areNH$_3$a

Advanced material and Reactor for ENergy storage tHrough Ammonia

Newsletter – December 2023

Editorial

Welcome to this 7th ARENHA project newsletter. ARENHA is a European four-year project with global impact seeking to develop, integrate and demonstrate key material solutions enabling the use of ammonia for flexible, safe and profitable storage utilization of energy. Ammonia is an excellent carrier due to its high energy density, carbon-free composition, industrial know-how and relative ease of energy storage. ARENHA demonstrates the feasibility of ammonia as a dispatchable form of large-scale energy storage.

The present newsletter is the seventh release, and it is 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.arenha.eu you will find public presentations, all the public information of the project and many other interesting news. Stay tuned!

In this Issue:

What is ARENHA?

The concept

For decades, utility-scale energy storage has been used to balance load and demand within an energy generation system composed mainly of base load power sources enabling thus to large nuclear or thermal generating plant to operate at peak efficiencies. Energy storage has contributed over the time to meet peak demand and regulate frequency beside peak fossil fuel power plants that usually provided the bulk of the required energy. In the aforementioned context where inherent variability of the power generation asset was mainly a minor issue, energy storage capacity remains nevertheless limited for economic reasons storing electricity during low electricity demand and releasing it back into the grid during high demand, typically over a daily cycle.

In the current context of global momentum in favour of renewable electricity catalysed by spectacular levelized production cost decrease, higher storage capacity is required to ensure security and flexibility providing a portfolio of services from grid services to the decarbonization of energy intensive sectors like the transport, industry or heating and cooling sector.

For that purpose, hydrogen produced from electrolysis reveals to be a key pathway to unlock the full potential of renewable and especially for seasonal energy storage of large energy quantity and more specifically for all situations dealing with a large energy-to-power ratio situation. Hydrogen having a low volumetric energy density, it has to be compressed to high pressure, liquefied or combined as hydrogen carrier. Among all possibilities, ammonia is a carbon-free and dispatchable energy carrier allowing storing large quantities of renewable electricity. It is a primary candidate to allow a secure and clean supply of renewable energy for various stationary or mobile applications and with ability to provide a wide range of energy storage services using existing infrastructures and both well-defined regulation and acceptable safety history for over 75 years. If state-of-the-art ammonia production plants produce between 3,000 and 6,000 ton NH_3/day, its well-known process involves H_2 production from natural gas reforming. Technical challenges remain to be overcome in order to ensure a flexible and cost comparable production of ammonia from intermittent renewable electricity sources. In addition to that, efficient energy discharge processes from NH_3 must be developed in order to best leverage the clean energy produced upstream by the renewable asset.

The ARENHA project aims at using ammonia as a green hydrogen carrier and for that purpose it develops its main activities around the green hydrogen production, ammonia synthesis, storage and dehydrogenation (Figure 1). Innovative materials are developed and integrated into ground-breaking systems in order to demonstrate a flexible and

profitable power-to-ammonia value chain but also several key energy discharge processes. Specifically, ARENHA is developing advanced SOEC for renewable hydrogen production, catalysts for low temperature/pressure ammonia synthesis, solid absorbents for ammonia synthesis intensification and storage, catalysts and membrane reactors for ammonia decomposition for pure hydrogen (>99.99%) production. Energy discharge processes studied in ARENHA tackle various applications from ammonia decomposition into pure H_2 for FCEV, direct ammonia utilization on SOFCs for power and ICEs for mobility.

