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

Annual Public Progress report

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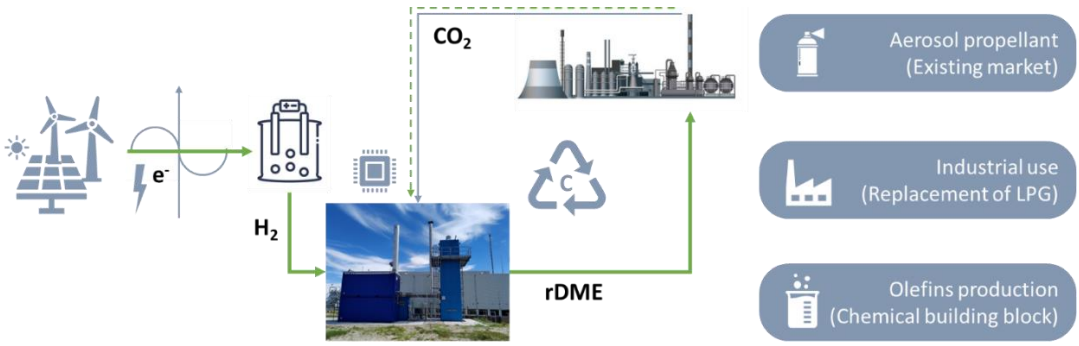
POWERED



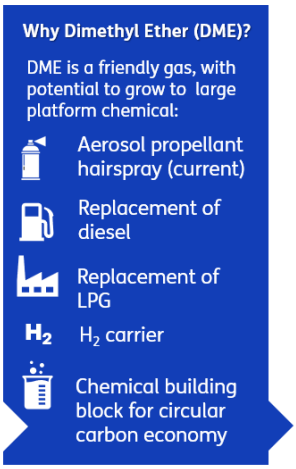
This project is carried out with Topsector Energie subsidy from the Ministry of Economic Affairs and Climate Policy, executed by the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland). The specific subsidy for this project pertains to the MOOI subsidy round 2022.

1 Basic principles, project goals and consortium partners

1.1 Introduction and basic principles

To reach the climate objectives of achieving climate neutrality and a minimum of 80% circularity by 2050, the industrial sector has to transition to renewable fuels and materials. The synthesis of fuels and materials from CO_2 found in various sources, such as residual biomass and industrial streams, embodies the ultimate form of carbon recycling.

Converting CO_2 to added value renewable hydrocarbons through hydrogenation requires substantial amounts of green hydrogen. Therefore, it is key to ensure that processes for CO_2 conversion provide the highest possible energy efficiency and selectivity towards desired products as well flexibility to accommodate the intermittency of renewable energy supply.



The POWERED project is advancing an efficient technology to convert CO_2 and green hydrogen into renewable dimethyl ether (rDME). DME is a commodity chemical, currently mainly used as a propellant in aerosol products such as hair spray, but with a high potential as replacement of petroleum-based fuels (diesel and LPG) and chemical building block in the future.

The novel Sorption-Enhanced DME Synthesis (SEDMES) process, leveraging in-situ steam removal with a solid adsorbent, ensures high CO_2 conversion efficiency to DME in a single unit operation. The in situ removal of steam, shifting the equilibrium to the product side, has proven to increase catalyst lifetime and boost process efficiency. Compared to conventional DME production, the SEDMES technology can significantly reduce internal recycling streams, simplify heat management, allow nearly complete single-pass H_2 conversion. Therefore, costs for compressors, utilities and downstream purification processes for this carbon capture and Utilisation (CCU) technology can be reduced compared to the conventional process.

The SEDMES technology was successfully tested on lab and bench scale on existing infrastructure up to TRL5: experimental validation of the complete SEDMES operating cycle. In a previous project the first dedicated SEDMES facility has been realized (Figure 1), designed and engineered in-house by TNO. This SEDMES pilot unit is employed for the experimental testing within POWERED and extension are added to make the process more efficient and purify and store the produced DME. The unit will also be tested in an industrial relevant environment at the Energy Transition Campus Amsterdam (ETCA; TRL6).

