Project no. 608535

# INTERACT

INnovaTive Enzymes and polyionic-liquids based membRAnes as CO2 Capture Technology

## Deliverable D6.1:

# Report on expected energy penalty for each technology based shortcut models developed based on data of initial performance testing of each technology

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# Summary

The objective of this deliverable is to report the expected energy penalties of the innovative carbon capture technologies under investigation by the INTERACT project. These information should indicate if these novel technologies are capable to lead to a breakthrough in terms of carbon capture.

Different technologies are investigated: enzyme supported absorption/desorption processes, gas separation membrane processes and membrane contactor processes. For each of these key technologies individual process concepts for whole carbon capture applications have been developed. Shortcut models of the innovative process steps have been created based on data of initial experimental performance testing as well as on fundamental insights obtained from the analysis of the chemical and thermodynamic behaviour of the components involved. They facilitate heat and mass balancing using the commercial process simulation software Aspen Plus. For each process concept a parameter study is conducted to investigate the impact of operating selected unit-operations on different operations conditions (e.g. operation of absorbers or strippers at different pressure levels etc.). Based on the outcome of the simulation the performance of each technology is estimated.

To enable a fair and significant evaluation of the resulting performances a so-called Base Case is developed that serves as a benchmark process. This conventional carbon capture scenario represents the application of state-of-the-art technology along with best practice of operation and has been set-up using the information and data published by the European Benchmark Task Force (EBTF) by its document "European best practice guidelines for assessment of $CO_2$ capture technologies" [1].

For all the cases investigated, a $CO_2$ capture rate of 90 % is applied. The energy consumptions of each case are quantified as primary energy equivalent. By definition the Base Case represents an energy penalty ratio of 100% caused by the conventional EBTF-$CO_2$ capture process. The results of the application the novel technologies are expressed relative to the one of the base case:

| **Innovative Case** | **Energy penalty ratio[1]: $EP_{Innocative\ Case}$ / $EP_{Base\ Case}$ * 100%** |
|---|---|
| Enzyme-intensified capture processes | 74 … 116 % |
| Gas separation membrane processes | 62 … 98 % |
| Membrane contactor processes | 79 … 121 % |

It becomes obvious that for each INTERACT technology a process configuration can be identified that exhibits a superior performance compared to the Base Case. Taking into account the best process configurations available at this stage, the energy penalty of the conventional capture is undercut by up to 38%.

[1] The given ranges represent the energy penalty ratios of different process configurations that have been investigated in the framework of the parameter studies on the diverse technologies.

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# 1. Introduction

The INTERACT project aims at the development of innovative technologies to capture carbon dioxide selectively from industrial gas mixtures. Innovative processes steps, like the usage of enzyme-supported solvents as well as of novel membranes for gas separation and membrane contactor application, are applied to intensify the $CO_2$ removal and recovery process.

The capabilities and limitations of these novel key technologies are investigated experimentally by the partners of the INTERACT project. Based on insights obtained from initial performance tests as well as from the analysis of the thermodynamic and chemical behaviour of the capture systems promising process concepts for intensified carbon capture are developed. Exploiting short cut models these concepts are used to examine the performance of the particular technologies in the framework of an industrial $CO_2$-emission scenario (decarbonization of the flue gas of a coal based power plant, 'ASC' [1]).

The commercial process simulation software Aspen Plus is used to conduct heat and mass balancing of the INTERACT process concepts. Upon the results generated the performance of the novel capture technologies is estimated.

The comparison of process alternatives is carried out based on their expected energy consumption which represents the energy penalty (EP) of the capture process from a $CO_2$ emitter's point of view. A Base Case, reflecting the use of state-of-the-art technology and corresponding operating practice, serves as benchmark.

The current report summarizes the findings of the above mentioned study and presents the energy penalties related to the application of the innovative INTERACT technologies. Commencing with general information and definitions in section 2, section 3 describes the Base Case. The outcome of the investigation of the enzyme-intensified processes is given by section 4, followed by the discussion and results of the gas separation membrane processes as well as of the membrane contactors in the sections 5 and 6, respectively.

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# 2. Procedure, framework and comparability

The key target of the scouting study is to compare innovative INTERACT $CO_2$ capture technologies upon the basis of their specific energy demands and the corresponding energy penalties in a meaningful and fair way.

## 2.1. Procedure and framework

For each novel INTERACT technology conceptual design is carried out to develop process set-ups that allow the selective separation and recovery of carbon dioxide from a gas mixture. These whole process concepts are created systematically based on fundamental insights on the thermodynamic and chemical behaviour of the components present.