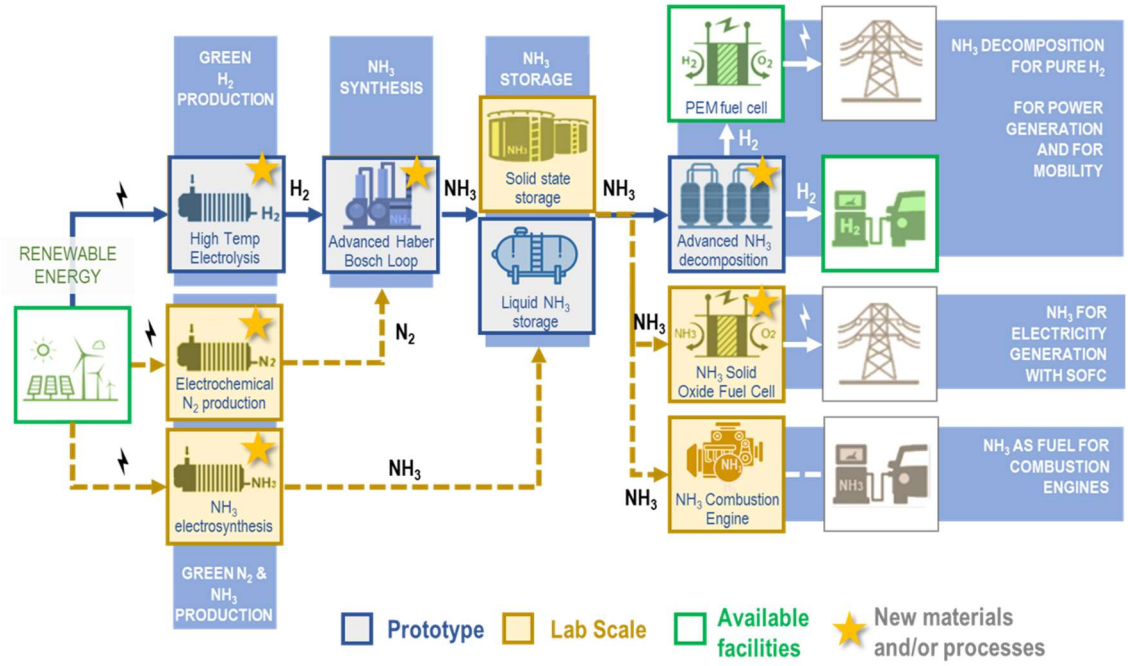

Figure 1. Power-to-ammonia-to-usage value chain in ARENHA

Project objectives.

ARENHA will demonstrate the full power-to-ammonia-to-usage value chain at TRL 5 and the outstanding potential of green ammonia to address the issue of large-scale energy storage through LCA, sociological survey, techno-economic analysis deeply connected with multiscale modelling. For this purpose, breakthrough technologies will be developed and integrated along the overall value chain. The main technical objectives on material and system level are the following:

- To develop and integrate innovative solid oxide cell materials into a flexible high temperature electrolysis demonstration unit producing 1.5 Nm^3/hr hydrogen at ambient pressure to be connected on a real PV plant.

- To develop and integrate innovative materials into a synthesis loop enabling to operate a flexible Haber Bosch production unit of 10 kgNH_3/day at lower pressure (<50 bar) and temperature (<450 °C).
- To develop and integrate innovative materials into a decomposition reactor able to generate 10 Nm^3/hr of pure hydrogen (>99.99%) from green ammonia.
- To develop and test innovative materials and solutions for the alternative direct synthesis and utilization of next-generation green ammonia.
- To demonstrate ammonia as a flexible energy carrier through the development of a fully integrated prototype for green ammonia synthesis and decomposition.
- To assess the social acceptance, techno-economic-environmental feasibility, and replication potential of the developed value chains.

Latest news from the project.

Business case definition

ENGIE is working on the business model for ARENHA based on value propositions that have been identified by partners up to M42. A general business model canvas has been constructed for all categories of the canvas plus individual canvas have been proposed for the main value propositions identified so far in ARENHA. For these value propositions, the value proposition canvas has been used to identify customer jobs, gains and pains, and to understand fit with customer segments.