Figure 1: SEDMES pilot facility (3kg/h DME)

1.2 Project goals

The primary goal of POWERED is to validate the innovative SEDMES technology including DME purification and storage and prepare for a first commercial demonstration in a follow-up project led by industry partners.

The intermittent character of wind based electricity production inherently requires flexibility of the overall production process, electrolysis, DME synthesis and purification. The electricity cost is also expected to fluctuate according to availability. POWERED will develop an agile energy management system (EMS) allowing for the overall required flexibility and mitigate possible risks of a system failure.

Furthermore, the successful roll-out of the SEDMES technology will be ensured by demonstration of the environmental benefits and cost competitiveness.

1.3 Consortium partners

The POWERED project brings together a strong consortium from the entire value chain (Table 1) to realize the goal of the project and commercial demonstration afterwards. It includes CO_2 heavy industries and sites (Tata Steel, Aramco, VDL) and off takers of the DME product that have the desire to use sustainable alternatives (Dimeta, 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
Dimeta	Lizzie German
Aramco OC (AOC)	John Henn
Nouryon	Cees Kooijman
Technolution	Jop Spoelstra
Phase to phase (PtoP)	Jop Spoelstra

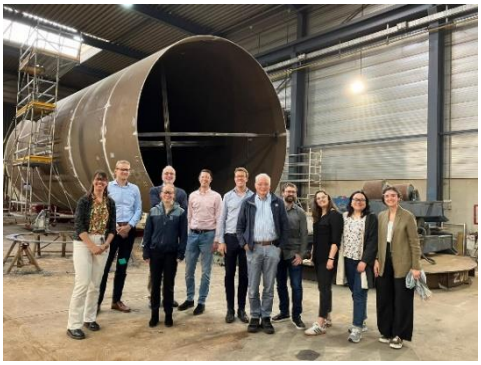


Figure 2: Consortium at the most recent progress meeting at VDL-KTI in Mol.

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 an additional purification and recycle loop to the currently existing SEDMES pilot and optimisation of the operational (cycle) design for the defined use cases, to the development of an advanced system controller, and market and environmental assessments. The technology will be piloted in industrially relevant environments in the FLIE facilities in Petten and ETCA.

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

- Use case definition: CO_2 source and DME purity
- SEDMES cycle designs for different H_2 inputs and CO_2 sources
- Design 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
- Policy assessment

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

MS1: Specifications/input for process design

MS2: Hardware/adaptations ready for testing

MS4: Draft policy analysis 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 were defined and the purity requirements for rDME product were set based on the application. This is used as input for the cycle design for the SEDMES unit and product purification train. Based on these data, the 2nd purification column is being designed and built.

The following main use cases have been formulated with different CO_2 sources and DME applications and corresponding purities:

Steel plant. Current and future steelmaking will have some unavoidable CO_2 emissions originating from the processing, the reduction of iron ore at high temperatures to produce hot metal. For the use of SEDMES in (future) steel making, like direct reduction of iron (DRI) or HIsarna, two options can be envisaged. In the first option, the CO_2 from the off-gas will be removed by an absorption process. In the second option, no CO_2 removal is needed, and the

off-gas stream (with CO_2, CO and H_2) is used directly as a feed for the SEDMES reactor. Considering the advantages of the SEDMES process, being able to handle a wide range of gas compositions in terms of CO_2, CO and H_2 in the feed gas, this second option only requires a section to remove the water and particulates from the off-gas of the DRI process.

Local seasonal storage. In the world and even in Europe there is enough green energy available. However, not at the time and location where it is needed. Some electricity grids are already overloaded today. So using the energy, where it is produced will be a big part of the solution. In that case storage becomes the most important factor. Storage in batteries or storage in compressed hydrogen takes a lot of space and costs. Also for E-Fuels no abnormal safety measures have to be taken to store it locally. VDL is evaluating together with the consortium whether local seasonal storage for business area's with DME could be feasible technically and economically.

