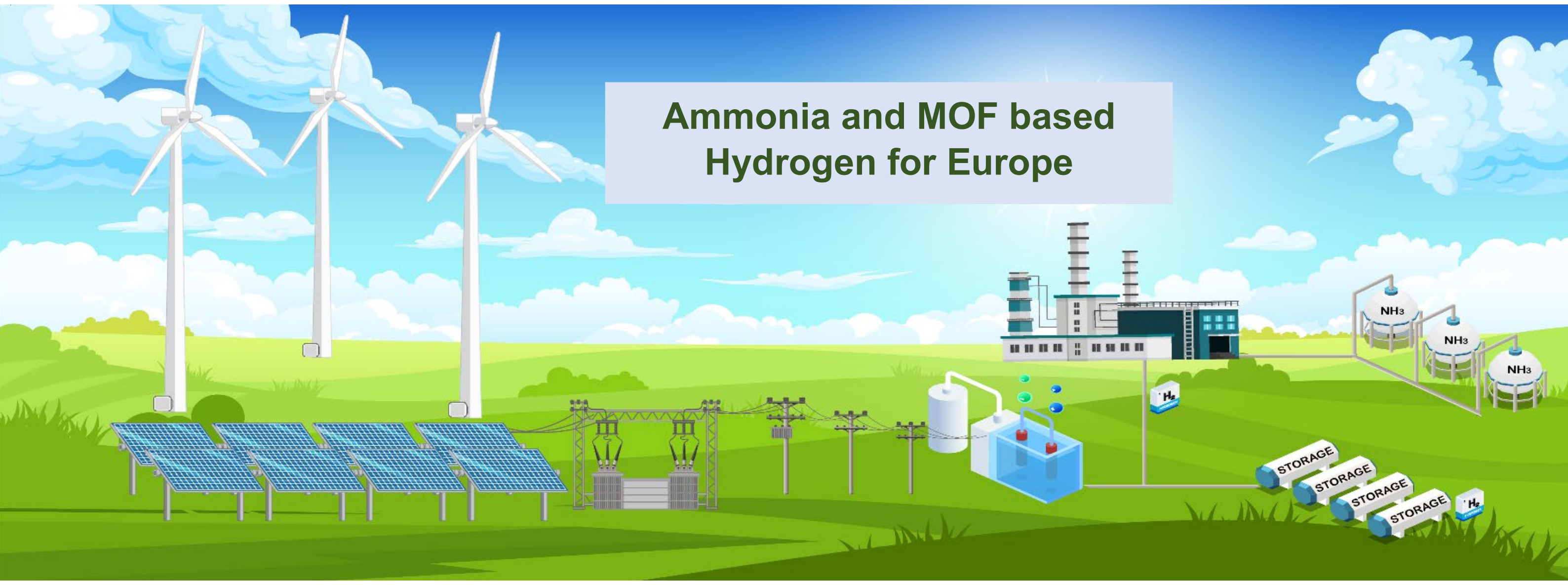


Welcome to this sixth AMBHER newsletter. AMBHER is a four-year project targeting the development of high-performance, cost-effective hydrogen storage technologies. Two different technologies are addressed: novel nanoporous metal organic frameworks (MOFs) for the short time hydrogen storage in vessels for transport applications and membrane reactors integrating new catalysts and membranes for ammonia synthesis for long term hydrogen storage media.

The present newsletter is the sixth release of the biannual letter that will be published by AMBHER presenting the progress on the project and highlighting information related to the R&D fields addressed. Hope you will find the info in this newsletter interesting. On our website www.ambherproject.eu you will find public presentations, all the public deliverables of the project and many other interesting news. Stay tuned!

In this newsletter:

About the Project

AMBHER (Ammonia and MOF based Hydrogen for Europe) is a European project providing a holistic approach to tackle the short- and long-term energy storage challenges raised by the high degree of electrification our society is aiming for. Firstly, AMBHER is addressing the main societal, economic and technological questions coming together with the use of green ammonia as seasonal renewable energy storage. Simultaneously, AMBHER is developing and demonstrating innovative and cheaper compressed hydrogen storage potentially solving the gap toward local and economically relevant power-to-hydrogen hub.