System requirements, design and modelling

ENGIE continues its activities related to the complete Power-to-Ammonia system modelling and techno-economic evaluation. High-temperature electrolysis and ammonia synthesis models have been coupled together: thermal integration and system efficiency gain potentials have been evaluated. System economic analysis started and is still ongoing.

Key component development

Main activities of key component development have been already finished while they have been scale-up for the prototype.

Key component scale-up

CNH2 continues the progress on the development of the SOEC system that will test the stacks developed by IKTS and ELCOGEN. System is expected to be ready in Q1 2024 and the results aims to increase the current TRL3 to 5 of this technology.

Proton Ventures has completed the design of the advanced ammonia synthesis loop system and is currently constructing the demonstration unit with subcontracting partner

in the Netherlands. This demonstration unit will be shipped to Spain in Q1 2024 and it will be operated at Fertiberia Site.

H2SITE is almost finishing the construction of their ammonia cracking unit system, that transforms ammonia back to hydrogen with a high purity level. The system is expected to be shipped to Spain in Q1 2024 and it will be also operated at Fertiberia Site.

Environmental LCA, economic and safety assessment

ENGIE and CNH2 are progressing on the assessment of activities related to LCA, LCS and LCC and study of sociological acceptance of the use of ammonia as energy carrier. HAZOP sessions on the SOEC, ammonia cracker and ammonia synthesis prototypes are achieved. The next step is to have ready the 3 prototypes under development in order to carry out the final modelling of LCA activities. The final assessment of LCC and LCS activities are ongoing. Additional work will include a complete survey on social acceptance.

Highligths

ARENHA M42 Consortium Meeting (19-20th October 2023)

This face-to-face meeting of the ARENHA project took place during October the 19-20th of October 2023 and was held in the facilities of Tecnalia in San Sebastian (Spain). This meeting was the fourth presential meeting after the COVID-19 situation and boosted the cooperation between each of the partners of the project. The status of the project was discussed being a main point the status of the prototypes development.

AMBHER - ARENHA webinar Membranes and Reactors for ammonia energy (5TH DECEMBER)

The second webinar of AMBHER project organized together with ARENHA Project took place the 5th of December, in which it was delved into the objectives of both projects, and it was focused on learning about the different advances in the development of Membranes and Reactors for ammonia energy.

The recording is available at https://www.youtube.com/watch?v=GyjFvQH3yC8

2nd Symposium on Ammonia Energy organised by Université d´Orléans (France) on July 11th-13th, 2023.

Université d´Orléans, member of ARENHA, is organising the 2nd symposium on Ammonia Energy. The event will take place on July 11th-13th (2023) at the University of Orleans.

Information can be found at https://ammonia-energy.sciencesconf.org.

Dissemination activities, publications and presentations

ARENHA public presentations as well as open access articles and public reports are available online in the dissemination section of the project website: www.arenha.eu.

