areNH$_3$a

Advanced material and Reactor for ENergy storage tHrough Ammonia

Newsletter – December 2022

Editorial

Welcome to this 5th ARENHA project newsletter. ARENHA is an 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 fifth 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.

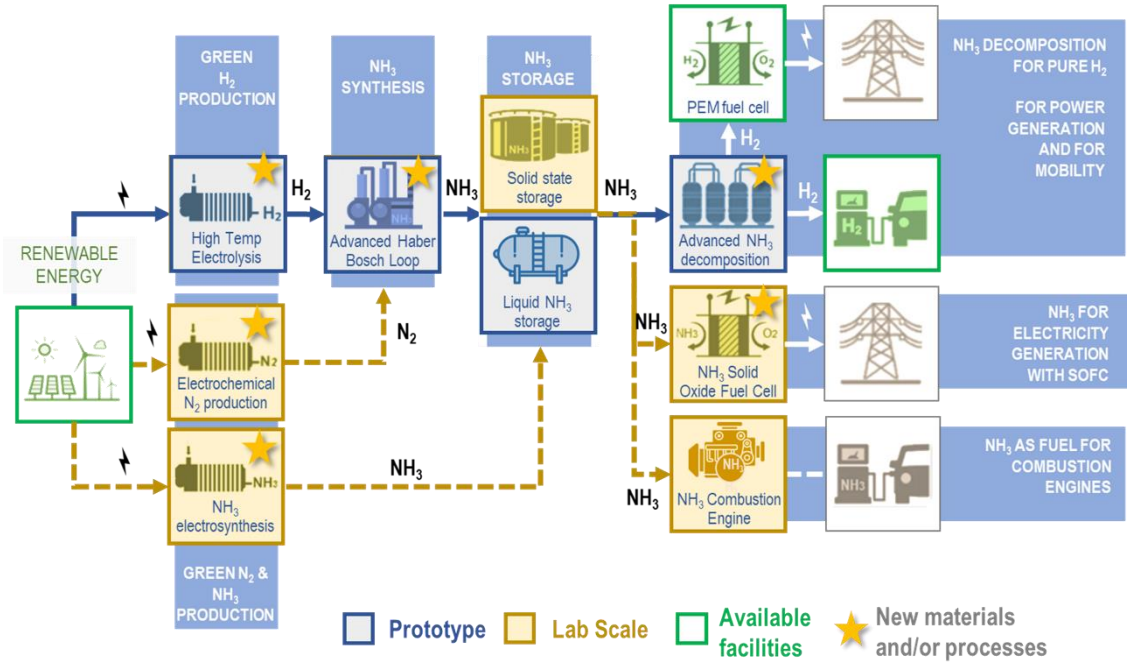

Figure 1. Power-to-ammonia-to-usage value chain in ARENHA

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 initial business model for ARENHA based on value propositions that have been identified by partners up to M30. 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

DTU is working on the modelling of a novel solid state ammonia storage tank considering two different heat integration scenarios.

TUE continued working on the topic of ammonia decomposition focusing on the modelling of the catalyst kinetics. Experimental data have been obtained in a dedicated lab-scale setup and subsequently used to derive a kinetic law. As a next step, this kinetic law will be used to finalize and optimize the model of the ammonia decomposition unit.

At ENGIE, SOEC modelling activities have been finalized and the last modification of the model consists of a stack temperature variation introduction through a time dependent heat balance equation. Stack temperature is an important parameter to be evaluated because it is strictly related to cell performance, total system efficiency and system degradation. A temperature control strategy has been introduced in the model in order to avoid the excessive stack cooldown or heating during respectively endothermic and exothermic operation. The new model has then been tested with test power profiles and is ready to be fine-tuned with real data.

Regarding system integration between and electrolysis production related activities to modelling have started. Keeping in mind all the constraint related to SOEC and ammonia

synthesis loop, an Aspen Dynamics simulation of hydrogen storage subsystem has been built.

Activities related to roadmap of ARENHA technologies are ongoing. Literature research is ongoing in order to identify the actual status of technology and its potential, allowing for the investigation of perspectives for the future and the decision of roadmap milestones.