AMBHER will thus increase the number of applications in the energy and transport sectors and the possibilities for success and industrial adoption by key players. For short-term hydrogen storage, novel nanoporous MOFs (Metal Organic Frameworks) of high surface area (>2.500 m^2/g) and low-cost synthesis will be developed following an original shaping process (3D printing). Furthermore, AMBHER will develop a conformable cryo-vessel that can accommodate stacks of MOF bodies of tailored-made shape.

A capacity of 40 g/L of usable space at 100 bar is achieved at competitive cost with respect to current high-pressure cylinders. For long-term storage, advanced materials (both catalysts and membranes) and their combination in an intensified 3D-printed intensified periodic open cell structured reactor will be developed to allow hydrogen storage in the form of ammonia (NH3) in a cost-efficient and resource-effective process at lower temperatures and pressures compared to conventional systems. AMBHER project is validating both solutions at TRL 5 addressing the positioning of the solutions developed in relevant business cases.

Impacts

AMBHER project will contribute to the objectives of the European Green Deal towards making the European Union (EU) climate neutral in 2050. It will play an important role in addressing some of the key challenges facing today's global society, such as the cost of energy, energy security and climate change. It will not only reduce the EU's energy dependence, but also make its energy system more resilient by balancing the energy generation and consumption curve facilitating the integration of the renewable energy in the grid through long-term storage hydrogen technologies.

The use of renewable energy storage solutions in the short and long term enables the decarbonisation of many sectors that would otherwise be difficult to decarbonise, such as transport sector. These innovations will have an impact on the entire value chain of these sectors and improve the overall competitiveness of the European economy. AMBHER will also contribute to the generation of wealth by creating around 20,000 jobs (direct, indirect and induced) accumulated (2030-2035). It will connect material developers with key players in the hydrogen economy, additive manufacturing companies, chemical companies and end-users of ammonia, matching existing needs and new products with the essential link provided by innovative organizations that can develop advanced technologies that will meet the challenges of the coming years.

Other research articles have been published during the last period of AMBHER , showcasing innovative advancements in materials science and sustainable energy solutions.

If you haven't had a chance to explore these works yet, here's a quick summary to keep you informed:

Upscaled Al-Fumarate Synthesis and Shaping by Spray Drying

This study presents a spray-drying Al-fumarate synthesis that allows simultaneous synthesis and workup. Thisallin-one step synthesis produces calibrated Al-fumarate grains of high quality without the need for further processing. Obtained materials are characterized by PXRD, TGA, N2 and H2O adsorption, PSD, andmicroscopy imaging. The synthesis has been upscaled to the 60kg scale. Whereas all reported synthesis routes in the aqueous phase proceed in base conditions by addition of NaOH, the synthesis reported here in is obtained at a pH below 3, with aluminum isopropoxide acting as a base that can steadily react with fumaric acid without the need for pH adjustment. Major differences in the large meso- to macroporous structure are observed depending on the drying process, with an absence of intergranular porosity for the spray-dried pilot batch, reflecting the high-density nature of the obtained MOF powder. Large productivity can be achieved at spray-driers due to their important evaporation capacity (up to several hundreds of tons of/h), opening the perspectives of mass production of Al-fumarate. Air dehumidification in a fluidized bed is carried out as a proof-of-concept application. The fluidized bed's breakthrough curve profile, with alonger t50%, is in line with a better column isothermicity, connected to the fluidization conditions. Ultimately, we developed a comprehensive 3-in-1 process that integrates synthesis, drying, and shaping while also exploring its potential for production intensification. We believe that this synthesis approach could pave the way for the scalable production of other Al-MOFs, atopic currently under investigation.

Scalable one-step syntheses of aluminium-based MOFs

MOF manufacture consists of multistep processes, including filtration and washing steps to remove coproduced salts and wash out the solvent, if any. This constitutes a productivity bottleneck, together with significant costs for waste disposal. We show here a robust single-step route for the synthesis of aluminium-based MOFs that has been successfully applied to Al-fum, MIL-96, MIL120, and MIL-160, all using aluminium alkoxide as a precursor. Highly crystalline MOFs are obtained with high yields (490%). No wash-up or separate drying steps are necessary.