Peer Reviewed Articles

1. Jaysree Pan, Heine Anton Hansen and Tejs Vegge, Vanadium oxynitrides as stable catalysts for electrochemical reduction of nitrogen to ammonia: the role of oxygen., *J. Mater. Chem. A*, **2020**, *8*, 24098- 24107. https://doi.org/10.1039/D0TA08313E.
2. Valentina Cechetto, Luca Di Felice, Jose A. Medrano, Camel Makhloufi, Jon Zuniga and Fausto Gallucci. H2 production via ammonia decomposition in a catalytic membrane reactor. *Fuel Processing Technology*, **2021**, *216,* 106772. https://doi.org/10.1016/j.fuproc.2021.106772.
3. Christine Mounaïm-Rousselle, Pierre Brequigny, Clément Dumand and Sébastien Houille, Operating Limits for Ammonia Fuel Spark-Ignition Engine, *Energies*, **2021**, *14*(14), 4141, https://doi.org/10.3390/en14144141.
4. Freddy Kukk, Sergii Pylypko, Enn Lust and Gunnar Nurk, Influence of Active Layer Thickness of Reversible Solid Oxide Cells on the Electrochemical Performance of Water Electrolysis, *ECS Transactions,* **2021**, *103*(1), 511, https://doi.org/10.1149/10301.0511ecst.
5. Valentina Cechetto, Luca Di Felice, Rocio Gutierrez Martinez, Alba Arratibel Plazaola and Fausto Gallucci. Ultra-pure hydrogen production via ammonia decomposition in a catalytic membrane reactor., *International Journal of Hydrogen Energy*, **2022**, *47*, 21220-21230. https://doi.org/10.1016/j.ijhydene.2022.04.240
6. A. Mercier, C. Mounaïm-Rousselle, P. Brequigny, J. Bouriot, and C. Dumand, Improvement of SI engine combustion with ammonia as fuel: Effect of ammonia dissociation prior to combustion, *Fuel Communications*, **2022**, *11*, 100058, https://doi.org/10.1016/j.jfueco.2022.100058.
7. Valentina Cechetto, Cynthia Lan Struijk, Luca Di Felice, Anouk W.N. de Leeuw den Bouter, and Fausto Gallucci, Adsorbents development for hydrogen cleanup from ammonia decomposition in a catalytic membrane reactor., *Chemical*

Engineering Journal, **2023,** *455*, 140762. https://doi.org/10.1016/j.cej.2022.140762.

8. Christine Mounaïm-Rousselle, Adrien Mercier, Pierre Brequigny, Clément Dumand, Jean Bouriot and Sébastien Houillé, Performance of ammonia fuel in a spark assisted compression Ignition engine, *International Journal of Engine Research*, **2023,** *23* (5), 781, https://doi.org/10.1177/14680874211038726.

Conference proceedings or presentations.

1. Christine Mounaïm-Rousselle, Pierre Brequigny, S Houillé, C Dumand. Potential of Ammonia as future Zero-Carbon fuel for future mobility: Working operating limits for Spark-Ignition engines. SIA POWERTAIN & ENERGY 2020, Nov 2020, Online, France. France. https://hal.archives-ouvertes.fr/hal-03188481.
2. V. Cechetto, L. D Felice, A. Arratibel Plazaola and F. Gallucci. Ammonia inhibition on H2 produced via ammonia decomposition in a catalytic membrane reactor. World Online Conference on Sustainable technologies. March 17-19, 2021. Oral presentation. https://wocst.org/index.php.
3. Camel Makhloufi. Utilising Liquid Ammonia for Cost-effective storage and distribution of large Quantities of Renewable Energy. 14th Energy World Forum. May 19th, 2021. Oral presentation. https://energystorageforum.com/session/utility-utilising-liquid-ammonia-.
4. F. Kukk, S. Pylypko, E. Lust, and G. Nurk. Influence of active layer thickness of Reversible solid oxide cells on the electrochemical performance of water electrolysis. SOFC XVII conference. July 18th-23rd, 2021. Oral presentation. https://www.electrochem.org/sofc-xvii/.
5. Christine Mounaim-Rousselle. Ammonia as zero-carbon fuel for Internal Combustion Engine: where are we today? 15th International Conference on Engines and Vehicles. September 12th-16th, 2021. Keynote Lecture. https://www.sae-na.it/.
6. José Luis Viviente. Advanced materials and Reactors for Energy storage tHrough Ammonia (ARENHA). Online workshop: NON-BATTERY BASED ENERGY STORAGE: Four sustainable European solutions. September 15th, 2021. Oral presentation. https://recycalyse.eu/recycalyse-joint-workshop/.
7. Zançat Sahin, Valentina Cechetto, Luca Di Felice, Fausto Gallucci, H2 Production through Ammonia Decomposition in a Catalytic Membrane Reactor: A computational and experimental study, 12th International Conference on Hydrogen Production (ICH2P-2021 – On-line conference). September 19th-23rd, 2021. Oral presentation. https://www.innomem.eu/event/12th-edition-of-the-international-conference.
8. CNH2, Assess stage and opportunities of ammonia as an element for decarbonising the shipping sector, World Hydrogen & Ammonia Shipping. 15-16/12/2021.

