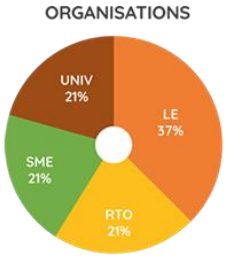
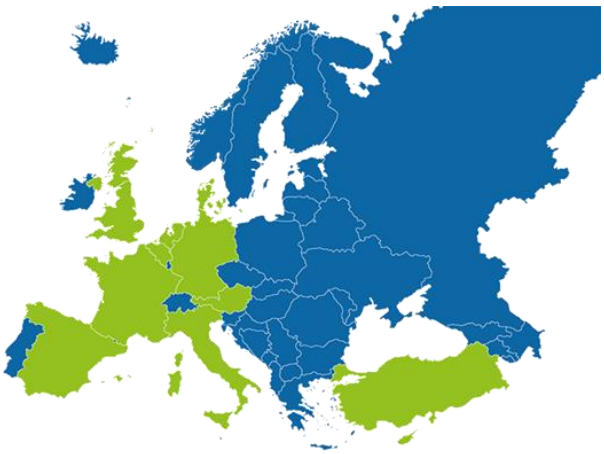
MACBETH IN A NUTSHELL

Duration: November 1st, 2019 – April 31st, 2024 (54 months)

Project Coodinator: Evonik Performance Materials GmbH (EPM)

Partner involved:





In the process industry, downstream processes are the steps with the highest consumption of energy and resources in industrial operations. Moreover, the integration of new processes often requires a large portion of the CAPEX and OPEX. To significantly enhance the competitiveness of the European process industry and to contribute to Europe's goal of a clean and liveable environment, it is highly desired to have a **very broadly applicable concept for an efficient integration of downstream operations** in the overall process chain.

The MACBETH (**M**embranes **A**nd **C**atalysts **B**eyond **E**conomic and **T**echnological **H**urdles) consortium provides a breakthrough technology by combining catalytic synthesis with the corresponding separation units in a single highly efficient catalytic membrane reactor (CMR).

This disruptive technology can reduce greenhouse gas (GHG) emissions of large volume industrial process by up to 35 %. Additionally, resource and energy efficiency will be increased by up to 70%. The revolutionary new reactor design will not only guarantee substantially smaller and safer production plants but has also a tremendous competitive advantage since CAPEX is decreased by up to 50% and OPEX by up to 80%.

