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POWERED- Production Of Wind Energy and other Renewable Energy based DME

Annual Public Progress report

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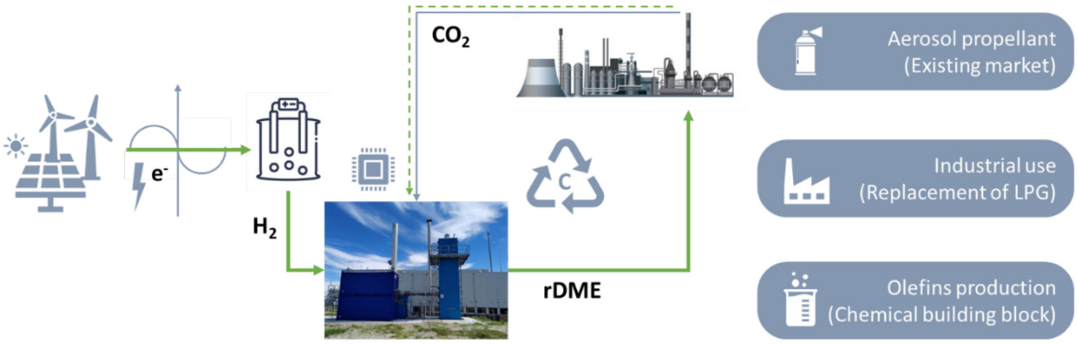


This project is carried out with Topsector Energie subsidy from the Ministry of Economic Affairs and Climate Policy, executed by the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland). The specific subsidy for this project pertains to the MOOI subsidy round 2022.

1 Basic principles, project goals and consortium partners

1.1 Introduction and basic principles

To meet climate targets for net-zero emissions and increased circularity, the industrial sector must transition toward renewable fuels and circular carbon use. One promising pathway is the conversion of CO_2 from industrial and biogenic sources into valuable chemicals and fuels.

Such conversion processes require large amounts of green hydrogen and must therefore be energy-efficient, cost-effective, and flexible, enabling alignment with intermittent renewable energy supply.

The POWERED project addresses this challenge through the development of the Sorption-Enhanced DME Synthesis (SEDMES) process. This technology integrates reaction and separation in a single step by removing steam in situ using a solid adsorbent, thereby enhancing CO_2 conversion efficiency.

The process converts CO_2 and hydrogen into renewable dimethyl ether (r-DME), a versatile molecule that can be used as a clean fuel (diesel/LPG substitute) or as a chemical building block.

The SEDMES technology has been validated at lab and bench scale (up to TRL5), and the POWERED project aims to demonstrate its performance in an integrated pilot setup including purification, storage, and flexible operation.

1.2 Project goals

The main goal of the POWERED project is to demonstrate the SEDMES technology at pilot scale as a fully integrated system, including downstream purification and storage, and to contribute to the preparation of a future demonstration at industrial scale.

Given the fluctuating nature of renewable electricity, the project also investigates the flexible operation of the SEDMES process. This includes the development of models and specifications for an Energy Management System (EMS) to support operation under dynamic conditions.

In parallel, the project delivers techno-economic and sustainability assessments, as well as conceptual designs for large-scale implementation, to evaluate the feasibility of industrial deployment.

During the course of the project, the approach toward full system demonstration has been adapted to reflect practical constraints encountered during implementation. The originally planned testing in an external industrial environment has therefore been replaced by full-chain commissioning and testing at the TNO pilot facilities in Petten. This adjustment ensures that the project objectives can be achieved within a controlled and feasible setting, while maintaining focus on system integration and preparation for future scale-up.

By involving stakeholders across the value chain, the project aims to lay the groundwork for future scale-up and commercialisation of renewable DME production.

1.3 Consortium partners

The POWERED project brings together partners across the value chain, including industrial CO_2 sources, technology providers, and end users, to advance the development and future deployment of SEDMES-based r-DME production (Table 1). Over the course of the project, the consortium has undergone several organizational updates, including changes in partner names and organizational structures. These changes have been formally agreed within the consortium and do not affect the overall objectives of the project.