In addition, shortcut models of the novel INTERACT key technologies have been developed upon data that has been extracted from first experimental investigations. By the use thereof the generation of heat and mass balances is facilitated using the commercial process simulation software Aspen Plus. Concerning each process concept a parameter study is carried out to investigate different operation conditions, e.g. operating absorption and/or desorption processes at different pressure levels etc. The impact of the varied parameters on the whole process performance becomes visible and promising ranges of operations parameters are indicated.

The process concepts are generated in the framework a $CO_2$-emission scenario; the same scenario is applied consistently for all processes investigated. Coal-based power plants are selected as emitters of the $CO_2$-rich gas stream which needs to be purified. The reason for this choice is their wide-spread application and their significance for climate change by high volume emission of carbon dioxide. Following the European Benchmark Task Force (EBTF) [1], the Advanced Supercritical Pulverized Bituminous Coal power plant (ASC plant) represents this class of power plants. Thus, its flue gas stream as given by [1] is used as feed stock to the $CO_2$ capture processes investigated in this study.

The processes are designed to separate 90 % of the carbon dioxide found in the flue gas stream of the ASC plant. The $CO_2$ captured is provided “ready for storage” at “Recommended for EBTF”-conditions [1].

## 2.2. Comparison of alternatives

The energy consumptions of the different INTERACT capture processes are compared to the energy consumption of the Base Case. This Base Case serves as a benchmark process as it represents a conventional capture process that comprises the utilization of state-of-the-art technology as well as of standard solvents used today.

The comparison is done considering primary energy equivalents. The application of the concept of primary energy (fossil fuel) consumption grants a major benefit: based on suited conversion factors the energy content of thermal utilities, of electricity as well as of others can be attributed to the amount of primary energy required to produce them. Being reduced to the amount of an energy carrier used for utility generation, the calculated amounts of primary energy – no matter if originating from the generation of thermal, electrical or other utilities – can be summed up to reflect the overall demand on energy of a process examined.

### *2.2.1. Energy penalty ratio (EP): Indicator of Performance*

As mentioned before the Base Case represents the usage of today’s best practice and equipment to conduct carbon capture industrially. In this sense its demand on primary energy defines the minimum amount of energy that is currently required to perform the operation. Accordingly, this amount of energy quantifies the state-of-the-art energy penalty that needs to be accounted for decarbonizing a flue gas stream.

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To arrive at a simple and easy-to-read indicator, the performances of all technologies examined are referenced on the specific minimum energy demand of state-of-the-art technology. The expected energy penalties are expressed as the ratio of these energy demands:

$$EP_{Process\ examined} = \frac{\frac{Demand\ on\ Primary\ Energy\ of\ the\ examined\ process}{ton\ CO2\ captured}}{\frac{Demand\ on\ Primary\ Energy\ of\ the\ Base\ Case}{ton\ CO2\ captured}} * 100;\ [\%].$$

It becomes obvious that the energy penalty ratio of the Base Case amounts to a value of 100 %. Processes of superior performance will result in lower values.

### *2.2.2. Conversion to Primary Energy – Thermal utilities*

Thermal energy required for heating is considered by the application of a primary energy efficiency factor of $\eta_{PE\_TH} = \frac{Thermal\ Energy\ (heating)}{Primary\ Energy} = 0.945$. It is assumed that heating is conducted by condensation of steam that has been generated by the boiler of the ASC plant from fossil fuel (see EBTF-report [1]).

### *2.2.3. Conversion to Primary Energy – Electrical utilities*

Concerning the usage of the electrical energy an assumption is made that electricity is directly provided by the ASC power plant. Any transfer losses etc. are neglected resulting in a conversion factor of electrical energy into primary energy equivalents of $\eta_{PE\_EL} = \frac{Electrical\ Energy}{Primary\ Energy} = 0.455$. This value matches with the net cycle efficiency of the coal-based power plant presented by the EBTF [1].

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# 3. Base Case

The Base Case is developed to reflect the performance of a conventional $CO_2$-capture plant as it would be "newly built" today. State-of-the-art technology is applied along with best practice of operation; the process concept follows the guidance of the European Benchmark Task Force, ASC Test Case with Capture [1].

## 3.1. Description of the process

The $CO_2$ capture Base Case utilizes a rather simple process scheme. An absorber and a stripper (desorption) are exploited to capture and recover carbon dioxide by the use of a solvent that consists of 70 wt% water and 30 wt% monoethanolamine (MEA).