Key component development

IKTS is working on new cell materials for optimized SOEC stacks for hydrogen production: Development and characterization of the modified electrode compositions and architectures and investigation of thinner electrolytes for optimized SOEC hydrogen production using electrolyte supported cells for SOEC electrolyser for hydrogen production. Influence of thinner electrolytes, modifications to the electrode architecture and manufacturing parameters on the cell performance have been investigated. Thinner electrolytes and electrode architecture modification show lower cell resistance at operation temperatures between 700 °C and 850 °C and therefore an increased cell performance. Adjustments of manufacturing parameters show mixed results. By decreasing electrolyte thickness, it is possible to significantly improve the electrochemical ESC performance saving the mechanical stability and cell planarity. Several new materials/additives were tested in the fuel electrode and oxygen electrode layers to enhance electrochemical activity towards water splitting and decrease degradation at high current density. The most promising combination of microstructure and new materials/additives were chosen, tested, and validated at cell level. The final cell compilation was then manufactured for stack tests which will be reported in upcoming reports. In previous reports simulation results for ammonia driven SOFC systems were described. Based on those results stack tests with ammonia are up for investigation. For those stack tests to be realized adaptations to the test rigs at IKTS are necessary. These test rigs are completed. Stack tests will be done, and results will be described in the next report.

Elcogen concluded the electrochemical characterization of experimental SOEC designs and conducted extensive analysis of the results. The most promising cell designs were chosen for manufacturing and testing in a stack environment in WP4.

DTU continue with the NH_3 sorbent production procedure which has been optimized and different absorbent with various metal halide loading has been prepared and characterized the metal halide loading on NH_3 absorption capacity as well as kinetics on NH_3 absorption/desperation. Synthesis of VNOx material has been performed under different temperatures and gas atmospheres, the influence of synthesis condition on its phase and oxidization status has been investigated by XRD, XPS etc. Second generation Co free electrode material supported electrochemical cell has been manufactured and

the cell show very stable operation and capable of production 95% purity of N_2 without any degradation for 1000 hours operation. Also, binary metal halide system $Ca_xSr_{1-x}Cl_2$ has been prepared and the optimal composition in terms of absorption capacity and volumetric capacity has been identified for NH_3 solid storage.

STFC have developed the ammonia synthesis and decomposition catalysts by focusing on the fine-tuning of chemical composition in order to maximise catalyst activity and retention over multiple thermal and pressure cycles. Further studies have been performed with the aim of providing an exact mechanism for these catalysts. In parallel to those efforts, characterization of state-of-the-art industrial catalysts has taken place in order to complement the work being done on the ammonia synthesis pilot plant.

TECNALIA continue preparing Pd-based and composite Al-CMS membranes for hydrogen separation with improved separation properties. Regarding de recycling of Pd-based membranes, the study of homogeneous and heterogenous phase electro leaching process were started, while further optimization of the selected DES leaching systems with different additives was also performed.

As the hydrogen purity achieved with the membrane reactor technology (TUE) is not always sufficiently high for fuel cell application. Particularly, since the NH_3 concentration in the hydrogen stream to be used as feedstock in PEMFCs must not exceed 0.1 ppm, strategies must be implemented in order to increase the hydrogen purity by reducing the residual ammonia concentration in the hydrogen stream. The addition of a small adsorption unit downstream the membrane reactor has been investigated at TUE.

STELLANTIS and UORL have tested NH3 combustion process in an optimized engine with a higher compression ratio (largely higher than 10.5 corresponding to conventional gasoline engine). A comparison of this optimized internal combustion engine results with those obtained during M1-M12 with the reference gasoline engine and the Diesel base engine has been done. Pure NH_3 combustion process, combustion stability, efficiency, pollutants have been assessed. Partners also assessed the dissociated H_2 effect on NH_3 combustion process. Finally, it has been demonstrated that NH_3 can be used in conventional engine with slight modifications on most of the operating conditions.

Key component scale-up

The key components of the demonstration unit that have been developed in the WP3, such as SOEC by IKTS and Elcogen, advanced synthesis loop by Proton Ventures in collaboration with DTU for sorbents, ammonia cracker by TUe, H2SITE and TECNALIA, will be built and integrated in Spain.