Modeling of a packed bed membrane reactor for ammonia synthesis: on the role of membrane performance and operating conditions

Ammonia (NH_3) has gained attention as a potential hydrogen carrier for its high hydrogen content and absence of carbon atoms. However, the main route for ammonia production is still the energy intensive Haber-Bosch process. In this study, the membrane reactor technology is proposed as an alternative to integrate ammonia synthesis reaction and its simultaneous separation within a single unit. A non-isothermal 1-D packed bed membrane reactor model was developed, in which ammonia synthesis is promoted by a ruthenium-based catalyst, and its in situ separation takes place by means of NH_3-selective membranes. The mathematical model was first validated with experimental data in a packed bed reactor, and afterward used to study the feasibility of a packed bed membrane reactor, aiming to identify the optimal membrane performance required to enhance the reactor efficiency, in terms of H_2 conversion, NH_3 purity and NH_3 recovery. Initial results under isothermal conditions, demonstrate that a PNH3 >10 7molPa 1m2s 1 and SNH3/H2 =50 are required to significantly boost H_2 conversion. On the other hand a SNH3/N2 =100 was selected as a trade-off value influencing NH_3 purity and NH_3 recovery. The operating conditions study revealed that both sweep gas-to-feed flow ratio and pressure difference across the membrane are crucial for enhancing reactor performance, with optimal conditions identified at SW =6 and ΔP =20 bar. Furthermore, in the adiabatic case study, the investigation of the heat exchange integration between feed gas and sweep gas streams, highlights the importance of the latter as cooling fluid, achieving the best results at inlet permeate temperature of 200 ◦C. This enabled to achieve an H_2 conversion of 93 %, along with NH_3 recovery and purity of 99.14 % and 5.65 % respectively. Hence, the mathematical model demonstrates that an adiabatic packed bed membrane reactor with the integration of heat exchange has the potential to attain greater H_2 conversion compared to the equilibrium constraint observed in a conventional packed bed reactor.

A solvothermal approach to nano-designing M-N-H systems: unveiling new pathways to dimensional control in the lithium nitride hydride ammonia synthesis catalyst

The Li–N–Hsystemspansarich networkof reactive phases that encompassLi3N– Li4NH– Li2NH–LiNH2–LiH, interconnected through a number of solid solutions and mediated via NH_3,H_2, and/or N_2 exchange. Realizing the full potential of these Li–N–H systems in ammonia catalysis and hydrogen storage applications has been hindered by the inability to 'nano-design' them beyond conventional bulk synthesis. Here, we present a novel solvothermal route for the synthesis and nanostructurisation of LiN–H and Li–Na–N–H materials, providing a solution-phase route to these air-sensitive and reactive materials. The method enables enhanced morphological and dimensional control compared to solidstate routes, yielding nanostructures such as wires, rods, and particles with characteristic sizes from 300 to 900 nm. We systematically explore the structural and microstructural evolution of these phases, and demonstrate the influence of mineralisers on the sample morphology. We report evidence of enhanced nitrogen activation, air-stability and ammonia synthesis activity for these samples, balanced against their propensity for carbon contamination. This work opens the possibility of a significantly expanded synthesis approaches to Li–N–H materials, and M-N-H materials more broadly.

Activated triply periodic minimal surfaces (TPMS) gyroid supports for efficient ammonia synthesis in membrane-integrated reactors