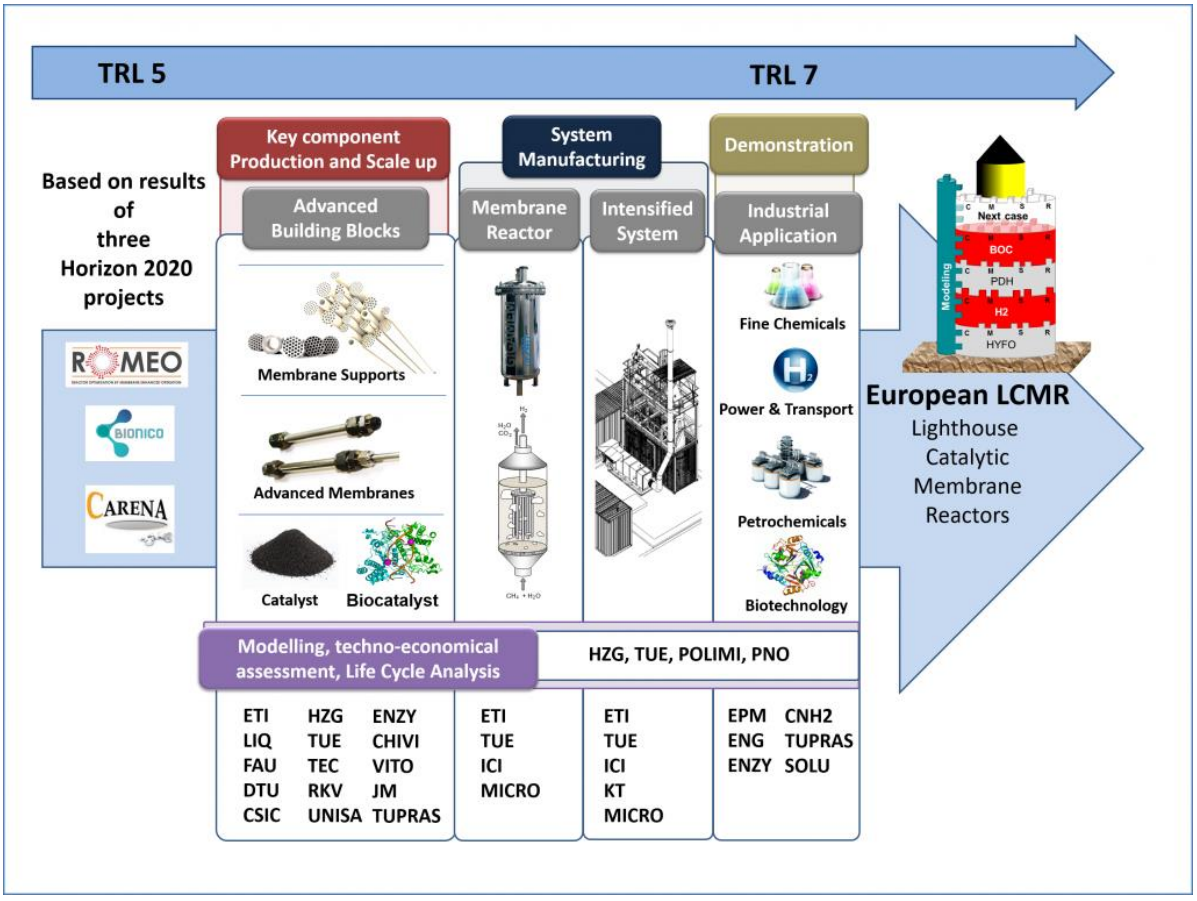
To achieve this, the MACBETH consortium combines the catalytic synthesis step with the highly efficient separation step via a tailor-made membrane. The predecessor EU funded projects **ROMEO,* **BIONICO* and **CARENA* and further fundamental developments have laid a strong basis by showing the proof of concept for CMRs.

Successful pilot plants have been operated for highly relevant and large-scale processes: i) Hydroformylation (*HYFO), ii) Hydrogen production (*H2) and iii) Propane dehydrogenation (*PDH).

Key members of these consortiums have now joined forces in MACBETH to bring CMR to the next level and build the basis to move forward for commercialization of the three novel technologies. Moreover, the knowledge and experiences from the three successful European projects provides the basis for tailor-made CMR solutions broadly applicable at significantly different conditions in almost any sector of the process industry requiring separation after catalytic synthesis.

To demonstrate the exploitation potential, MACBETH will extend the CMR technology to the field of biotechnology, as most biotechnological reactions involve the use of bacteria or enzymes, which are special types of catalysts. In this field, the selective enzymatical cleavage of fatty acids is of particularly high commercial interest. Based on a large variety of already established building blocks (such as catalysts, membranes, support materials and reactor concepts) a demo plant for bio-catalytical oil cleavage (BOC) will be developed, showing the commercial applicability of CMR in biotechnology for the first time.

To take a further step forward and to extend the benefits of CMR technology to other sectors, a European competence center will be established. At the end of the project this will culminate in the foundation of the "Lighthouse Catalytic Membrane Reactors" (LCMR) based on a detailed business plan and including partner commitment. This spin-off company will provide access to the combined knowledge of the MACBETH project with respect to all relevant disciplines such as building blocks, modelling and system integration, valorizing the project's results through the structured offering of commercial services to interested stakeholders.



MACBETH project has been structured into 8 work packages (WP), which will be implemented in 54 months.

