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

Annual Public Progress report

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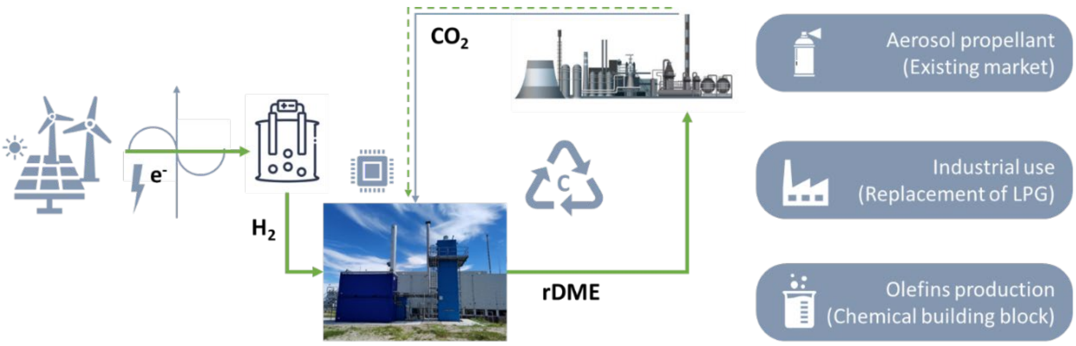

VDL Nouryon Shell PHASE TO PHASE TNO Technolution FUTURIA FUELS TATA STEEL T.EN TECHNIP ENERGIES Aramco Overseas Company B.V.

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 the climate targets of achieving net-zero emissions and at least 80% circularity by 2050, the industrial sector must transition to renewable fuels and materials. One of the most promising pathways is the conversion of CO_2 from industrial and biogenic sources into valuable renewable chemicals and fuels, enabling a circular carbon economy.

This conversion process, however, requires large volumes of green hydrogen. Therefore, it is essential that emerging CO_2 conversion technologies are not only energy-efficient and selective but also economically viable and flexible enough to handle the variability of renewable energy supply.

The POWERED project is developing an innovative solution to answer to this challenge: the Sorption-Enhanced DME Synthesis (SEDMES) process. This technology converts CO_2 and green hydrogen into renewable dimethyl ether (rDME), a versatile molecule. DME is a commodity chemical, currently used as an aerosol propellant, but with strong potential as a clean fuel alternative to diesel and LPG, and as a chemical building block.

SEDMES integrates in-situ steam removal using a solid adsorbent, which shifts the reaction equilibrium and significantly improves CO_2 conversion efficiency in a single reactor step. The technology has been validated at lab and bench scale (up to TRL5), and a dedicated pilot unit, designed and built by TNO, is now being completed with downstream purification and DME storage and used for experimental testing within the POWERED project.

1.2 Project goals

The main goal of the POWERED project is to pilot the full chain SEDMES technology and prepare for a first commercial demonstration in a follow-up project led by industrial partners.

Given the fluctuating nature of wind-based electricity, the project also focuses on flexible operation of the SEDMES system. To this end, an energy management system (EMS) is designed to ensure stable and efficient operation under dynamic power conditions. This EMS will help mitigate risks of system failure and optimize energy use.

By involving key stakeholders across the value chain, from CO_2 emitters and technology providers to end users, the project is positioned for rapid scale-up. The design of the next scale multi-kiloton-per-year rDME production facility is part of the project scope along with the techno-economic and sustainability assessment to show both environmental benefits and economic feasibility.

1.3 Consortium partners

The POWERED project brings (Table 1) together a strong consortium from the entire value chain to realize the goal of the project and commercial demonstration afterwards. It includes CO_2 heavy industries and sites (Tata Steel, Aramco Oversees Company, VDL) and off takers of the DME product that have the desire to use sustainable alternatives (Futuria Fuels, Nouryon) as well as companies that can deliver the technology to industry (Technip Energies, VDL for hardware; Phase to Phase and Technolution for software) and an open innovation pilot location (Shell ETCA).

Table 1: The POWERED consortium

Name participant	Contact person
Netherlands Organisation for Applied Scientific Research (TNO)	Soraya Sluijter
Technip Energies (T. En.)	Jan-Jaap Riegman
Shell ETCA (ETCA)	Tim Baart
Tata Steel Nederland Technology B.V. (Tata)	Peter van den Broeke
Futuria Fuels (SHV Energy) (FF)	Akhil Golla
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 at the most recent progress meeting at TNO Petten.