Table 1: The POWERED consortium

Name participant	Contact person
Netherlands Organisation for Applied Scientific Research (TNO)	Claire Ferchaud
Technip Energies (T. En.)	Maria Liouta
Shell ETCA (ETCA)	Dennis De Vlieger
VDL	Ruud Bouwman
Tata Steel Nederland Technology B.V. (Tata)	Peter van den Broeke
SHV Energy	Jakub Kozlowski
Aramco OC (AOC)	John Henn
Nouryon	Cees Kooijman
Technolution	Jop Spoelstra
Phase to phase (PtoP)	Jop Spoelstra

Figure 1: Consortium in front of the SEDMES full chain 2025 progress meeting at TNO Petten.

2 Activities, results, bottlenecks & perspective

2.1 Activities carried out in the reporting period

The POWERED project includes a broad set of activities to advance the SEDMES technology, ranging from system integration and commissioning of the pilot installation to process modelling, energy system integration, and techno-economic and sustainability assessments.

During this reporting period, activities primarily focused on commissioning and integration of the full SEDMES chain at the TNO site in Petten, as well as aligning the project scope and execution with practical constraints encountered during implementation. These activities directly contribute to the achievement of key project milestones, in particular MS2 (hardware ready for testing), MS3 (EMS development), and MS5 (testing results).

The main activities included:

- Continued commissioning of the full SEDMES pilot system, including purification and storage units (MS2)
- Resolution of key technical issues related to auxiliary systems (e.g. chiller) and preparation for integrated operation (MS2)
- Implementation of safety measures required for operation of the full chain, particularly related to Emergency ShutDown scenarios (MS2)
- Completion and reporting of lab-scale and pilot-scale experimental campaigns (MS5)
- Further development of energy system models and EMS specifications, including simulations for flexible operation and energy storage concepts (MS3)
- Advancement of techno-economic and sustainability assessment activities, including conceptual design and evaluation of large-scale implementation

Compared to the previous reporting period, the focus has shifted from system construction and initial testing to **system-level integration, commissioning, and preparation for first full-chain operation under realistic conditions**.

2.2 Obtained results and bottlenecks

2.2.1 MS1: Specifications/input for process design

MS1 (Specifications/input for process design) was completed in an earlier phase of the project and defined the key use cases and specifications that underpin the process design, modelling, and experimental activities in POWERED. The main use cases considered are:

- Steel production, including both cleaned CO_2 streams and direct utilization of steel off-gases, reflecting current and future low-carbon steelmaking routes.
- Local seasonal energy storage, in which renewable electricity is converted to r-DME to balance supply and demand and alleviate grid congestion

- Refinery integration, using CO_2 streams from refinery operations, requiring additional gas treatment due to impurities.

In addition, different application pathways for r-DME (fuel, LPG substitute, and chemical feedstock) were defined, which set the requirements for product purity and downstream processing.

2.2.2 MS2: Hardware/adaptations ready for testing

A key objective of POWERED is to demonstrate the full DME production chain, including purification and storage, in an integrated pilot setup. In the current reporting period, the full chain construction was completed and commissioning activities continued at the TNO pilot facilities in Petten.

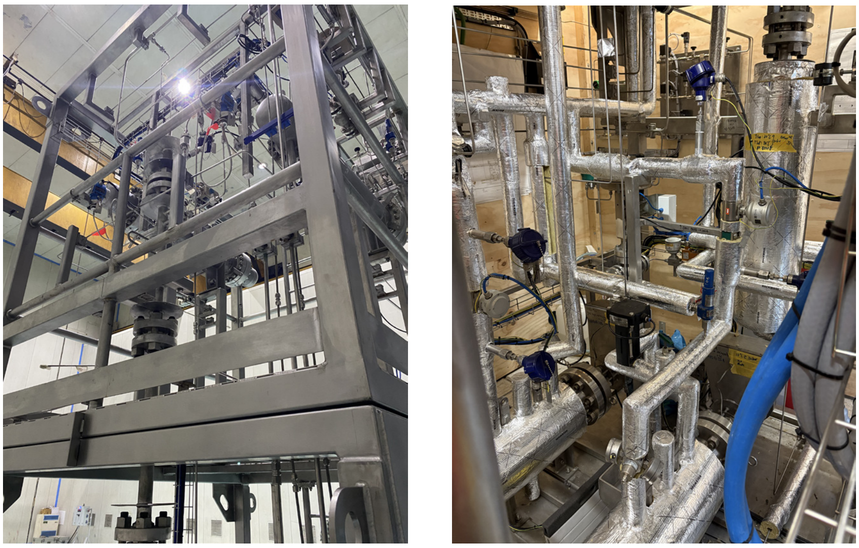
Commissioning progress included resolution of earlier issues with the chiller system and completion of cold commissioning of the first purification unit (DPU1). As the system moves toward operation with process gases, additional challenges have been identified at system level:

