows many of the impacts of the Membrane systems to be negative. This is because the impacts of producing the coproducts in a conventional system are greater than the impacts of recycling the used oil in the Membrane System. However, the substitution of coproducts does not compensate all the impacts. The analysis shows that for the impact categories of Global Warming and Ionizing Radiation, including the substitution of coproducts does not compensate for all the impacts in case a high level of pre-treatment is required in the membrane system.

Some model parameters were adjusted to see the sensitivity in the baseline assumptions case. These include the doubling of membrane lifetimes from 3 to 6 years, switching from the French National Electricity Mix to the European average (RER), and the already completed scenario for substitution.

As noted above, addressing coproducts and substitution assumptions will be most important when comparing the Membrane processes with other Lubricating Oil Systems. Regarding electricity source, the more energy intensive membrane processes with a high level of pre-treatment are more sensitive to a change in the electricity source. This is an obvious conclusion when comparing processes that are energy intensive. Depending on the final setup of the membrane processes the source of electricity may be a relevant parameter. Doubling the lifetime of the membranes had a small effect on the Global Warming category. However, a future sensitivity check needs to be conducted across all impact categories when there is a detailed understanding of the membrane production systems.

Contribution Analysis - Climate change

Figure 5 shows overall system impacts across impact categories, but do not show the contribution of the individual system processes. As a first contribution analysis, the focus was on contribution to Climate Change. The 3 membrane systems and the Benchmark with Hydrotreatment are focused on. From this analysis, it is possible to gain more insight into the main contributing processes within each system. For the membrane alternatives, including a pre-treatment process the membrane contribution on Climate Change. In the Benchmark case with Hydrotreatment the main contributor accounting for around 90% is the Hydrogen used in the hydrotreatment process.

Endpoint Impacts

Going to the Endpoint impact categories can be informative as an exploration as it allows an overall comparison across all impact categories. Aggregating results to the Endpoint adds additional uncertainty and value judgements, and should be interpreted with caution. The method used is ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H (Huijbregts et al., 2016). It is possible to compare the Endpoint results as a single score as well as at the damage level in 3 different Areas of Protection. Human health is measured in Disability Adjusted Life Years (DALY), Ecosystem Health in Species/year, and Resources in 2013 United States Dollars. The single score results are normalized to the unit milli points (MPt).

The Endpoint results show the different scales of the Benchmark with Hydrotreatment (>10x Membrane Systems) and Virgin Lubricating Oil production (>6x Membrane Systems). This reiterates the value in developing membrane systems and especially on reducing the energy intensity.

Liquid treatment line - LCA summary

- All membrane systems perform significantly better than the modelled Benchmark and Virgin Lubricating Oil production systems.
- The Membrane systems perform best when no pre-treatment is needed.
- The Climate Change contribution analysis shows one should avoid hydrotreatment if possible. The Benchmark with Hydrotreatment is the only system to perform worse than Virgin Lubricating Oil. An interesting future study would be testing the effect of different sources of Hydrogen.
- The Substitution scenario results reveal that the value of coproducts is important and how one accounts for their associated environmental impacts can affect the results greatly. The capture and sale of coproducts is essential to displace the virgin production of these streams. This assumption and the treatment of coproducts are identified as important assumptions and will be addressed further during the full LCA work.

Gas separation line

The Gas Separation System has 3 different systems to compare across all impact categories. These includes the systems: Benchmark (with PSA and MEA), Membrane System, and direct release of Coke Oven Gas.

Including a scenario in which the Coke Oven Gas is directly released to the air can provide some context and answer the question "is the investment worth it?". Emissions controls systems are usually driven by government regulation, but by using LCA we can ignore economic penalties or incentives and answer this question on an environmental accounting basis.

As with the Liquid Separation Line, these systems will be presented with Baseline Assumptions, a Substitution scenario, and a sensitivity check for membrane lifetime and electricity source. In the Gas separation case, the potentially substituted products include Hydrogen captured during the PSA and SiC Membrane steps, and the Steam produced from Oxyfuel combustion.