Proton Ventures has completed the detailed engineering of the advanced ammonia synthesis loop. The containerized pilot plant will be built in the Netherlands by Proton Ventures and shipped to CNH2 by end of 2023. The innovation aspects of the ammonia synthesis system are associated with ammonia catalysis, ammonia sorption, and the flexible operation capacity of ammonia production. The pilot plant is designed to produce pure liquid ammonia for storage at ambient temperature and it is suitable for operation under conditions of varying hydrogen feed flow rates.

Environmental LCA, economic and safety assessment

After the definition of goal and scope of the sociological survey, LCA assessment, LCS safety analysis and LCC assessment, ENGIE and CNH2 have detailed their approach on both ammonia and hydrogen as energy carriers. First results on preliminary study of the assessment of sociological acceptance, LCA, LCS and LCC part have been presented. In the next steps, additional work will include a complete survey on social acceptance. For LCA part, a comparison of the environmental impacts of green ammonia scenario with 3 alternative scenarios will be carry out. Regarding LCC assessment, the next steps will Include final use part of the chain into the analysis.

Highligths

ARENHA M30 Consortium Meeting (6th October 2022)

The second face-to-face meeting of the ARENHA project took place during October the 6th of 2022 and was held in the facilities of DTU in Paris. This meeting was the Month 20 Consortium meeting and the second presential meeting after the COVID-19 situation and boosted the cooperation between each of the partners of the project.

ARENHA at the 15th International Conference on Catalysis in Membrane Reactors

The ARENHA project had several presentations in the frame of the 15th International Conference on Catalysis in Membrane Reactor that took place in Tokyo from August 1st to August 4th (2022). A Keynote Lecture presented ARENHA project, and two oral presentations described some development related to hydrogen production via ammonia decomposition in a catalytic membrane reactor.

Open ammonia event organised by PV in the frame of ARENHA on March 29th, 2023.

PV, member of ARENHA, is organising an open hybrid event on ammonia in the frame of the ARENHA project. The event will take place on March 29th (2023) at the Het nieuwe

instituut in Rotterdam. Information on the agenda and registration will be soon available. Stay tuned.

NH3 Academy: Open ammonia event organised by PV in the frame of ARENHA on March 29th, 2023.

PV, member of ARENHA, is organising an open hybrid event on ammonia in the frame of the ARENHA project NH3 Academy. The event will take place on March 29th (2023) at the Het nieuwe instituut in Rotterdam. Information on the agenda and registration will be soon available. Stay tuned.

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.

ARENHA at the 16th International Conference on Catalysis in Membrane Reactors (ICCMR16)

TECNALIA coordinator of the ARENHA project is organising the 16th International Conference on Catalysis in Membrane Reactor. The event will take place in Donostia-San Sebastián on October 18th-20th. ARENHA project will be presented during the special session on EU granted project. Information on the conference and deadlines can be found at http://www.iccmr16.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, 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. 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 Powertrain & Energy 2020, Nov 2020, Online, France. ⟨hal-03188481⟩. https://hal.science/hal-03188481/document.

3. Valentina Cechetto, Luca Di Felice, Jose A. Medrano, Camel Makhloufi, Jon Zuñiga, Fausto Gallucci. H_2 producion via ammonia decomposition in a catalytic membrane reactor. Fuel Processing Technology 216 (2021) 106772. https://doi.org/10.1016/j.fuproc.2021.106772
4. Valentina Cechetto, Luca Di Felice, Rocio Gutierrez-Martinez; Alba Arratibel-Plazaola, Fausto Gallucci. Ultra-pure hydrogen production via ammonia decomposition in a catalytic membrane reactor. International Journal of Hydrogen Energy 47, (2022), 21220-21230. https://doi.org/10.1016/j.ijhydene.2022.04.240
5. C. Dumand, C. Mounaïm-Rousselle, P. Gaillard, E. Gérard, J. Dedeurwaerder, J. Op de Beeck. Ammonia powertrain for a carbon free mobility. International Congress: SIA Powertrain & Energy 2022, Rouen 2022, June 15th-16th, 2022, Rouen (France). (hal-03920639). https://hal.science/hal-03920639/document.
6. Valentina Cechetto, Cynthia Lan Struijk, Luca Di Felice, Anouk W.N. de Leeuw den Bouter, Fausto Gallucci. Adsorbents development for hydrogen cleanup from ammonia decomposition in a catalytic membrane reactor. Chemical Engineering Journal 455 (2023) 140762. https://doi.org/10.1016/j.cej.2022.140762.