Ammonia is an essential chemical widely used in industry, with its production dominated by the highly energy- intensive Haber-Bosch process. Membrane reactor technology offers a promising alternative by integrating reaction and selective product separation, thereby enabling higher process efficiencies and milder operating conditions. In this work, we investigate a new membrane reactor composed of a carbon membrane immersed in an Activated Triply Periodic Minimal Surface (TPMS) gyroid support uniformly coated with a Ru-based catalytic layer. Different operating conditions have been investigated; The most favourable baseline conditions were identified at the lowest WHSV (715 mLn gcat 1 h 1), and with an under-stoichiometric H2:N2 feed ratio of 2:1, reflecting both the proximity to thermodynamic equilibrium and the beneficial impact of reduced hydrogen partial pressure on Ru-based catalysis. At 250 ◦C and 40 bar, increasing the sweep gas to feed flow ratio (SW) to 10 led NH3 production rate enhancements of approximately 43 % and corresponding NH3 yield gains of 15 %, with an NH3 recovery factor of 84 %. At lower pressure (30 bar) and higher temperatures (350–450 ◦C), the membrane reactor still enhanced NH3 production rate at reduced sweep ratios, with gains of about 1-20 % at SW =1 and 17–41 % at SW =4 relative to the SCR. However, the NH3 recovery factor dropped to 64-70 % for SW =1 and 41-66 % for SW of 4, compared with 87-95 % at 40 bar. This behaviour indicates a clear trade-off between productivity and product recovery as pressure and sweep ratio are adjusted. At 450 ◦C and 10-40 bar, with a SW =4, H2 conversion exceeded the equilibrium value by approximately 15–30 %, and the conversion achieved at 400 ◦C in the SCR was already attained at 300 ◦C in the SCMR. At 400 ◦C and 40 bar with SW =4, H2 conversion, NH3 production rate, and NH3 yield increased by 83.4 %, 76.9 %, and 53.4 %, respectively, compared to the structured reactor. Overall, these results provide a clear proof of concept for the application of structured membrane reactors to ammonia synthesis, demonstrating that an appropriate combination of structured Ru-based catalysts and carbon membrane integration can deliver enhanced efficiency and equilibrium shifting under milder operating conditions, and offering a solid basis for future scale-up and process optimization studies.

For those eager to dive deeper into these studies, full details can be found on the https://www.ambherproject.eu/article-papers/

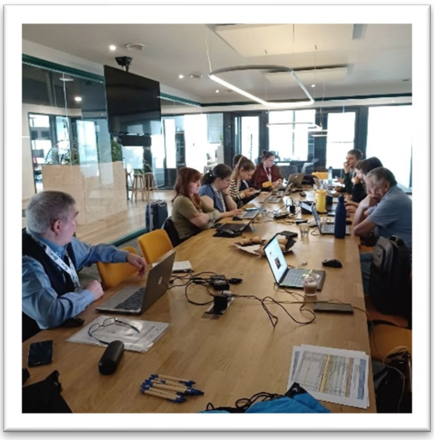
Deliverables

During the four-year project, our partners also produced a range of public deliverables, which are aloso available here: https://www.ambherproject.eu/article-papers/

- “Report on the market and stakeholder analysis“
- “Report of performances of storage in an up to 1L vessel that can accommodate MOFs“
- “Project logo and set of public document templates”
- “Public project website“
- “First Dissemination video“
- “First report on the dissemination activities carried out in AMBHER“

Consortium meeting

The AMBHER Project consortium has held a series of important in-person meetings across Europe, reinforcing collaboration and accelerating progress as the project approaches its final stage.



The M36 review meeting, hosted by 1-CUBE BV, brought together consortium members for two days of presentations and strategic exchange. Partners showcased progress across core technologies, while hands-on demonstrations and workshops helped align efforts for the final phase, including upcoming demonstration activities.

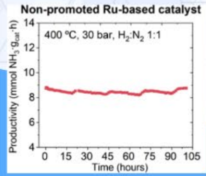
The consortium met at the Milan headquarters of RINA for the M42 meeting. Discussions focused on consolidating progress and preparing for key milestones ahead. A dedicated workshop on social acceptance and market readiness highlighted the importance of integrating environmental, economic, and societal perspectives to ensure successful large-scale deployment of hydrogen solutions.

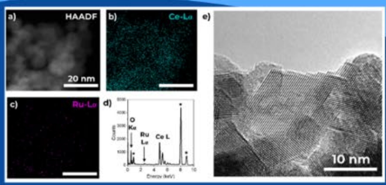
Most recently, at Eindhoven University of Technology, partners gathered to review technical developments and align on next steps. A key highlight was a guided lab tour, where participants explored state-of-the-art facilities and observed a working prototype developed within the project. Seeing the system in operation provided valuable insights into performance, scalability, and future improvements, sparking in-depth technical discussions.