2 Activities, results, bottlenecks & perspective

2.1 Activities carried out in the reporting period

POWERED project includes a wide range of activities to advance the SEDMES technology ranging from the engineering and building of additions to the currently existing SEDMES pilot and optimisation of the operational (cycle) design for the defined use cases, to the design of an advanced system controller and market and environmental assessments. The technology has been planned to be piloted in industrially relevant environments in the FLIE facilities in Petten and the Energy Transition Campus Amsterdam (ETCA).

The main activities within the reporting period, the second year, of the project included:

- Construction of and Integration of recycles & Product purification & storage
- Green electricity input based on weather forecast for risk mitigation Energy Management System (EMS) for dynamic SEDMES operation
- Experimental testing to analyse the effect of impurities from industrial gases
- Long duration testing of the SEDMES pilot (without purification) at Petten

This annual report focuses on the milestones of which the main results are described in 2.2:

MS2: Hardware/adaptations ready for testing

MS3: EMS ready

MS5: Testing results

2.2 Obtained results and bottlenecks

2.2.1 MS1: Specifications/input for process design

One of the objectives of POWERED is to investigate the flexibility of the SEDMES process to cope with renewable energy production fluctuations as well as carbon sourcing variations In Result 4 the specification for different CO_2 sources as feedstock and the purity requirements for rDME product were defined in the first year. The defined use cases are input for the modelling and experimental testing in the project:

Steel plant. In both current and future steelmaking processes, certain CO_2 emissions are unavoidable, particularly those arising from the high-temperature reduction of iron ore to produce hot metal. Within the POWERED project, two integration pathways for the SEDMES process in steel production have been explored: i) In the CO_2 Absorption approach, CO_2 is first separated from the off-gas using an absorption process before being fed into the SEDMES reactor. This allows for a more controlled and purified input stream. ii) In the direct Off-Gas Utilization approach, the raw off-gas, containing CO_2, CO, and H_2,can be used directly as feedstock for the SEDMES reactor. Thanks to the inherent flexibility of the SEDMES process, which can handle a wide range of gas compositions, this route is technically feasible. It only requires pre-treatment to remove water and particulates from the off-gas, such as those produced in direct reduction (DR) or HIsarna processes. This second option is particularly attractive for future steelmaking scenarios, as it simplifies the process chain and leverages the robustness of SEDMES to accommodate variable gas compositions.

Local seasonal storage. While there is ample green energy available globally and even within Europe: it is often not accessible at the time or location where it is most needed. In many regions, electricity grids are already experiencing congestion, limiting the ability to transport renewable energy efficiently. One promising solution is to use renewable electricity directly at the point of generation, which shifts the focus toward local energy storage. Traditional storage options, such as batteries or compressed hydrogen, can be costly and require significant space. In contrast, e-fuels like rDME offer a more compact and potentially safer alternative for on-site storage, without the need for extraordinary safety measures. Together with the consortium, VDL is evaluating the technical and economic feasibility of using rDME produced by SEDMES for local, seasonal energy storage in business parks and industrial areas. This use case could provide a flexible and scalable solution to balance supply and demand in renewable energy systems.

Oil refinery. Refineries offer multiple opportunities for CO_2 utilization, with both residual and captured CO_2 streams available for conversion. Within the POWERED project, three specific refinery-based use cases were identified, and one was selected for further investigation. Similar to the steel industry, the CO_2 streams in refinery applications often contain impurities that must be removed before they can be processed by the SEDMES system. These impurities, such as sulfur oxides (SO_x) and nitrogen oxides (NO_x), are known to degrade catalyst performance, while high moisture content can significantly reduce productivity. As a result, additional purification steps are required to ensure stable and efficient operation of the SEDMES process when using refinery-derived CO_2. This use case highlights the importance of robust gas pre-treatment and the flexibility of SEDMES to adapt to varying industrial gas compositions.

DME application: The SEDMES process enables the conversion of CO_2 into rDME, which can be used in several valuable applications. One key opportunity is its use as a drop-in fuel or as a substitute for liquefied petroleum gas (LPG), particularly in off-grid sectors where access to clean energy alternatives is limited. Additionally, rDME can serve as a sustainable heating fuel, replacing natural gas in industrial settings. For applications in the chemical industry, where DME is used as a commodity chemical or feedstock, the purity requirements are significantly more stringent. These varying applications defined the specifications for the purification process and influenced the design of the downstream system within the POWERED project.