9. J.L. Viviente, F. Gallucci, R. Campana, X. Sun, S. Megel, W.I.F. David, G. van Zee, S. Pylypko, J.A. Medrano, C. Dumand, C. Rouselle and A. Ramirez-Santos. Advanced materials and Reactors for ENergy storage tHrough Ammonia (ARENHA). European Hydrogen Energy Conference 2022 (EHEC2022). Madrid (Spain), May 18th-20th, 2022. Oral presentation.
10. C. Dumand, C. Mounaïm-Rousselle, P. Gaillard, E. Gérard, J. Dedeurwaerder, J. Op de Beeck. Ammonia powertrain for a carbon free mobility, SIA Powertrain & Energy 2022, June 15th-16th, 2022, Rouen (France). Oral presentation.
11. J.L. Viviente. Advanced materials and Reactors for ENergy storage tHrough Ammonia (ARENHA). 15th International Conference on Catalysis in Membrane Reactors (ICCMR15), Tokyo (Japan). July 31st-August 4th, 2022. Keynote Lecture.
12. V. Cechetto, L. Di Felice, F. Gallucci. Adsorbent materials for residual ammonia removal from hydrogen produced via ammonia decomposition in a catalytic reactor. 15th International Conference on Catalysis in Membrane Reactors (ICCMR15), Tokyo (Japan). July 31st-August 4th, 2022. Oral presentation.
13. Z. Sahin, V. Cechetto, A. Rahimalimamaghani, F. Gallucci, M. Gazzani, L. Di Felice, M. Llosa Tanco, A. Pacheco Tanaka. Ammonia decomposition in Ru-based catalytic membrane reactors. 15th International Conference on Catalysis in Membrane Reactors (ICCMR15), Tokyo (Japan). July 31st-August 4th, 2022. Oral presentation.
14. V. Cechetto, L. Di Felice, F. Gallucci, Hydrogen production and purification via ammonia decomposition in a catalytic membrane reactor, 1st Symposium on Ammonia Energy, 1-2 September 2022 Cardiff, UK.
15. Vito Verde, Álvaro Ramirez Santos, Fausto Gallucci, Techno-Economic Analysis of a Small-Scale, 1st Symposium on Ammonia Energy, 1-2 September 2022 Cardiff, UK
16. Bill David, Matthew Cummings, 1st Symposium on Ammonia Energy, 1-2 September 2022 Cardiff, Keynote Speech, UK https://www.ammoniasymposium2022.com/
17. G. Nurk, S. Pylypko, E. Lust, Modification of the state-of-the-art solid oxide cells to increase performance and durability in electrolysis operation, Graduate School of Functional Materials and Technologies Scientific Conference, Tallin 2022
18. S. Pylypko, ELCOGEN SOFC/SOEC cell and stack technology, 4th International Workshop on Degradation Issues of Fuel Cells and Electrolysers, Corfu, Greece 03.05.2022
19. E. Monge, ARENHA Advanced materials and Reactors for Energy storage tHrough Ammonia, H2 Revolution International Congress, Puertollano, 29.10.2022
20. Xiufu Sun, HANNOVER MESSE 2022, Advanced materials and Reactors for ENergy storage tHrough Ammonia (ARENHA), May30-June 2.