Additionally, the Captured CO_2 must be taken into consideration. In the current Scope, the Coke Oven Gas is seen as a free input and therefore we lose some insight. Whether it is worth it to invest in Carbon capture technology will depend on the overall system impacts and not just the post combustion steps, which includes the system that created the Coke Oven Gas. Additionally, the fate of the captured carbon is not determined yet: will it be stored long term? Will it be used as a feedstock? Likely there will be different answers depending on the quality and market demand. To clearly distinguish the impact of capture, the amount of Captured Carbon will remain separated from the impact assessment and is treated as a product. In the Climate Change Contribution Analysis, the amount of Captured Carbon will be compared to the LCA Climate Change impact of the processes.

Midpoint

It is difficult to present the results for all impact categories in a succinct but meaningful way as the impact category results span a range of magnitudes. As with the Liquid Separation, the following results have been normalized to the maximum value within each impact category, such that the relative impacts can be displayed in one image.

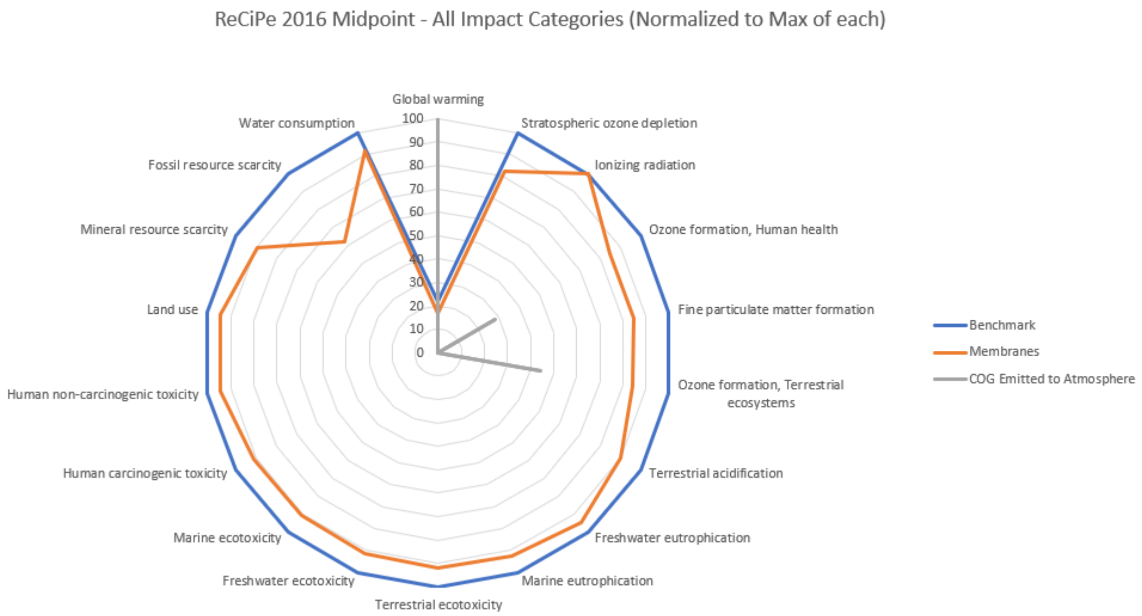

Figure 6. Gas Separation Baseline LCA Midpoint Results

The analysis shows that at the baseline assumptions, the Membranes system is likely to perform better than the benchmark case using PSA and MEA across all impact categories except for Ionizing Radiation It is interesting to see the impact of releasing the COG directly to the atmosphere; its contribution to Global Warming is a magnitude higher than the benchmark case but has the lowest contribution in all other impact categories.

The effect of including substitution of coproducts is not as visible as in the Liquid line case. Both capture systems show that absolute impacts decrease but the relative impacts stay similar. This is due to the two systems producing similar amounts of the coproducts.

Some model parameters were adjusted to see the sensitivity in the baseline assumptions case. These include the doubling of membrane lifetimes from 5 to 10 years, switching from the Turkish National Electricity Mix to the European average (RER), and a scenario for substitution. The greatest reduction across impact categories is seen by substituting virgin Hydrogen and Steam production with the captured coproducts. Regarding electricity source, there is a similar reduction in impacts by switching to the less carbon intensive European Grid average from the Turkish grid. Doubling the lifetime of the membranes has a relatively small effect (~-4.8%) on Climate Change. A future sensitivity check needs to be conducted across all impact categories when there is a detailed understanding of the membrane production systems.