2.2.2 MS2: Hardware/adaptations ready for testing

A key objective of the POWERED project is to demonstrate the full DME production chain, including purification and storage of commercial-grade rDME. This involves integrating a downstream purification system, a storage solution, and a recycling loop for unconverted gases into the existing SEDMES pilot setup.

Over the past year, significant progress was made toward achieving this milestone. All major components required for the downstream purification and storage systems have been delivered and are now on-site in Petten. The first purification unit (DPU1), to separate DME from the unconverted gases, has experienced substantial delays and technical issues. However, it was completed at the start of the year and successfully connected to the SEDMES unit, including the necessary buffer system. The second purification unit (DPU2), to separate DME from methanol and water by-products, has also been constructed. Furthermore, the rDME storage system is now fully prepared, with all components in place. Construction is scheduled for the summer, and the permit for storage, previously under review, has been approved and extended through summer 2026.

Despite these advancements, MS2 remains delayed. The full system is expected to be ready for testing after the summer, primarily due to the earlier setbacks with DPU1 and the complexity of integrating the various subsystems. In addition, the integration of the unconverted gas loop (UGL) has been paused due to time and budget constraints. While the design and procurement phases were completed in the previous reporting period, implementation has been deferred.

2.2.3 MS3: EMS ready

The POWERED project aims to demonstrate the flexibility of the SEDMES process under fluctuating renewable electricity supply. Result 3 focuses on integrating the advanced DME production chain with dynamic energy sources and developing an Energy Management System (EMS) to optimize operation based on electricity availability and cost.

Over the past year, significant progress was made in defining the energy profiles and simulation framework required to support the EMS design. Deliverable D3.1. was finalised and this outlines the definition of two key use cases: i) Energy Storage in DME (VDL Case): Using DME as a seasonal storage medium to decouple local energy generation and consumption, reducing grid congestion and enabling energy independence for industrial sites. ii) Power-to-DME (Wind at Sea Case): Aligning DME production with periods of low electricity prices, typically associated with high renewable generation, to reduce energy costs and avoid curtailment.

Initial simulations of the SEDMES process under varying load conditions showed promising results. At lower flow rates, carbon selectivity increased, although productivity decreased. These findings support the hypothesis that SEDMES can operate flexibly, but also highlight the need to understand trade-offs between efficiency and throughput.

The EMS itself will not be physically implemented within the current project scope. Instead, its functional architecture and specifications are being developed based on simulation results and experimental input. The EMS will be designed to:

- Maintain safe operation of the SEDMES unit.
- Use weather forecasts and electricity price signals to manage production.
- Coordinate energy flows between assets such as batteries, solar panels, and the SEDMES unit.

The experimental campaign planned under Result 2 will provide critical data to refine the EMS specifications. Key questions being addressed include acceptable operating windows, ramp-up/down dynamics, system bottlenecks, and safety thresholds.

While the EMS will not be deployed in hardware, the simulation-based design will serve as a blueprint for future implementation and will feed into the techno-economic assessment under Result 5.

2.2.4 MS5: Testing results

The POWERED project reached a major milestone this year with the successful completion of over 1000 hours of pilot-scale testing at the FLIE site in Petten. The experimental campaign focused on validating the SEDMES process based on the defined use cases and the first assessment of its flexibility in response to dynamic energy inputs. Also, the results on impurity testing have been finalised.

Pilot Results

The pilot focused on three primary use cases: captured CO_2 from oil and gas operations, diluted CO_2 from steel industry off-gases, and dynamic H_2/CO_2 supply scenarios representing seasonal energy storage. Each case was designed to test the flexibility and robustness of the SEDMES process under different feed compositions and operating conditions.

For the oil and gas case, testing with high-purity CO_2 streams revealed that while the general performance trends aligned with model predictions, the actual productivity was lower than expected. This discrepancy is believed to be linked to earlier sorbent degradation, a known issue from previous projects. To address this, improvements in regeneration strategies were explored, including longer purge durations, which showed a positive impact on performance. In contrast, increasing the purge flow rate had minimal effect, suggesting that energy consumption can be optimized by using the minimum effective flow. Another hypothesis under investigation is that catalysts may require a reactivation process. To address this, new materials will be employed in the upcoming campaigns.