The lean solvent is fed to the upper section of the absorber and is counter-currently contacted with the $CO_2$-rich flue gas stream that originates from the ASC power plant. To overcome any pressure drops arising from the operation of the absorber and related piping etc. the pressure level of the flue gas is slightly increased upfront of the device. Inside the absorber, an intensive gas-liquid-contact is enabled and the $CO_2$ is progressively absorbed by the liquid solvent. A decarbonized gas stream becomes present at the top of the unit and is supplied to the stack. The rich, loaded solvent stream is recovered at the bottom of the absorber; after pressure and temperature increase it is directed towards the desorption column.

The rich solvent enters the desorber on the upper stages of the column. This unit operates at a slightly increased but close to atmospheric pressure level [1]. Initialized by the change of temperature and pressure carbon dioxide is released from the loaded solvent into the vapor stream of the column. Due to the endothermic nature of the reaction and the desorption process a constant heat supply via a reboiler is inevitable.

As a result of the stripping operation a lean solvent at a $CO_2$ loading close to equilibrium condition is forthcoming at the bottom of the column. At the top of the stripper the $CO_2$-rich stream is withdrawn. While the latter stream is compressed to the specified pressure level exploiting the compression train described by [1], the liquid solvent stream is cooled down and recycled to the absorber. The energy efficiency of the process improves significantly as the heat content of the lean solvent stream is recovered by a process-process-heat exchange which increases the temperature of the liquid absorber effluent.

It needs to be noted that a purge stream of solvent prevents from the accumulation of any impurities that are formed e.g. by the degradation of the amine.

## 3.2. Performance of the Base Case

The performance of the Base Case along with its specific demand on primary energy forms the reference of the presented evaluation of process performances. Its relative energy penalty ratio amounts to

$$EP_{Base\ Case} = \frac{\frac{Demand\ on\ Primary\ Energy\ of\ the\ Base\ Case}{ton\ CO2\ captured}}{\frac{Demand\ on\ Primary\ Energy\ of\ the\ Base\ Case}{ton\ CO2\ captured}} * 100 = 100\ \%.$$

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# 4. Processes enhanced by enzyme application

In the field of carbon capture numerous species are used to store $CO_2$ chemically. A favourable way of storing $CO_2$ is given by the formation of bicarbonates and carbonates as the corresponding conversions exhibit comparably moderate heats of reaction. Several benefits are forthcoming: on the one hand a strong increase of temperature is avoided while absorbing; on the other hand, the amount of thermal energy required to perform the $CO_2$-stripping process is reduced.

Unfortunately, the kinetics of the reactions forming and decomposing the relevant carbonate species are relatively slow. This becomes a major drawback as larger residence times and holdups are required to achieve a targeted capture rate. Along with an increase of dimensions of the reactive separation apparatuses, the pressure drop that needs to be compensated by upstream compression of the flue gas stream increases. Consequently, the demand on electrical energy of the whole capture process rises.

To counter this disadvantage and to enhance the performance of $CO_2$ capture processes that store carbon dioxide via carbonate-modifications an enzyme is added. This enzyme improves the rates of the addressed chemical conversions. As a result, the uptake of carbon dioxide that is physically dissolved in the liquid solvent is accelerated [2], [3]. The loading of the absorption stream approaches chemical equilibrium conditions in a faster way enabling an efficient decarbonization of the flue gas stream.

To quantify the advantages of capturing $CO_2$ by the use of “low energy reaction systems”, e.g. in form of bicarbonates and carbonates, an aqueous solution of a tertiary amine is applied as solvent mixture.

## 4.1. Limitations arising from the use of enzymes

The application of enzymes adds additional constraints to the process which needs to be considered when developing conceptual designs of the innovative, enzyme-intensified INTERACT carbon capture technologies [4], [5].

## 4.2. Enzyme enhanced capture processes using a tertiary amine

A solvent mixture composed of a tertiary amine (TA), namely Methyldiethanolamine (MDEA), and water is applied to operate the carbon capture process. By the addition of an enzyme the process is intensified.

### *4.2.1. Process concept*

The basic concept of enzyme-enhanced processes follows the set-up of the Base Case. However it needs to be highlighted, that, while dimensioning the reactive distillation devices, the constraints dedicated to the chemical conversion overrule the common design principles of distillation columns to tribute the comparably slow rates of reaction.