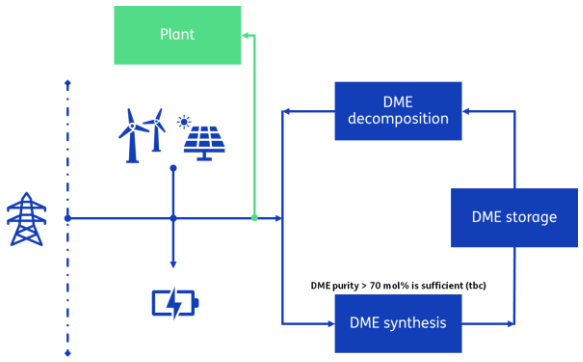


Figure 3: Schematic overview of the seasonal storage case

Oil refinery. There are multiple sources of residual CO_2 streams or captured CO_2 streams in refineries. Three specific use cases were defined. One of these was selected for further investigation within the POWERED project. The CO_2 source streams both in this application and the Steel industry contain impurities that need to be removed and thus require additional purification before these streams can be processes by SEDMES. For example, certain impurities (e.g. SOx and NOx, see 2.2.4) are known to poison the catalyst and high contents of water reduces the productivity significantly.

DME application: SEDMES can valorise the CO_2 to produce a drop-in fuel or as LPG substitute for the off-grid sector. Alternatively DME could be used for heating on site replacing natural gas DME. Finally, the most stringent purity restriction are related to DME as a (commodity) chemical.

2.2.2 MS2: Hardware/adaptations ready for testing

One of the objectives of the POWERED project is full chain piloting of DME production, including purification and storage of commercial-grade DME. To achieve this goal a complete downstream purification system and a storage tank for produced rDME will be realised. To demonstrate increased efficiency of the technology, the SEDMES unit will be complemented with a recycling loop for unconverted gases.

The design and engineering of the second purification column for the separation of DME from methanol and water by-products as well as the unconverted gas recycle and rDME storage is finished. The PFD, P&ID and HAZOP are completed, and most components were ordered and are expected in Q3 2024.

The first purification column (part of another project) is significantly delayed. Therefore, the whole downstream purification train will be realized later in the project than initially anticipated. The planning is now to have the full train ready in Petten end of 2024.

2.2.3 MS4: Draft policy analysis ready

Assessment of the sustainability of rDME production is essential both to its acceptance by the customer, maintaining market integrity for producers and distributors, and facilitating access to subsidies and policy support. In results 4 an initial review of the policy support for rDME produced via power-to-liquid technologies was performed by Dimeta, focusing on the European and Dutch regulatory and policy landscape. A long-list of relevant policy documents was identified, and their potential impact on commercial-scale SEDMES deployment was mapped. Subsequently, the five key policy documents were selected and analysed in detail

2.2.4 MS5: Testing results

To assess SEDMES process efficiency under industrial conditions and study the response to the electrical grid, in result 2 the first experimental activities at Petten were started:

1. Lab-scale testing of impurities of HIsarna off-gas on the catalyst/sorbent mixture under different SEDMES operating conditions
2. SEDMES experimental campaign based on use cases (without purification)

Based on the use cases described above, cycle design and simulations were performed in Result 1 to find the optimal operating conditions for the SEDMES process to reach the desired specifications and maximise the selectivity-productivity trade-off. These results provided the basis for the experimental plan for Result 2. The labscale testing has started and is investigating the effect of impurities of off-gas from the HIsarna process on the existing catalyst/sorbent: a commercial mixture based on Cu, Zn, γ-alumina and zeolites. The first test focus on NOx and SOx as well-known catalyst poisons. Furthermore, Tata Steel will collect and provide a bottled industrial off-gas from HIsarna unit (at the IJmuiden site of Tata Steel) in one of their campaigns this year that will be used as feedstock for testing. For this the Hisarna campaign and availability of TNO infrastructure has to be well aligned. As a consequence, the testing is delayed.

On the pilot installation, several cycle designs and gas compositions based on the use cases are tested that fall outside the specifications of the design of the purification system, are being tested, including long duration SEDMES experimental campaign based on DRI steel off-gas.