Climate Change Contribution Analysis

The above results show overall system impacts across impact categories, but do not show the contribution of the individual system processes. As a first contribution analysis, the focus will be on contribution to Climate Change. From this analysis, it is possible to gain more insight into the main contributing processes within each system. In the Benchmark system, impacts stem from the production of Oxygen for the Oxyfuel Combustion process (~47.5%) and the MEA Carbon Capture process (~44%). The Membranes system impacts can be contributed to the production of Oxygen for Oxyfuel

Combustion (~61%), followed by the PEBA process (~16%), and production of both Membranes (~9.5%). Sourcing Oxygen from a less impactful production method may have a significant effect on the results for both capture systems.

LCA Endpoint

The Gas separation case presents an interesting case for using the Endpoint method to derive additional meaning. As seen in the Midpoint results, the direct release of COG has a relatively high Climate Change impact, but none to minimal impact in all other categories. Does that mean it would be better to not invest in the capture processes and simply release the COG? We can answer this question by weighting the relative importance the different impact categories to allow a comparison. As identified previously, the method and weighting set used is ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H. This analysis shows the Membrane process to perform best in the Human Health and Ecosystems Area of Protection, but only second best in Resources. Directly releasing the COG to atmosphere requires no resources.

When weighed further against each other and normalized, a single score is calculated measured in MPt. The single score of releasing COG is still higher than the capture options even after accounting for the low impact in most Midpoint categories. The Membranes capture system performs better than the benchmark, and any capture process is better than none.

Gas separation line - LCA summary

- The membranes capture system performs better compared to the benchmark across all Midpoint impact categories except Ionizing Radiation.
- In the Climate Change category, the Benchmark system impacts stem from the production of Oxygen for the Oxyfuel Combustion process (~47.5%) and the MEA Carbon Capture process (~44%). The Membranes system impacts can be contributed to the production of Oxygen for Oxyfuel Combustion (~61%), followed by the PEBA process (~16%), and production of both Membranes (~9.5%)
- Sourcing Oxygen from a less impactful production method may have a significant effect on the results for both capture systems. This is a point for future exploration in the full LCA.
- It is an environmentally beneficial investment to capture the COG. Its significantly higher contribution to Climate Change overshadows any savings in the other Midpoint impact categories. This is also supported by the Endpoint analysis.

5. CONCLUSIONS AND NEXT STEPS

The main conclusions of the preliminary TEA and LCA studies are summarized as follows:

Liquid treatment line

- Membranes and optional pre-treatment equipment constitute the bulk of the CAPEX for the membrane alternative processes.
- The total CAPEX of the membrane processes is significantly lower (≈50%) when no pre-treatment is performed.
- The membrane processes consume less energy (by up to ≈72%) compared to the benchmark, resulting in cheaper energy expenditures.
- Membrane lifetimes significantly impact the base oil recovery cost, especially when shorter than 5 years.

- Variations in the membrane fluxes (when > 5 kg/hr/m² range) have a moderate to low impact on the base oil recovery cost.
- The LCA results suggest all membrane systems perform significantly better than the modelled Benchmark and Virgin Lubricating Oil production systems.
- Across impact categories, the Membrane systems perform best when no pre-treatment is needed.
- The Climate Change contribution analysis shows one should avoid hydrotreatment if possible. The Benchmark with Hydrotreatment is the only system to perform worse than Virgin Lubricating Oil. An interesting future study would be testing the effect of different sources of Hydrogen.
- The Substitution scenario results reveal that the value of coproducts is important and how one accounts for their associated environmental impacts can affect the results greatly. The capture and sale of coproducts is essential to displace the virgin production of these streams.

Gas separation line

- The membrane process requires 57% less capital investment compared to traditional coke oven gas treatment processes.
- The major contributions to the membrane process' CAPEX comes from compressors and gas cleaning units (82% of CAPEX).
- Electricity purchase for the membrane process is higher by 43% due to additional equipment requirements.
- Purchase prices of membranes have no noticeable impact on the financial performance of the membrane process.
- Increasing the coke oven gas treatment capacity decreases the hydrogen recovery cost significantly, reaching competitive hydrogen recovery costs (less than 3 €/kg) at capacities higher than 5 kg/s.
- The LCA results suggest the membranes capture system performs better compared to the benchmark across all Midpoint impact categories except Ionizing Radiation.
- In the Climate Change category, the Benchmark system impacts stem from the production of Oxygen for the Oxyfuel Combustion process (~47.5%) and the MEA Carbon Capture process (~44%). The Membranes system impacts can be contributed to the production of Oxygen for Oxyfuel Combustion (~61%), followed by the PEBA process (~16%), and production of both Membranes (~9.5%)
- Sourcing Oxygen from a less impactful production method may have a significant effect on the results for both capture systems. This is a point for future exploration in the full LCA.
- It is an environmentally beneficial investment to capture the COG. Its significantly higher contribution to Climate Change overshadows any savings in the other Midpoint impact categories. This is also supported by the Endpoint analysis.