In the steel use case, the SEDMES pilot was tested with nitrogen-diluted CO_2 streams to simulate off-gases from processes such as direct reduction of iron (DRI) and HIsarna. While a reduction in productivity and selectivity was observed under these conditions, the results provided valuable insights into the system's behaviour when processing more complex gas mixtures. These findings highlight the adaptability of the SEDMES process and reinforce the importance of tailoring upstream gas treatment strategies to specific industrial applications.

The seasonal energy storage use case assessed the SEDMES unit's ability to operate under fluctuating feed conditions, simulating the variability of renewable electricity supply and its corresponding hydrogen availability. The system showed promising flexibility, maintaining DME production even during simulated power outages. In these tests, the adsorption step was paused without significant loss in yield, indicating that the process can tolerate interruptions and ramp-downs, an essential feature for integration with intermittent energy sources.

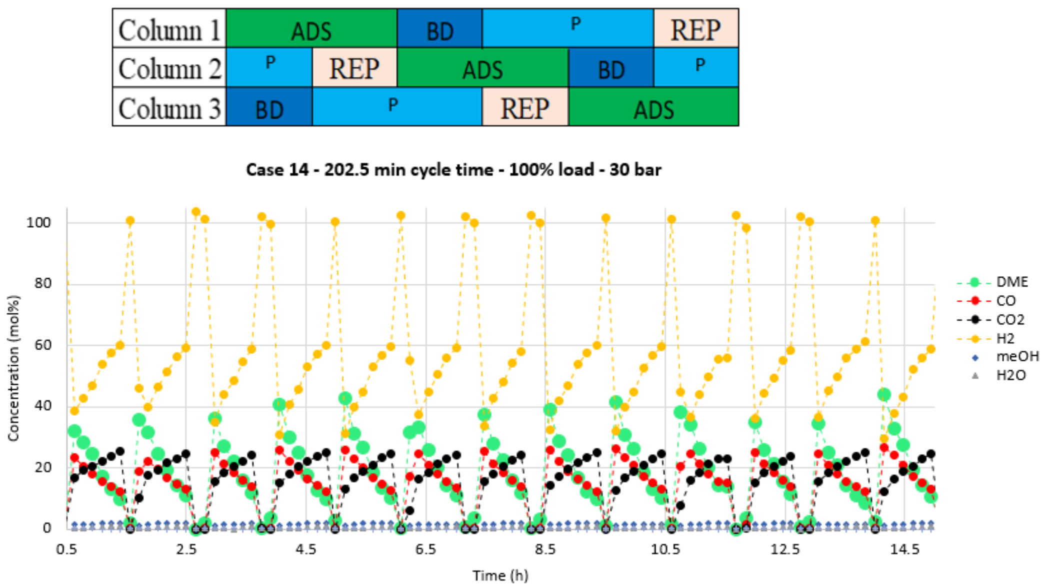

Figure 2: Cyclic results of 15 hours continuous SEDMES operation at 30 bar.

Lab-Scale Impurity Testing

In parallel, lab-scale experiments investigated the impact of impurities in HIsarna off-gas. Synthetic gas mixtures were used to simulate real conditions. Results showed that NOx causes reversible declines in DME production, whereas SOx leads to irreversible catalyst poisoning .

Based on these findings, and due to delays in the HIsarna campaign and limited test setup availability, real gas testing was not pursued.

2.2.5 Bottlenecks, challenges and learnings

Full System Integration of a Dynamic Process

Bringing together the full SEDMES chain, including purification, storage, and gas recycling, proved more complex than anticipated. A practical challenge was the delay in the readiness of key components, such as the first purification unit (DPU1), which impacted the timeline for full system commissioning, as described above.

A key technical challenge emerged from the contrast between the dynamic nature of the SEDMES process (designed to respond to fluctuating renewable energy supply) and the more rigid behaviour of the downstream distillation system. Aligning these two systems required careful design, as the distillation unit operates best under steady conditions, while SEDMES is inherently dynamic and developed to be more flexible within the project. This enforced the need for designing smart control strategies and including buffer systems that can bridge the gap between dynamic and static operations.