- Sound emissions, previously identified as a bottleneck for operation at external sites, remain relevant for operation in Petten and require continued mitigation measures to be able to operate 24/7
- Safe handling of process gases during Emergency ShutDown (ESD) has emerged as a critical new challenge. This issue is related to the gas volume present in the buffer system upstream of DPU1, which must be safely discharged during emergency situations.

Technical solutions for the ESD challenge have been identified and are currently being implemented, including modifications to the gas handling system and procurement of additional components. Commissioning of the downstream processing units (DPU1 and DPU2) and storage with gases from the SEDMES system is expected in the next phase once these safety measures are in place.

MS2 is achieved in terms of hardware readiness, while full system operation is pending completion of safety and integration measures required for stable and safe operation.

Figure2: DPU1 installation for purification of DME produced in the SEDMES pilot.



(a) DPU1 top (b) DPU1 bottom including vaporizers

Figure3: DPU1 connected to the SEDMES pilot.

2.2.3 MS3: EMS ready

The POWERED project aims to investigate the flexible operation of the SEDMES process under fluctuating renewable electricity supply through the development of energy profiles, simulations, and specifications for an Energy Management System (EMS).
During the course of the project, the scope of MS3 was adapted to reflect both technical insights and the revised project context. In particular, it became clear that the flexible operating window of the current SEDMES pilot is limited, and that the direct implementation of an EMS controlling the pilot system is less relevant than initially anticipated.
As a result, the focus of MS3 has shifted from implementation of an EMS for the pilot system toward development of EMS concepts, system modelling, and broader energy integration strategies.

In this reporting period, the following progress was achieved:

- Completion of D3.1 on energy profiles and connection to renewable electricity sources
- Development of system models and simulations for flexible operation and seasonal storage concepts
- Continued work on EMS architecture (D3.2)
- Initiation of additional activities on local seasonal energy storage (LESS), including technical and economic comparison of storage technologies (D3.4)

The EMS work therefore progressed primarily through modelling, specification development, and conceptual design. These activities provide a foundation for future implementation of advanced energy management in industrial systems, rather than a fully operational EMS within the current project scope. In this context, the work has also shown that effective integration of renewable electricity and chemical production systems requires system-level optimization across multiple assets, including reactor operation, storage strategies, and interaction with the energy system, rather than direct control of a single pilot installation.

2.2.4 MS5: Testing results

MS5 covers the experimental validation of the SEDMES process, including catalyst performance, operational behavior, and system response under conditions representative of the defined use cases. In the current reporting period, the focus was on analysis, consolidation, and interpretation of experimental data obtained in earlier phases of the project, while preparing for integrated full-chain testing following completion of commissioning.

The lab-scale testing on the effect of impurities in steel off-gases (NOx and SOx) has been finalized and reported in Deliverable D2.1. These results confirmed that NOx leads to a temporary decrease in DME production during exposure with substantial recovery after switching to clean feed, while SOx causes strong and largely irreversible deactivation of the catalyst system.

In addition, pilot-scale results from earlier campaigns have been consolidated in Deliverable D2.2, demonstrating stable operation of the SEDMES reactors across different use cases and confirming key trends related to pressure, feed composition, and operating conditions.

Further analysis of these data has provided deeper insight into the factors affecting process performance. It has become apparent that the observed deviations between experimental results and model predictions cannot be explained by sorbent behavior alone, and that the catalyst system is also affected during operation.