Preparations for the experimental campaigns at ETCA are ongoing. Focus was on ensuring the required permit to operate the pilot at Amsterdam and the storage of DME.

2.2.5 Challenges regarding permitting and DME storage regulations

With the change of the Omgevingswet on the 1st of January 2024, new opportunities have arisen regarding the permitting requirements and timelines. While interpreting the Dutch regulations for the storage of DME posed some challenges, the POWERED project successfully navigated these complexities . The project's unique production and storage volume of rDME did not perfectly align with any single 'Publicatiereeks Gevaarlijke Stoffen' (PGS) guidelines, that describe the regulations, requirements and criteria that can be used in environmental permit granting, the formulation of general rules, and supervision of companies for occupational safety, environmental safety, and fire safety. However, through collective efforts from experts from TNO, Dimeta and subcontractor Royal Haskoning DHV, an effective solution was ultimately developed by combining elements of PGS-15 and PGS-19.

2.2.6 Bottlenecks EMS control full SEDMES system

It has become apparent that an overarching EMS system for the intermittent rDME production using SEDMES process cannot be built and tested within the scope of this project as only SEDMES, purification and storage are part of the physical process train. Furthermore, there are still many open questions about the limits of SEDMES flexibility, which are the topic of this project. To study the dynamic behavior of the process the built-in control system can be used to control the full chain. Therefore, no EMS will be used for the experimental campaigns. However, the description of the EMS specifications and description of EMS system technical architecture will be created. The defined use cases for intermittent rDME production will be described in this deliverable as well as the planned simulations that serve as an input to the techno-economic assessment in Results 5 (as well as potential follow-up projects).

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 'Meerjarig Missiegedreven InnovatieProgramma' (MMIP) 6, 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

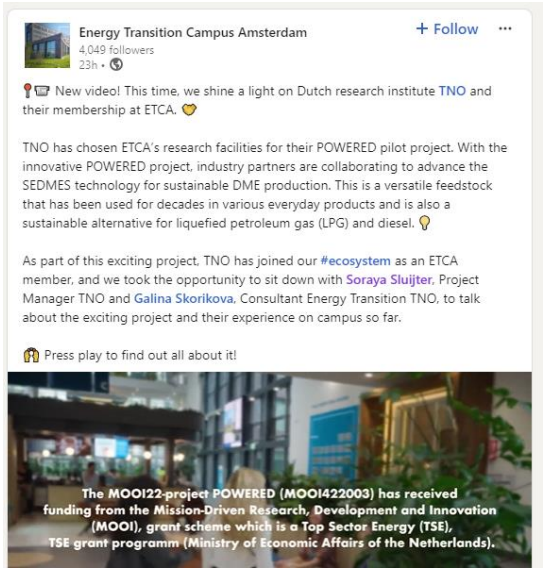
At this moment it is too early in the project to identify specific spin-offs of the project. However, VDL and TNO are trying to accelerate the seasonal storage use case by creating a follow-up project for a 10kg/h SEDMES unit already.

5 Overview project's publications and sources

In this reporting period, the following dissemination and knowledge sharing activities were conducted:

- Project webpage at the TNO website was set-up: https://www.tno.nl/en/sustainable/co2-neutral-industry/biobased-fuels-chemicals/powered-efficient-co2-conversion/
    - Project description on consortium partners websites: e.g. https://www.technolution.com/spark/powered-project-net-conscious-energy-management/?noredirect=en-GB
- LinkedIN posts on the start of the project
- Blogpost interview Dimeta's new Business Development Director Katrien Wijsman and POWERED project manager Soraya Sluijter: Pioneering collaboration and innovation in sustainable fuel production: The Powered Project - DIMETA
- An ETCA member video was prepared and published on LinkedIn: https://www.linkedin.com/feed/update/urn:li:activity:7217091094402985985/

It is expected that more publications and presentations at conferences will be done once more results will come out of the project.



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TNO Energy & Materials Transition Petten, 18 July 2024

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