Designing for Energy Flexibility Requires Thorough System-Level Insight

Developing an Energy Management System (EMS) to support flexible operation under intermittent renewable electricity supply revealed that flexibility is not just a control challenge. It is a system-wide consideration. The scope of the project does not fit the development of a full EMS system. One of the early challenges in developing the Energy Management System (EMS) was aligning perspectives. Using an EMS for aligning fluctuating sustainable energy demand with an industrial process with a high need for continuity and stability is important yet relatively new in the process and chemical industries. Applying an EMS to such a process is different than for other processes where EMS are a commodity (e.g. battery management, households and offices) and the field was unfamiliar to EMS experts. It took time to build a shared understanding. In addition, designing an effective EMS requires detailed insight into how each part of the system behaves under different conditions. This learning phase was essential to define realistic control strategies and ensure the EMS can eventually support flexible, renewable-powered operation. The foundational work, including energy profiles, use case definitions, and system architecture, will support future deployment and integration with dynamic energy sources.

Industrial Deployment Requires More Than Just Technical Readiness

One of the original goals of the POWERED project was to relocate the pilot installation to Shell's Energy Transition Campus Amsterdam (ETCA) for long-duration testing in an industrially relevant environment. This would have provided valuable experience with transporting, installing, and operating the system at a third-party site. However, despite extensive preparation including engineering, permitting, and safety planning—the move had to be cancelled in May 2025 due to unresolved noise issues.

The problem stemmed from the incinerator, a safety device used during pilot testing to handle (excess) gases. While it is not part of the core SEDMES technology, it is essential for safe operation during testing. Unfortunately, the incinerator produced high sound levels (+100 dB) that exceeded ETCA's site limits. Multiple mitigation efforts were attempted, including the design and testing of custom outlet extensions, but none were able to reduce the noise to acceptable levels. Redesigning the incinerator was not feasible within the project's budget and timeline. As a result, the consortium is now activating a fallback plan to continue long-duration testing at TNO's FLIE site in Petten. While this ensures that the technical goals of the project can still be achieved, it does mean that the team will not gain the hands-on experience of relocating and operating the system in a new industrial setting, an experience that would have helped de-risk future scale-up.

Nonetheless, the preparatory work for ETCA has yielded valuable insights into the practical challenges of industrial deployment, which will inform future demonstration efforts and follow-up projects. A key insight was the difficulty of integrating a pilot unit, especially one that is being further developed and extended with in this case purification and storage, into an existing industrial site. It was challenging to match the evolving design and progressing insights about SEDMES with fixed and stringent site requirements, especially around safety, infrastructure, and permitting. The collaboration also highlighted the importance of openness. Transparent communication about constraints and expectations helped build trust and improve collaboration. Furthermore, the SEDMES team gained valuable experience in the safety and operational aspects of running SEDMES at a larger scale. These reflections underscore that industrial deployment is not just a technical challenge; it also requires alignment across organizations, clear communication, and mutual understanding. The POWERED project not only strengthened the collaboration between Shell and TNO, but also reaffirmed that the complexity of the energy transition demands joint effort and shared learning.

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

At this moment it is too early in the project to identify specific spin-offs of the project. However, VDL and TNO are already pursuing a follow-up project to accelerate the seasonal storage use case.

5 Overview project's publications and sources

In the reporting period, June 2024 to May 2025, dissemination efforts for the POWERED project focused on expanding visibility across scientific, industrial, and public platforms. A key highlight was the publication of the peer-reviewed article "Performance optimization of sorption-enhanced DME synthesis (SEDMES) from captured CO_2 and renewable hydrogen" in Frontiers in Chemical Engineering, authored by I. Tyraskis, A. Capa, G. Skorikova, S. N. Sluijter, and J. Boon. This paper, which received 559 views and 92 downloads as of February 2025, underscores the project's scientific impact. In addition, a manuscript titled "Sorption-enhanced DME synthesis provides high flexibility: evidence from modelling four industrial use cases" has been submitted to Industrial Chemistry & Materials and is under revision at the end of this reporting period.

The public progress report for 2024 was published on the Topsector Energie website, providing a transparent overview of project milestones and learnings. The SEDMES technology was nominated for the Best CO_2 Utilisation Innovation Award 2025 by nova-Institute, recognizing its contribution to sustainable fuel production through the SEDMES technology and in this framework the POWERED project was presented at the CO_2-based Fuels and Chemicals Conference in Cologne (Figure 3). Tim Baart presented the POWERED project to showcase possibilities at ETCA at the final event of LeapSprong. A TNO vodcast on e-fuels, featuring the POWERED project, has been recorded and is expected to be released in the next reporting period.

Figure 3: Nominees of the Best CO_2 Utilisation Innovation Award 2025 by nova-Institute, including SEDMES.

Signatures

TNO Energy & Materials Transition, Petten, 17 July 2025

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