21. Elena Monge, Present ammonia among other European projects about green energy production, storage and usage, IMPROVEMENT Project Conferences, 29/11/2022.
22. Carlos Merino, Widespread the knowledge of the ammonia as an energy carrier in Japan to establish synergies for future projects between Spain and Japan within this sort of technology, The 11th NEDO CDTI Joint Workshop, 2023.
23. ELCOGEN, Providing a platform for the state-of-the-art presentations and information exchange on the cutting-edge ceramic and composite technologies., 47th International Conference and Exposition on Advanced Ceramics and Composites, Daytona Beach, 2023.
24. Anastasiia Karabanova, Development of Sorbents for Novel Ammonia Synthesis Routes, 6th European Power to Ammonia® Conference June 2023.
25. Valentina Cechetto, "A Comparison Between Pd-Ag and Carbon Molecular Sieve Membranes for Hydrogen Separation During Ammonia Decomposition in A Membrane Reactor", 2nd Symposium on Ammonia Energy, July 2023.
26. Mary HANHOUN, Raphael BRIERE, Elena MONGE, Assia SAKER, Pierre OLIVIER, Anne PRIEUR-VERNAT, "Preliminary environmental impacts of ARENHA project with life cycle assessment", the 11th International Conference on Life Cycle Management, 7th September 2023.
27. V. Verde, A. Saker, A. Berrady, A. Ramirez Santos, P. Olivier, F. Gallucci, "Integration of Solid Oxide Electrolysis and Enhanced Ammonia Synthesis for Green Ammonia Production: A Techno-economic Analysis", the European PhD Hydrogen Conference, 20th to 22nd of March 2024.
28. KUMAR, Richi, Mr SHANKAR, Ojas; Dr TRTIK, Pavel; Ms BYBJERG BROCK, Mette; Dr OKKELS BIRK, Jonas; Prof. KAISER, Andreas; Dr SUN, Xiufu, KARABANOVA, Anastasiia, "Ammonia Sorbents for Novel Ammonia Synthesis Routes studied using in situ neutron imaging", the User meeting 4th and 5th December 2023.

Press articles

1. Katrin Schwarz, EU-Projekt ARENHA: Grünes Ammoniak für die Energiewende, on Fraunhofer IKTS website. https://www.ikts.fraunhofer.de/de/presse/news/2020_10_13_eu_projekt_arenha.html.
2. Christian Eckart, Ammonia as a tamer for green hydrogen. Public media article on the German newspaper "Background Tagesspiegel"
3. E. Monge, V. Sendarrubias, J. Martín, El proyecto ARENHA demostrará el potencial del amoniaco como forma de almacenamiento energético, Public media article on the Spanish newspaper "Energética". https://www.energetica21.com/revistas-digitales/septiembre-2021
4. María Hernández Solana, Elena Monge Ruiz, Un proyecto con dinero europeo impulsa el uso del amoniaco verde para almacenar energía, The objective.

5. V. Sendarrubias, E. Monge, J. Martin, Nueva reunión del consorcio del proyecto ARENHA en el que participa el CNH2 de Puertollano, La comarca de Puertollano.
6. J.L. Viviente. Advance materials and reactors for energy storage through ammonia. Issue 13 of The Innovation Platform. Energy Storage section, Pages 176-179. https://www.innovationnewsnetwork.com/publication/the-innovation-platform-issue-13/

Upcoming events

March 6-8, 2024	European Hydrogen Energy Conference (EHEC 2024). Bilbao (Spain) EHEC.
April 15, 2024	M48 Consortium meeting Arenha Project. H2SITE, Bilbao (Spain)
April 22-26, 2024	Hannover Messe 2024. Energizing a Sustainable Industry. Hannover (Germany) https://www.hannovermesse.de/en/hannover-messe-2024/
July 2-5, 2024	15th European SOFC & SOE Forum (EFCF2024), Lucerne (Switzerland) https://www.efcf.com/

ARENHA in figures:

11 partners (6RES, 2 IND, 3 SME)

7 countries

5,684,325 € project

Start: April 2020

Duration: 48 months

Key milestones:

April 2023 - Ammonia synthesis and decomposition prototypes ready

April 2024 - Ammonia- based energy storage system integrated and validated

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More information about ARENHA (including a non-confidential presentation of the project) is available at the project website: https://arenha.eu/

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