### *4.2.2. Process alternatives investigated*

Based on the process concept described above three process alternatives are examined which differ with respect to pressure levels at which the absorber and the stripper are operated.

#### *4.2.2.1. Process TA 1: Absorber: ambient pressure – Stripper: ambient pressure*

The first TA-process concept investigated reflects the most obvious setting: both columns, the absorber as well as the stripper, operate on ambient pressure levels. The enzyme that intensifies the process remains immobilized inside the absorber column.

As expected this process shows a superior performance compared to the Base Case with respect to energy use. Due to the exploitation of a chemistry that exhibits lower heats of reaction the relative energy penalty reduces by 22 %-points to a value of $EP_{TA\_A\_A}$ = 78 %.

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#### *4.2.2.2. Process TA 2: Absorber: elevated pressure – Stripper: ambient pressure*

To intensify the absorption process by an increase of the achievable cyclic solvent load, this process concept combines the use of an absorber operated at elevated pressures with a stripper operated atmospherically. The enzyme supports the absorption process. An immobilization inside the absorber is foreseen.

As the flue gas is available at close to atmospheric pressure, it first needs to be compressed to the operation pressure level of the absorber. Compared to the absorber operation at ambient pressure, additional compression work is required. Thus, it becomes obvious that the success of this mode of operation strongly depends on the trade-off between energetic savings related to the increased maximum possible cyclic load of the tertiary amine solvent and the amount of energy consumed additionally to put the flue gas to a more elevated pressure level.

Based on the results of the scouting investigation it can be concluded that this mode of operation is not well suited to decarbonize gases on low supply pressure level that contain moderate $CO_2$-concentrations only: the relative energy penalty increases by 16 %-points compared to the Base Case and 38 %-points relative to the TA-operation at ambient absorber pressure. The relative energy penalty amounts to $EP_{T\_E\_A}$ = 116 %.

The efficiency of the process can be enhanced in case the decarbonized flue gas is depressurized by gas expansion incl. energy recovery (expansion turbine driving a generator) before sending it to the stack. Heating up the absorber top gas stream and expanding it using a turbine, the relative energy penalty of this setting reduces by 8%-points to $EP_{T\_E\_A(turbine)}$ = 108 %.

#### *4.2.2.3. Process TA 3: Absorber: ambient pressure – Stripper: vacuum pressure*

An alternative way to increase the exploitable range of cyclic loads of the solvent is realized by operating the stripper at vacuum conditions while absorber operates at ambient pressure. With this set-up no immobilization of the enzyme is required.

Based on the simulation results an estimated relative energy penalty of $EP_{TA\_A\_V}$ = 86 % is forthcoming. Keeping in mind the preliminary nature of the presented data, it can be stated that this mode of operation leads to a performance that is comparable to the performance of the most efficient TA-process presented in section 4.2.1.1.

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# 5. Gas separation membrane processes

Gas separation membrane (GSM) processes make use of a membrane that separates carbon dioxide from a flue gas mixture. The permeability of $CO_2$ is high; the selective physical separation process prevents from the need of applying any energy-intensive chemical absorption/desorption procedure. The purified carbon dioxide is collected as permeate stream and is compressed to storage/use pressure.

## 5.1. INTERACT membranes

Generally speaking, membranes are characterized by two parameters of performance: transmembrane flux and selectivity for the separation of a desired component. Often these parameters are conflicting: high flux comes along with low selectivity, while membranes with high selectivity often facilitate low fluxes only.

The project partners of INTERACT project tribute this fact and report of gas separation membranes of deviant $CO_2/N_2$-selectivities [7]. Accordingly, the current study investigates process concepts with two different types of membranes

- High selectivity membrane: the $CO_2/N_2$-selectivity is a sufficiently high to recover $CO_2$ on spec with a single membrane stage applied and
- Low selectivity membrane: the $CO_2/N_2$-selectivity is low; therefore two or more membrane separation stages operate in series to recover carbon dioxide at the purity desired.

## 5.2. Membrane processes

### *5.2.1. Process concept*

The basic process concept applied for exploiting gas separation membranes for $CO_2$-capture is simple: after pre-compression and eventually cooling of the flue gas to the desired feed pressure and temperature the $CO_2$-rich gas stream is fed into the membrane module. $CO_2$ (and other gases) permeate through the membrane. The quality of the permeate stream strongly depends on the present $CO_2/N_2$-selectivity. The differences in partial pressure of the particular components on the feed and permeate side of the membrane sheet are accounted as driving forces.