Indications point in particular to the methanol synthesis catalyst (Cu–ZnO–Al_2O_3, CZA) as a key component in the observed performance changes. While the underlying mechanisms are still being investigated, possible contributing factors include water accumulation due to incomplete regeneration, structural changes of the active sites under operating and shut-down conditions, and interactions with impurities such as sulfur compounds and air during leaks. The samples taken from the reactor show attrition, particularly the catalyst samples at the top and bottom of the reactors after long testing of over 1000 hrs.

These observations are consistent with the gradual decrease in DME selectivity and the increasing deviation from model predictions over time. The reactor system has recently been unloaded and is currently undergoing post-mortem analysis of catalyst and sorbent materials to further assess these effects and improve the understanding of the underlying degradation mechanisms.

In preparation for the next testing phase, the system has been reloaded with fresh materials, enabling a renewed experimental campaign under improved and better-controlled conditions. The project is therefore transitioning from detailed understanding of reactor-level performance toward integrated full-chain testing, which will be carried out at the TNO pilot facilities in Petten once commissioning and safety measures are completed.

2.2.5 Results towards engineering next scale (R5)

In parallel to the experimental work, significant progress has been made on the process design and scale-up of the SEDMES technology within R5. The SEDMES process is based on cyclic operation, in which reaction and in-situ water adsorption are combined to enhance CO_2 conversion. The performance depends strongly on the applied cycle design and integration of adsorption, purge, and repressurisation steps.

The process was evaluated for different cycle configurations, including cases without and with pressure equalization (PEQ). PEQ is used to partially equalize pressure between columns, thereby reducing losses during depressurization. In particular, the use of feed repressurisation, instead of H_2) and PEQ steps were identified as a promising route to improve hydrogen efficiency and overall process performance. The results show that feed repressurisation leads to higher DME selectivity and productivity compared to H_2 repressurisation, while also reducing DME losses to the blowdown stream. In addition, the use of PEQ steps improves hydrogen efficiency showing the lower H_2 loss to blowdown step.

Furthermore, a complete process flow scheme for a 50 ktpa commercial-scale DME plant based on the integrated SEDMES process has been established in collaboration with Technip Energies, including definition of material balances, recycling strategies, and system integration concepts. The results indicate that recycling the blowdown stream, purge stream, and unconverted gases from the DPU1 unit back to the SEDMES feed is advantageous. This approach avoids the need for complete drying of all recycle streams. However, removal of water from the adsorption product prior to feeding it to DPU1 remains essential to prevent operational issues such as freezing in downstream units. Hence, a dryer was designed and included in the PFD.

This work provides the basis for ongoing techno-economic evaluation and commercial-scale design.

2.2.6 Bottlenecks, challenges and learnings

The current stage of the POWERED project is characterised by the transition from component-level validation toward integrated system operation. At this stage, system-level integration, safety, and operability become the dominant factors determining progress.

System integration and safety

The most critical bottleneck for initiating integrated operation is the implementation of a robust and safe Emergency Shutdown (ESD) strategy. This issue is linked to the handling of gas volumes in the buffer system upstream of the first purification unit (DPU1). Ensuring safe discharge and containment of these gases under all operating scenarios required additional engineering, system modifications, and validation before operation with process gases can be initiated. In addition, aspects such as noise emissions and overall system operability continue to require attention, reflecting the challenges of implementing a complex multi-unit pilot system under realistic conditions.

Material performance and degradation

A second key challenge relates to the performance of the catalyst and sorbent materials under prolonged and operation. Further analysis of experimental data and recent inspection of reactor internals indicate that performance limitations are not only linked to the sorbent, but also to changes in catalyst behaviour over time. The materials have been exposed to a range of operating conditions, including long-duration testing, commissioning phases, idle periods, and potential exposure to off-spec or unintended gas compositions, which may have contributed to the observed degradation. While the exact mechanisms are still under investigation, this observation provides an important explanation for deviations between experimental performance and model predictions. To better understand these effects, the reactor system has been unloaded and is currently undergoing post-mortem analysis, and a new test campaign with fresh materials is being prepared.