Watch the last video of M46 Consortium Meeting on 1CUBE YouTube channel: https://youtu.be/fFZPLLUHCu8

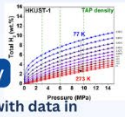
Together, these meetings underscore AMBHER's strong momentum and shared commitment to delivering innovative, scalable hydrogen storage technologies for Europe's energy transition.

CSIC has developed hydrothermally synthesized ceria with a high specific surface area, decorated with transition metal particles and achieving exceptionally high dispersion of these sites (< 1 nm). Twelve different formulations following this synthesis route were prepared, with the best-performing catalyst containing small amounts of Ru and showing stability for 100 h. As a final optimization step, the addition of different promoters to this catalyst enabled a productivity of 17.68 mmol NH_3/g·h at 400 ºC and 30 bar. The best-performing catalysts were extensively characterized and kinetically evaluated through a detailed kinetic study and multiple techniques, including XRD, XRF, H_2-TPR, N_2 adsorption, Raman spectroscopy, ex-situ XPS, HRFESEM, and HRSTEM.



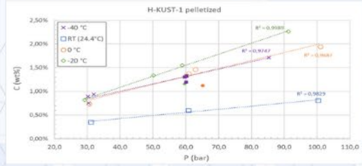


MAHYTEC



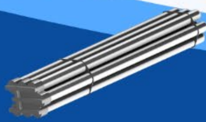
Preliminary tests on MOF capacity

- Linear fit for 20°C, 0°C and -30°C with data in accordance with literature on selected MOF
- Insufficient results for tests at -40°C
- MOF reactivating + tests performed after this step, capacity below even for the same temperature than tested before
- MOF degradation during cycling (tens of cycles)

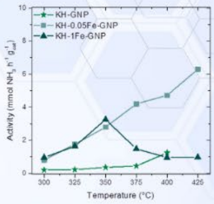


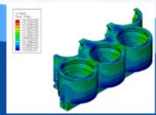
Conformable vessel design

- Design of conformable vessel
  - Unitary shell
  - Connection thanks to manifold
  - Vessel able to work at -100°C and until pressure of 165 bar
  - Evaluation of pressure withstanding by finite element analysis
- Investigation on low temperature sealing solutions
  - Confirmed by tests
- Work on cooling solution able to go at very low temperature
  - Work on carbonic ice as cooling vector



Utrecht University studies the use of nanoconfined and highly dispersed metal hydride-based catalysts for ammonia synthesis. We explored the use of alkali hydrides as independent ammonia synthesis catalysts, as well as in combination with transition metals. Although the pure metal hydride, especially KH, is catalytically active, we studied the effect of Fe addition on KH-based catalysts and found a significant increase in catalytic activity. Additionally, the Fe-loading showed to have a much bigger effect on catalyst stability compared to catalytic activity towards ammonia synthesis. We are currently studying the origin of the promotional effect (increased activity), and further improving these materials to contribute to the future use of ammonia as a hydrogen carrier.





AMBHER project is addressing the long- and short-term green hydrogen storage issue. First, it will develop advanced materials (catalyst and membranes) for the synthesis of ammonia (NH3) in a cost-efficient and resource-effective process via a membrane reactor. Then it will focus on the economic, societal and technological concerns that come with seasonal renewable energy storage in the form of green ammonia. Finally, it will develop new nanoporous metal organic frameworks (MOFs) and a cryo-vessel that can hold stacks of MOF bodies for short-term hydrogen storage.

Clusters of projects

AMBHER project is part of 2 clusters.