In case the specification for $CO_2$ capture as defined by [1] can be achieved by a single separation step, the permeate stream is compressed to storage pressure. The remainder of the flue gas, hence the retentate stream leaving the membrane module, is directed to the stack. Depending on the pressure level of the retentate stream gas expansion can be foreseen in order to recover the energy that is contained in pressurized gas.

Alternatively, in case the $CO_2/N_2$-selectivity of the membrane is too low to reach the specification of the $CO_2$-product in a single membrane separation step, the pre-concentrated permeate stream recovered from the first, most upstream membrane module is compressed. At given pressure level additional membrane operations take place in order to improve the quality of the $CO_2$-rich stream. The by-product stream that contains the impurities and some $CO_2$ is recycled to the upstream membrane modules. The main-product stream which mainly consists of $CO_2$ at the purity desired is compressed to storage conditions.

### *5.2.2. Membrane processes investigated*

Membrane processes offer a simple and efficient way of recovering carbon dioxide selectively from a flue gas mixture. However, removing 90 % of the $CO_2$ from a gas stream can become a challenging task as the target component undergoes a significant reduction of partial pressure on the feed side of the membrane. As a consequence severe vacuum pressure conditions may be required on the permeate side of the module to maintain sufficient driving forces for separation.

To relax this technical challenge, membrane scenarios applying different feed pressure levels are investigated. Supplying the flue gas at elevated pressure levels to the membrane module increases the

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partial pressure of the $CO_2$ in the feed mixture. Experiencing a higher $CO_2$-partial pressure on the retentate side, the permeate stream can be operated at an increased pressure level while supporting sufficiently driving forces for separation.

#### *5.2.2.1. Process GSM 1: highly selective membrane*

The first process concept using membrane gas separation applies a membrane of a sufficiently high $CO_2/N_2$-selectivity to produce carbon dioxide at the product quality desired using single membrane stage only. Upfront of the membrane module the feed gas is compressed and, in case required, cooled down to the maximum temperature at which the membrane shows long-term thermal stability.

Different feed pressure levels are investigated to study the impact of the vacuum pressure level required on the permeate side of the membrane. Hereby, the minimum pressure increase is given by the need to compensate the pressure drop of the apparatus.

Applying more elevated feed pressure levels requires additional efforts of flue gas compression. However the permeate side operates with less technical challenges at less severe vacuum conditions. By the latter, the compression power is reduced that is required to put the resulting $CO_2$-product stream to storage pressure conditions. The upper pressure level that was considered in the framework of this parameter study was limited by the application of a single stage compressor that has been operated according to good engineering practice.

Preliminary calculations reveal that membrane processes are highly promising from an energetic point of view. Depending on the feed pressure levels realized the relative energy penalties of these process alternatives amount to $EP_{GSM\_HS}$ = 62 … 88 %.

#### *5.2.2.2. Process GSM 2: membrane exhibiting a low $CO_2/N_2$-selectivity*

This process concept applies membranes that exhibit a low $CO_2/N_2$-selectivity. The purity of the permeate stream recovered from a single membrane stage does not fulfil the purity requirements of the $CO_2$-storage. Therefore, additional membrane separation steps have to be performed in series downstream to meet the specification of product quality. In between the different membrane stages the enriched $CO_2$-stream is pressurized. The impurities recovered along with some carbon dioxide are recycled to upstream separation steps to facilitate the decarbonization process another time. At the end, the $CO_2$-stream resulting from the final membrane operation is compressed to the storage pressure.

Similar to the membrane processes using highly selective membranes the investigation of this type of process is conducted including a variety of flue gas feed pressures. Similar limits of flue gas pressurization, as described in section 5.2.1.1, have been considered.

The preliminary results of the investigation reveal that processes using this type of membrane becomes less efficient compared to GSM-processes applying membranes of high $CO_2/N_2$-selectivity. This can be expected as stronger efforts are required to prepare a stream of carbon dioxide at the quality desired. However, exhibiting relative energy penalties between EPGSM_LS = 74 … 98 % (depending on the flue gas feed pressure level applied) it becomes obvious that this process concept still is superior to the Base Case considering energy uses. This is valid in particular with respect to the more efficient alternatives that save more than a quarter of the energy consumption to operate the state-of-the-art process.

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# 6. Membrane contactors

Membrane contactors are well suited for performing gas-liquid reactions or operations because they offer some key benefits: on the one hand, a tremendous volume-specific interfacial area can be realized inside a most compact apparatus. On the other hand, the streams of liquid and gas can be operated independently from each other which significantly increases the number of degrees of freedom to design and operate the process; i.e. an option to optimize gas and liquid residence times etc. is given.