Conference proceedings or presentations.

1. C. Mounaïm-Rousselle, P. Brequigny, S. Houillé, C. Dumand. Potential of Ammonia as future Zero-Carbon fuel for future mobility: Working operating limits for Spark-Ignition engines. International Congress on Energy and Powertrains (Rouen, France, November 2020). Oral presentation. https://www.sia.fr/evenements/193-sia-powertrain-energy-rouen-2020
2. Valentina Cechetto, Luca Di Felice, Jose Medrano, Camel Makhloufi, Jon Zuniga, Fausto Gallucci. Ammonia inhibition on H_2 produced via ammonia decomposition in a catalytic membrane reactor. World Online Conference on Sustainable technologies. March 17th-19th, 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-for-cost-effective-storage-and-distribution-of-large-quantities-of-renewable-energy#.
4. F. Kukka,b, S. Pylypkob, E. Lusta, and G. Nurka. Influence of active layer thickness of Reversible solid oxide cells on the electrochemical performance of water electrolysis. SOFC XVII conference. July 18th-23th, 2021. Oral presentation. https://www.electrochem.org/sofc-xvii/.
5. Christine Mounaim-Roussellle. 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, H_2 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-on-hydrogen-production-ich2p-2021/
8. 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.
9. 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.
10. J.L. Viviente. vanced 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.
11. 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.
12. 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.

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

Upcoming events

Jan. 20 – Feb. 2, 2023	6th Ammonia as Fuel World Summit 2023. Online. https://www.equip-global.com/ammonia-as-fuel-world-summit
March 29th, 2023	NH3 Academy: Open ammonia event organised by PV in the frame of the ARENHA project. Rotterdam (The Netherlands)
May 9-11, 2023	World Hydrogen Summit 2023, Rotterdam (The Netherlands). https://www.world-hydrogen-summit.com/
May 28-June 1, 2023	18th International Symposium on Solid Oxide Fuel Cells (SOFC-XVIII), Boston (USA).
June 8 & 9, 2023	6th edition of the NH3 Event Europe - European Power to Ammonia Conference. Rotterdam (The Netherlands). https://nh3event.com/.
July 4-7, 2023	Low Temperature Fuel Cells, Electrolysers & H2 Processing (EFCF 2023), Lucerne (Switzerland) https://www.efcf.com/2023
July 9-14, 2023	13th International Congress on Membranes and Membrane Processes (ICOM 2023), Chiba (Japan). http://icom2023.jp/
July 11-13, 2023	2nd Symposium on Ammonia Energy, University of Orleans (France). https://ammonia-energy.sciencesconf.org/
August 20-24, 2023	2023 Safety in Ammonia Plants & Related Facilities Symposium. Westin Grand Munich, Germany. https://www.aiche.org/conferences/annual-safety-ammonia-plants-and-related-facilities-symposium/2023
October18-20, 2023	16th International Conference on Catalysis in Membrane Reactors Donostia-San Sebastián (Spain). http://www.iccmr16.org/
November, 2023	Argus Clean Ammonia Europe Conference. Hamburg (Germany). https://www.argusmedia.com/en/conferences-events-listing/clean-ammonia-europe
May?, 2024	European Hydrogen Energy Conference (EHEC 2024). Bilbao (Spain)
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

Projet Coordinator

Dr. Jose Luis Viviente
TECNALIA

joseluis.viviente@tecnalia.com

Technical Manager

Prof. Fausto Gallucci
TUE

f.galluci@tue.nl

Dissemination Manager

Mr. Jesús Javier Martín Pérez
CNH2

jesus.martin@cnh2.es

Explotation Manager

PhD. Álvaro Ramirez
ENGIE

alvaro.ramirezsantos@engie.com

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

Acknowledgement: This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 862482.