SOME BACKGROUND INFORMATION

ROMEO – Reactor Optimization by Membrane Enhanced Operation

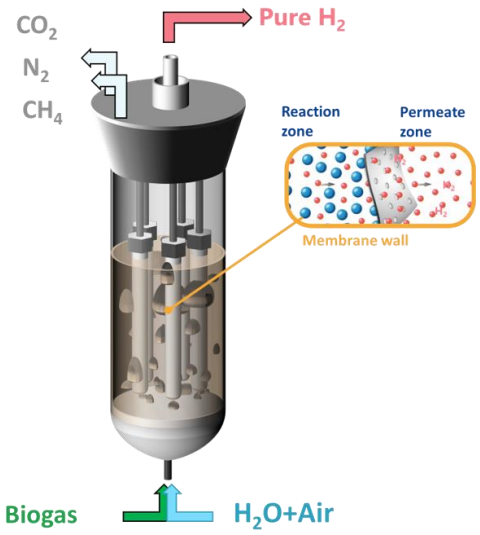
ROMEO's "two-in-one" reactors combine optimized membrane modules and the immobilization of highly active and selective homogeneous catalysts to carry out chemical synthesis and downstream processing in a single step. As demonstration cases two important reactions were investigated from nano- to macro-scale: hydroformylation (conversion of olefins and syngas to aldehydes) and water-gas shift reaction (use of CO-containing syngas derived from biomass to generate hydrogen).

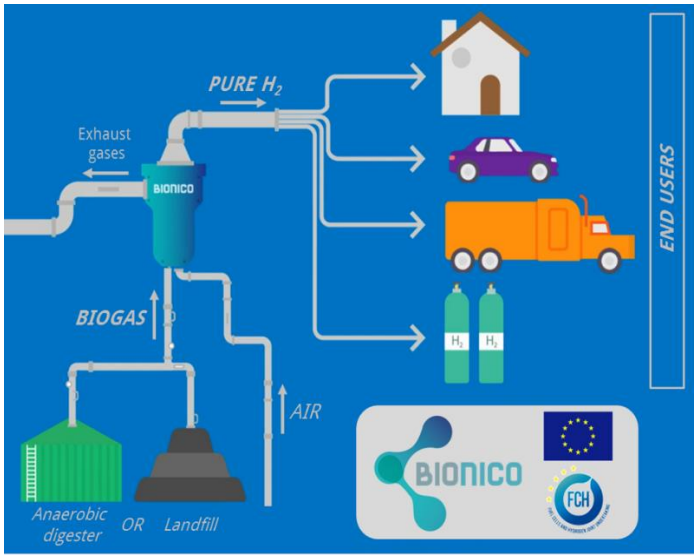
With this innovative approach ROMEO will:

- improve selectivity and productivity of industrial reactions, including raw material savings and catalyst recycling
- reduce energy consumption by up to 80% in industrial catalytic gas-phase reactions reduce related emissions by up to 90%

The ROMEO project focused on the combination of a homogeneously catalyzed reaction step with a membrane separation step in one reactor. To do so, homogeneous catalysts were supported on membranes. Embedding homogeneous catalysts in thin films of non-volatile ionic liquids (SILP technology) maintained their catalytic abilities as in the homogeneous phase while the anchoring directly on or even in the membrane ensures a most efficient separation.

BIONICO – BIOgas membrane reformer for deceNtrallzed hydrogen produCtiOn





CARENA – CAtalytic Membrane REactors based on New mAterials for C1-C4 valorisation

These challenges could be overcome thanks to relevant Process Intensification (PI) along with the smart implementation of catalytic membrane reactors, contributing therefore to the reduction of

dependency of the European community on imported oil. CARENA project will address the key issues required to pave the way to marketing Catalytic Membrane Reactors in the European chemical industry.

EUROPEAN "Lighthouse Catalytic Membrane Reactors" (LCMR)

In order to go beyond the demonstration of CMR in the field of biotechnology and bringing their outstanding benefits to other sectors and an even wider field of applications, a European competence center will be established, which will at the end of the MACBETH project lead to the foundation of a spin-off company, tentatively called "Lighthouse Catalytic Membrane Reactors" (LCMR). The LCMR will provide access to the combined knowledge of the MACBETH project with respect to all relevant disciplines such as building blocks, modelling and system integration, valorizing the project's results through the structured offering of commercial services to interested stakeholders.

Realization of LCMR within MACBETH

The preliminary idea of the project partners is to create the spin-off as a light "start-up" organization, with 1-2 partners (TUE and POLIMI), technology providers in the lead for financing and managing the start-up phase, and the other partners contributing to create the knowledge base, building the products/services portfolio and provide them with a "on the call" basis.