Project execution and scope adaptation

In addition to technical challenges, the project required adjustments to its execution strategy. In particular, the originally planned demonstration in an external industrial environment has been replaced by full-chain testing at the TNO site in Petten. This shift reflects both practical constraints and the need to ensure safe and controlled system integration, while maintaining focus on achieving the project objectives.

Key learnings

The challenges encountered in this phase have led to several important insights:

- Successful scale-up of SEDMES requires not only component performance, but also robust system-level integration, including safety, control, and operability.
- Material performance, in particular catalyst stability, plays a critical role in long-term system behaviour and must be considered alongside process design.
- Flexible operation and integration with renewable energy systems are inherently system-level challenges, requiring coordination between process design, control strategies, and energy infrastructure.

These learnings directly inform the next phase of the project, which focuses on completing commissioning, validating system operation, and initiating integrated full-chain testing.

3 Contribution to MOOI objectives

The POWERED project contributes to the MOOI-theme Industry, mission C, *2a Circulaire of biogrondstoffen voor bulk- en platformchemicaliën*. POWERED develops technology with which recycled CO_2 can be converted to industrial feedstock and fuel for off-grid industrial heating and transport. As such POWERED will make it possible for Industry to make a transition to sustainable feedstock and offer its clients and consumers sustainable products. The POWERED project is specifically focused on MMIP6, the utilization of captured carbon, developing CCU technology. Naturally, there is a strong connection to MMIP 8 to the application of green H_2 in chemical production processes.

4 Spin-off

The POWERED project has generated several follow-up activities that build on the results achieved to date:

Within TNO, insights into flexible chemical processes, energy-system integration, and dynamic operation are being further developed through the internal Smart Chemical Industry (SCI) program. The work on SEDMES, energy management, and renewable-energy integration directly supports ongoing developments in flexible and electrified chemical production.

In the Dutch HYCARB project, part of the GroenvermogenNL program, the SEDMES work is being integrated into CO_2-based olefin production via a two-step MeOH/DME route. This approach supports carbon-efficient conversion of CO_2 into renewable olefins, with lower energy demand and higher yields than conventional methanol-based routes, while also strengthening links with Dutch industrial value chains.

Elements of the SEDMES technology and related learnings are also being explored in European initiatives. The ongoing Horizon Europe BUTTERFLY project investigates the integration of SEDMES with gasification-based routes, including feed flexibility and process optimization. In parallel, the NEOCAP proposal, submitted under Horizon Europe 2026, builds on POWERED results to further develop and scale up SEDMES in combination with olefins, plastics production concepts, and industrial integration.

Together, these activities show that POWERED contributes to a broader innovation pipeline for circular and electrified chemical processes.

5 Overview project's publications and sources

During this reporting period, the POWERED project has contributed to dissemination through scientific publications, presentations, and outreach activities across both academic and industrial communities.

Scientific publications

Several peer-reviewed publications related to the POWERED project have been published:

- *Sorption-enhanced DME synthesis provides high flexibility: evidence from modelling four industrial use cases*, by I. Tyraskis et al., published in *Industrial Chemistry & Materials*
- *Exploiting niche markets to enable competitive renewable DME production*, by Toribio Ramirez, D.A., et al. submitted.

In addition, further publications are in preparation, including scientific work led by TNO and Tata Steel researchers.

Presentations and conference contributions

Project results have been presented at international conferences and workshops, including:

- Presentation at the *Projecten op het Podium* event (Pitch: "POWERED: Enabling flexible CCU through SEDMES") 16-09-2025, Utrecht
- Oral presentations on CCUS innovation highlighting POWERED at (inter)national conferences (e.g. CATO winter day, and Fortes Industry CCUS conference)
- Contributions by industrial partners, including Aramco, at relevant industry events

Outreach and communication

In addition to scientific dissemination, the project has been communicated through:

- The public progress report for 2025 was published on the Topsector Energie website, providing a transparent overview of project milestones and learnings.
- Online communication channels, e.g. LinkedIn

These activities support both scientific knowledge development and broader awareness of SEDMES technology and its potential role in circular carbon utilization and industrial decarbonization.

Signatures

TNO Energy & Materials Transition, Petten, 30 July 2026

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on 30-07-2026

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