List of publications

- “Comparison of thermo-hydraulic performance among different 3D printed periodic open cellular structures”, Chemical Engineering Journal,
- “Carbon-Free H2 Production from Ammonia Decomposition over 3D-Printed Ni-Alloy Structures Activated with a Ru/Al2O3 Catalyst“, Processes Journal
- “Upscaled Al-Fumarate Synthesis and Shaping by Spray Drying”, I&EC Research
- “Combined dip/spin coating deposition of Ni/CeO_2 and Ni/CeO_2-Al_2O_3 onto 3D printed AlSi10Mg Periodic Open Cellular Structures (POCS)“, Applied Surface Science Advances
- Scalable one-step syntheses of aluminium-based MOFs, Royal Society of Chemistry
- “Modeling of a packed bed membrane reactor for ammonia synthesis: on the role of membrane performance and operating conditions“, International Journal of Hydrogen Energy
- “A solvothermal approach to nano-designing M-N-H systems: unveiling new pathways to dimensional control in the lithium nitride hydride ammonia synthesis catalyst”, Journal of Materials Chemistry

AMBHER

Ammonia and MOF Based Hydrogen storagE for euRope

Project details:
Project number: 101058565
Project name: Ammonia and MOF Based Hydrogen storagE for euRope
Project acronym: AMBHER
Starting date: June 1st 2022
Duration: 48 months
EU funding: 4,915,870 Euro
Coordinator: Tecnalia Research & Innovation

Website
www.ambherproject.eu

Follow us

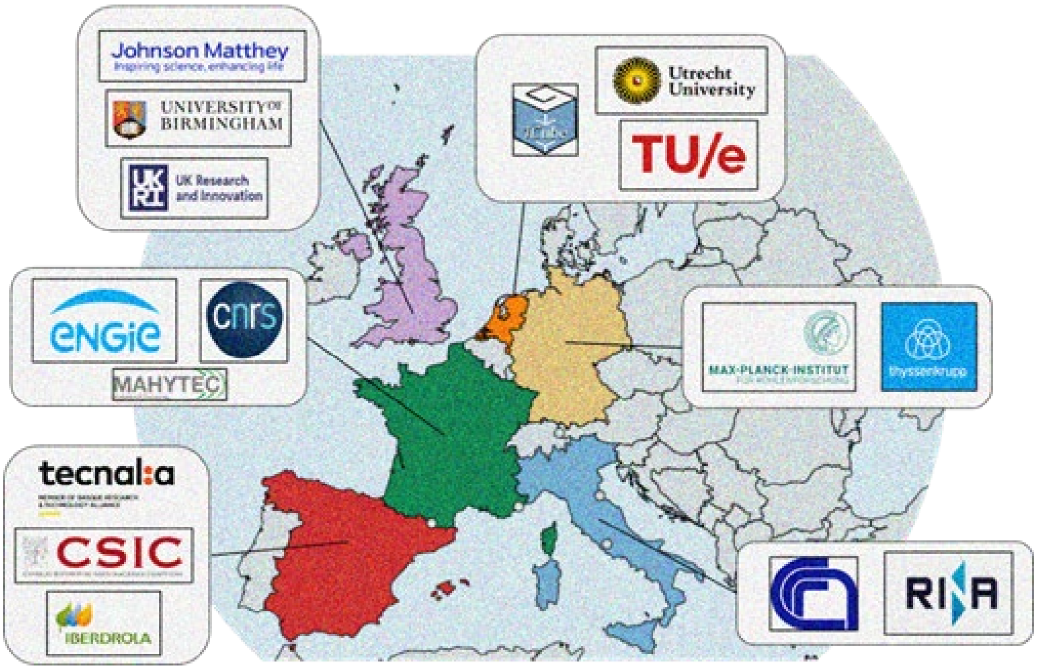
AMBHER partners are delighted to invite you to follow us on our social media platforms. By connecting with us, you'll gain access to the latest updates, industry insights, and opportunities to engage with our growing community.

Find us on Facebook and Instagram for a closer look at our event highlights through visual and stories, on LinkedIn for a professional insights and networking opportunities and on X (formerly Twitter) Real-time announcements and key discussions.

Your continued engagement strengthens our partnership.

We look forward to seeing you online!

AMBHER Consortium



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Project name: Ammonia and MOF Based Hydrogen storagE for euRope
Project acronym: AMBHER
Call: HORIZON-CL4-2021-RESILIENCE-01
Topic: HORIZON-CL4-2021-RESILIENCE-01-17
Starting date: June 1st 2022
Duration: 48 months
EU funding: 4,915,870 Euro
COORDINATOR: Fundación Tecnalia Research & Innovation
Project Coordinator: Angela Mary Thomas

Funded by the European Union

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