During the first 12 months of the project a feasibility study will be conducted by doing further market research to explore the potential market for these modelling services. In addition, opportunities for IP protection of the modelling software developed will be explored. Based on these results, a clear and concrete business model for a spin-off including business plan will be established for the "Lighthouse Catalytic Membrane Reactors" (LCMR). At the end of the project the spin-off shall start to serve as the European focal point for parties interested to improve the environmental impact as well as the cost efficiency of their processes with the help of ground-breaking CMR.

BOC – Bio Catalytical Oil Cleavage

The BOC case in MACBETH aims to establish a CMR-based system for the enzyme-catalyzed selective hydrolysis of plant oil fatty acids in an aqueous-organic system followed by an integrated membrane separation to isolate selected fatty acids. With the knowledge and experiences of the other MACBETH cases, tailor-made building blocks will be developed for a time-efficient transfer of the entire system to an industrial pilot plant. For testing of process robustness and long term-stability of the process in field tests, two project partners (ENZY and SOLU) will test the pilot plant. For an easy transfer between both testing sites a containerized set up of the system is foreseen. Therefore, both the adaptability of the MACBETHs results to new areas of application and a local flexibility of the system will be demonstrated.

HYFO – Hydroformylation

Hydroformylation, the conversion of olefins and syngas to aldehydes, is a key reaction in chemical industry to produce specialty chemicals, which are subsequently used as solvent or resource to produce detergents, cleansers or plasticizers. Based on the knowledge and results from the previous projects the HYFO case will focus on the implementation and optimization of already established building blocks and reactor systems for a more efficient hydroformylation reaction. Therefore, the following aspects are of interest for optimization:

- Support structure for efficient use of catalytic system: pore structure as well as support material
- Catalytic system for improved yield and selectivity: ratios between ionic liquid phase, ligand and active species
- Polymeric membrane for separation efficiency and permeates flow: polymeric composition, coating procedure
- Operating parameters for improved process: start-up procedure, pressure & temperature range, through-put

In parallel, different engineering phases for the pilot plant will focus on infrastructural modifications in the production environment to obtain real industrial conditions for the demo phase. For this purpose, the HYFO case will be placed in bypass to the conventional hydroformylation production plant at Evonik's Marl site. Here, the pilot plant will be run in the recycle stream of the plant (TRL 7), an ideal position regarding composition and flow of that stream to simulate a possible brownfield as well as green field implementation at a later stage.

H2 – Hydrogen Production

To improve the production of pure hydrogen from biogas or natural gas MACBETH will develop, build and demonstrate a novel reactor concept integrating hydrogen separation in situ during the reforming reaction in a single vessel under industrially relevant conditions. Here, biogas or natural gas methane will be converted to hydrogen at a much lower temperature compared with a conventional system resulting in an increase of the overall process efficiency and a strong decrease of volumes and auxiliary heat management units. The novel membrane reactor system will greatly simplify plant layouts resulting in a decrease of CAPEX (much less components/reactors) and OPEX (raising efficiency from 59% to more than 70% (for biogas)). Compared with any other membrane reactor project in the past (most advanced TRL 6), MACBETH will demonstrate:

- the membrane reactor will run at a much larger scale (>150 membranes implemented in a single fluidized bed membrane reactor)
- small-scale hydrogen production, very close to a commercial unit, paving the way towards a market exploitation of the reactor concept
- the reactor system will operate for more than 8000 h (for each of the H2 demo plants).

Equipped with an integrated advanced control system which improves the systems flexibility towards biogas composition, the reactor will be tested in a real biogas plant (H2a) at ENGIE and in a plant for natural gas (NG) (H2b) in the CNH2 facilities located in Puertollano (Spain).

PDH – Propane Dehydrogenation

Using process optimized CMRs, the harsh operating conditions of propane dehydrogenation process are expected to be mitigated (lower operation temperature) avoiding catalyst deactivation and therefore subsequent regeneration steps resulting in an improved process management and plant/catalyst lifetime. Additionally, the selectivity to propylene will be increased, thus dramatically reducing the presence of gaseous side products in the process stream. With the results of MACBETH´s building block optimization and modelling activities a smart design of PDH optimized CMR system will be established and implemented in a demonstration pilot plant at ENGIE in Stains, France with a continuous long-term operation.

EVONIK PERFORMANCE MATERIALS GMBH

Business Line Performance Intermediates

C4-chemicals@evonik.com

www.evonik.com/C4chemicals