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# HYBRID TANDEM CATALYTIC CONVERSION PROCESS TOWARDS HIGHER OXYGENATE E-FUELS

## E-TANDEM - Deliverable report

## D4.4 – Long-term stability and dynamics of hybrid catalytic conversion system

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**Project summary**

E-TANDEM aims to enable the efficient and direct production of a new, higher-oxygenate, diesel-like e-fuel for the marine and heavy-duty transport sectors. This oxygenated fuel is produced directly from water and $CO_2$ as the sole carbon source, with renewable power as the sole energy input, through a once-through hybrid catalytic conversion process that integrates three key branches of catalysis: (1) high-pressure electrocatalysis for syngas production coupled with a tandem catalytic e-syngas conversion, (2) thermocatalysis using solid catalysts, and (3) chemocatalysis with molecular complexes. The project will demonstrate this new e-fuel production process at the bench scale in a continuously operating mini-plant and assess its ability to handle fluctuating energy inputs.

# Publishable summary

Carbon-neutral e-fuels with high energy density are crucial for the decarbonization of long-distance road, maritime, and air transport, as well as heavy-duty transport. The Horizon Europe E-TANDEM project aims to develop and validate at the laboratory scale the first direct process for the selective production of carbon-neutral oxygenated e-fuels (HOEF) for maritime and heavy-duty transport. This oxygen-containing fuel is produced directly from $CO_2$ as the sole carbon source and renewable electricity as the sole energy source in a hybrid catalytic conversion process that integrates three key catalytic pathways: electrocatalytic synthesis gas generation coupled with a tandem catalytic e-synthesis gas conversion process, which encompasses thermocatalysis using solid catalysts and chemocatalysis using molecular complexes. As part of the project, the new process for producing e-fuel is being demonstrated on a laboratory scale, and its ability to handle fluctuating energy inputs is being evaluated.

In Work Package 4, various critical process steps required for the realization of a fully continuous e-fuel production system were successfully established and validated. The focus was on the continuous operation of a high-pressure co-electrolyzer for the production of e-syngas and, simultaneously, on the scale-up of the tandem reaction for converting syngas into long-chain alcohols. The stable and flexible operation of the co-electrolyzer under dynamically fluctuating conditions was demonstrated over 600 hours. In parallel, a custom-built lab-benchtop mini-plant enabled the successful implementation of continuous reductive hydroformylation with integrated membrane separation, representing an important milestone for downstream processing and product recovery. Furthermore, the scale-up of the olefin-selective Fischer-Tropsch reaction and the tandem reaction—combining the Fischer-Tropsch reaction and reductive hydroformylation—was achieved on a benchtop laboratory scale in continuous mode, effectively demonstrating the process at TRL4. Both systems demonstrated stable performance, and the tandem reaction achieved high selectivity for long-chain alcohols, demonstrating the robustness and effectiveness of the catalytic concept under relevant operating conditions. Catalyst stability, solvent selection, and membrane compatibility were systematically validated to ensure that all components are compatible for integrated operation.

In a 100-hour experiment including stress testing through changes in operating modes, it was shown that the system responds well and reproducibly to these variations, while maintaining high selectivity toward alcohols of up to 84.4%. In addition, stable operation over the full 100-hour period was demonstrated, confirming that both catalysts remain active and the system remains stable under these conditions. In addition, it was demonstrated that the RHF catalyst remains active even after 100 hours of exposure to the FTS catalyst, and that the membrane is capable of handling the post-tandem reaction solution.

Overall, the objectives of the task have been largely achieved. Although the initially targeted higher oxygenate productivity was not fully reached, the process delivered a significantly improved selectivity toward higher oxygenates, which is expected to have a more favourable impact on a key cost driver identified in the techno-economic analysis, namely the separation costs associated with higher alcohols derived from *n*-paraffin side products.

Overall, the objectives of the project have been largely achieved. The stable operation of the co-SOE, the catalytic processes, and the downstream process have been demonstrated and the key components of the integrated system have been successfully developed and validated. Additionally, the downstream separation unit was successfully demonstrated. The key components of the integrated process were developed, validated, and shown to function reliably under relevant operating conditions, and catalyst stability was confirmed over extended operation times and the individual

process steps, including semibatch tandem operation, continuous circulation with membrane separation, and reactor-only operation, were successfully tested and assessed.

A 100-hour experiment confirmed the operability of the tandem process under continuous operation and demonstrated reversible recovery of key performance indicators following cyclic stress testing. Target higher alcohol productivities were achieved, while alcohol selectivity notably exceeded the initially established targets, reaching 70–80% on a carbon basis under continuous conditions, with alcohol n/iso molar ratios of up to approximately 6. A trade-off between alcohol selectivity and overall productivity was observed, indicating that further optimization of the RHF catalyst (particularly ligand identity and concentration) may enable co-optimization of these two key performance metrics. In the present work in E-TANDEM, enhanced alcohol selectivity and stable ligand performance during downstream membrane nanofiltration were prioritized, as these factors are expected to positively impact key techno-economic drivers of the process, including product recovery, separation costs, and cobalt retention within the system.

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**Project partners:**

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|---|---|---|
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| **2** | MPG | MAX-PLANCK-GESELLSCHAFT ZUR FORDERUNG DER WISSENSCHAFTEN EV |
| **3** | DTU | DANMARKS TEKNISKE UNIVERSITET |
| **4** | OWI | OWI SCIENCE FOR FUELS GMBH |
| **5** | UNR | UNIRESEARCH BV |
| **6** | T4F | TEC4FUELS GmbH |
| **7** | AVL | AVL LIST GMBH |
| ***8*** | *GF (terminated)* | *GOODFUELS BV* |
| **9** | UZ | SVEUCILISTE U ZAGREBU, FAKULTET STROJARSTVA I BRODOGRADNJE |
| **10** | UCT | UNIVERSITY OF CAPE TOWN |
| **11** | KAUST | KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY |
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