In WP6, the analysis will be further refined by focusing on improving the TEA and LCA model's accuracy. This will be achieved by incorporating experimental data (provided by partners) into the models for mainly membrane fluxes and lifetimes, CO_2 capture rate, and base oil and H_2 recovery rates. It is also planned to include the membranes' manufacturing processes in the models, which will allow obtaining more realistic estimates for the costs and environmental impacts of the different considered membranes. Moreover, the interdependencies between the different parameters (e.g., flux and temperature) will be taken into account to make the developed model more dynamic. Specific to the LCA, more detailed scenarios for the substitution of coproducts, and alternative hydrogen and oxygen sources will be developed to better understand the future potential of these membrane systems.

References

Dilaver, M., Soydemir, G., Çelebi, M.D., Hocaoğlu, S.M., Keskinler, B., Ağtaş, M., Koyuncu, İ., Alp, K., 2023. Highly alkali caustic discharges recovery using tubular and disc type of ceramic membranes and its applicability as a near zero liquid discharge opportunity in the textile industry (preprint). In Review. https://doi.org/10.21203/rs.3.rs-2311523/v1

Emam, E.A., Shoaib, A.M., 2013. RE-REFINING OF USED LUBE OIL, I- BY SOLVENT EXTRACTION AND VACUUM DISTILLATION FOLLOWED BY HYDROTREATING.

Eurostat, 2022. Eurostat [WWW Document]. Energy Database. URL https://ec.europa.eu/eurostat/web/energy/database

GEIR, 2016. Waste framework directive revision: European waste oil re-refining industry position.

Kupareva, A., Mäki-Arvela, P., Murzin, D.Yu., 2013. Technology for rerefining used lube oils applied in Europe: a review: Technology for rerefining used lube oils applied in Europe. J. Chem. Technol. Biotechnol. 88, 1780–1793. https://doi.org/10.1002/jctb.4137

Lau, P.J., Ng, W.P.Q., How, B.S., Lim, C.H., Lam, H.L., 2022. Paving a way toward circular economy for oil and gas industry: A conceptual modelling of re-refining process through solvent extraction and hydrofinishing pathway. J. Clean. Prod. 380, 134839. https://doi.org/10.1016/j.jclepro.2022.134839

Li, J., Cheng, W., 2020. Comparative life cycle energy consumption, carbon emissions and economic costs of hydrogen production from coke oven gas and coal gasification. Int. J. Hydrog. Energy 45, 27979–27993. https://doi.org/10.1016/j.ijhydene.2020.07.079

Maxwell, C., 2023. Cost Indices [WWW Document]. Towering Ski. URL https://toweringskills.com/financial-analysis/cost-indices/ (accessed 6.13.23).

Oliveira, C., Schure, K.M., 2020. Decarbonisation options for the Dutch refinery sector.

Peters, M.S., Timmerhaus, K.D., West, Ronald E., West, Ronald Emmett, 2004. Plant design and economics for chemical engineers, 5. ed, international ed. 2004. ed, McGraw-Hill chemical engineering series. McGraw-Hill, Boston.

Pinheiro, C.T., Quina, M.J., Gando-Ferreira, L.M., 2021. Management of waste lubricant oil in Europe: A circular economy approach. Crit. Rev. Environ. Sci. Technol. 51, 2015–2050. https://doi.org/10.1080/10643389.2020.1771887

Portha, J.-F., Uribe-Soto, W., Commenge, J.-M., Valentin, S., Falk, L., 2021. Techno-Economic and Carbon Footprint Analyses of a Coke Oven Gas Reuse Process for Methanol Production. Processes 9, 1042. https://doi.org/10.3390/pr9061042

Raţiu, S., Josan, A., Alexa, V., Cioată, V.G., Kiss, I., 2021. Impact of contaminants on engine oil: a review. J. Phys. Conf. Ser. 1781, 012051. https://doi.org/10.1088/1742-6596/1781/1/012051

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