However, these benefits come at the expense of a more serious pressure drop that easily exceeds the pressure drop expected from the application of packed columns; pressure losses inside membrane contactors to range between 7000 and 20000 Pa, as reported in [6]. This is significant in particular with respect to the flow-through of the gas. To overcome the more severe pressure drop additional efforts need to be spent on compression upstream of the contactor to enable the flue gas to pass the membrane apparatus and end up in the stack on the required minimum pressure level.

## 6.1. Membrane contactors in the scope of this study

For the time being two different applications of the membrane contactor are investigated. First, the membrane contactor is expected to be well suited to replace the absorption or stripping column in processes that operate enzyme-intensified solvents, here the enzyme-supported tertiary amine solution. Secondly, membrane contactors could be used in “a more conventional set-up”. Regarding the later process, no details are disclosed, because of intellectual property right issues.

## 6.2. Membrane contactor processes

### *6.2.1. Membrane contactors in enzyme-intensified processes*

Due to the key characteristics of the membrane contactor, namely a high interfacial surface area, compactness and high flexibility, this apparatus can be applied to replace the absorber and/or stripper in the framework absorption-based $CO_2$-capture processes. This is of particular interest discussing processes that show a good capture performance but require larger hold-ups to perform the capture or release process because of moderate reaction rates. In such situations the membrane contactor offers the opportunity to adapt the liquid and gas flow independently from each other to realize optimal operation conditions.

The enzyme-intensified capture processes using an aqueous tertiary amine solution as given by sections 4.2.1.1 - 4.2.1.3 represents such a well performing but relatively slow capture process. To intensify this set-up a membrane contactor is used to carry out the absorption step. Making some basic assumptions the performance of a process can be preliminarily evaluated:

- Assumption 1: The performances of the absorption and the stripping operation of the examined processes using enzyme-supported tertiary amine-solution remain unaffected by the exchange of the reaction devices.
- Assumption 2: The resulting pressure drop inflicted to the flue gas is quantified by the conservative value of $\Delta p$ = 20000 Pa as presented by [6].

Based on these assumptions a first investigation shows that using membrane contactors can represent a promising alternative to the use of reactive distillation columns. It is revealed that - even applying the most conservative value of pressure drops of membrane contactors mentioned by [6] - the use of membrane contactors is expected to add 5%-points only to the relative energy penalty of the enzyme-intensified processes presented in section 4. The resulting energy penalty ratio amounts to $EP_{MC}$ = 79 … 121 %.

Consuming slightly more energy for operation, it has to be emphasized that this issue may well be compensated by the advantages of compactness and flexibility (additional degrees of freedom).

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# 7. Conclusion

In this document the results of a scouting study on the performance of the diverse $CO_2$ capture technologies under investigation in the framework of the INTERACT project are summarized. The presented data are generated at an early point in life-time of INTERACT project. They are understood as a first indication of the capability of the novel technologies to overcome the performance of today's state-of-the-art technology.

For each technology a promising process concept has been developed individually. Using the commercial process simulation software Aspen Plus, the process concepts are simulated. On each concept different modes of operation, i.e. operation of selected units on different pressure levels, are investigated.

From the heat and mass balances the performance of corresponding capture processes is estimated. The comparison towards the Base Case, a process that acts as the benchmark and represents the use of today's state-of-the-art technology and best practice, leads to a relative energy penalty.

Concerning all different technologies encouraging results are found. For each INTERACT technologies under investigation at least one process configuration could be identified that leads to significant reductions in the demand of primary energy - hence a significant reduction of the related energy penalty.

The following table summarizes the results obtained for the different novel technologies achieving a $CO_2$ capture rate of 90 %.

| **Innovative Case** | **Energy penalty ratio: $EP_{Innocative\ Case}$ / $EP_{Base\ Case}$ * 100%** |
|---|---|
| Enzyme-intensified capture processes | 74 … 116 % |
| Gas separation membrane processes | 62 … 98 % |
| Membrane contactor processes | 79 … 121 % |

It needs to be stressed that the results of this study are of preliminary nature only as they are based on data originating from initial performance tests of the INTERACT technologies. In the further course of the project the experimental as well as theoretical investigation of the innovative capture technologies proceeds; therefore more insights and data will become available. This will allow performing the estimation of performance in a more accurate way using less conservative assumptions.

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# 8. Literature

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