WP5 – D5.11. WHITE PAPER UPDATE M12

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Executive Summary

FASTER is developing and validating a modular, decentralized technology for sustainable ammonia (NH_3) production at mild operating conditions (target: <250 °C and <50 bar) with flexible operation over 0-100% load. The project integrates (i) non-noble metal catalysts supported on electron-donating materials (metal hydrides, amides, and nitrides), (ii) structured reactor internals to intensify heat and mass transfer, and (iii) absorption-enhanced Haber-Bosch (AEHB) separation using metal halide sorbents (e.g., $MgCl_2$, $CaCl_2$) in a temperature swing absorption (TSA) unit to continuously remove NH3 and shift equilibrium. The consortium targets TRL4 validation of a 0.25 kg NH3/day demonstrator, operated for 400 hours under load variations with <10% productivity drop.

This white paper summarizes the project scope and early findings and situates FASTER within the evolving EU policy and standards landscape for renewable and low-carbon ammonia. It highlights how FASTER can support the EU's climate-neutrality pathway by enabling long-duration energy storage and decarbonized nitrogen-based value chains (fertilizers, shipping fuels), while reducing dependence on fossil-based ammonia production.

Context: Ammonia in Europe's energy transition

Ammonia (NH_3) is central to Europe's food system as the basis of nitrogen fertilizers, and it is increasingly considered a complementary energy carrier for hard-to-electrify sectors and for long-duration storage of renewable electricity. NH_3 can be synthesized from nitrogen (from air) and hydrogen. If hydrogen and process energy are renewable, the product is commonly referred to as renewable (green) ammonia. If the hydrogen is fossil-based but emissions are abated (e.g., via carbon capture and storage), the product is often called blue ammonia. Conventional fossil-based production without abatement is commonly called grey ammonia.

1.1 Working definitions used in this white paper

Table 1. Definitions in the white paper.

Label	Typical production route	Key verification requirement in the EU context
Green / renewable ammonia	Air separation or air-derived N_2 + renewable H_2 (electrolysis) + renewable electricity/heat for synthesis	Compliance with RED III / RFNBO criteria (incl. electricity sourcing rules) and lifecycle GHG methodology
Blue / low-carbon ammonia	Fossil-derived H_2 (e.g., SMR/ATR) with carbon capture, utilization and storage (CCUS), plus NH3 synthesis	Lifecycle GHG savings meeting EU low-carbon fuels methodology; credible MRV for captured CO_2 and residual emissions

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Grey ammonia	Fossil-derived H_2 (SMR/ATR) without CCUS + conventional Haber-Bosch	Subject to carbon pricing, reporting, and border measures (e.g., EU ETS/CBAM) where applicable

These labels are widely used in industry, but they are not always defined identically across jurisdictions. In EU markets, legal compliance and certification increasingly depend on lifecycle GHG accounting and electricity sourcing rules under RED III and its delegated acts, and on emerging low-carbon fuel methodologies.

Figure 1. Representation of the reaction mechanism using the dissociative N_2-activation on classic Haber Bosch catalysts and the Mars van Krevelen-based activation of N_2.

1.2 Synthesis strategies

Although metal nitride–supported catalysts have shown very promising performance, their synthesis typically involves harsh and/or complex procedures due to the strong oxyphilic nature of the constituent metals (e.g., Ce, La). As result, both catalyst synthesis and subsequent treatment and storage generally require strictly inert conditions, limiting their industrial applicability. Synthesis routes include High temperature nitridation of the metal oxide in flowing NH_3 (>1000 °C), high-energy ball milling under inert atmospheres and gas-phase techniques such as sputtering, chemical vapor deposition and plasma-assisted methods.

To overcome these limitations, the synthesis strategies studied for WP1/WP2 rely on liquid-phase precursors containing an internal nitrogen source, enabling nitrogen build-in into the crystal lattice of the support. Examples of those N-sources are coordinated NH_3, cyanides, melamine and urea. This approach allows precursor handling and treatment in air, following an inert atmosphere during the calcination step only. Depending on the metal system, this strategy yields metal nitrides or oxynitrides.

1.3 Catalyst families selected based on DFT-calculations

Based on DFT calculations, this report describes two catalyst families: group 3A metals (represented by Ga) and group 3B metals (Ce, Sc, and La). Group 3B metal nitrides show favorable electronic properties for N_2 activation, including narrow band gaps (ca. 0–2 eV) and low nitrogen vacancy formation energies. However, these materials are highly oxyphilic making them unstable in air. For this reason, metal oxynitrides are considered as more stable and unstudied alternatives.

Group 3A metal nitrides exhibit larger band gaps (>3 eV) and higher vacancy formation energies but are significantly more stable. Within this group, Ga-based nitrides show greater potential for ammonia synthesis than Al- or Ti-based supports.

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Project scope and technical approach

FASTER validates an integrated AEHB platform for small (0.1-1 MW) and medium-scale (1-50 MW) NH_3 synthesis under mild conditions (<°°°, <50 bar), suitable for coupling to variable renewable electricity (VRE). The approach combines novel catalysts, advanced reactor and absorber structuring, and integrated process modeling with sustainability and regulatory assessment.

1.4 Work plan overview

FASTER is organized into six work packages (WPs) covering catalyst discovery through TRL4 validation and impact preparation:

- WP1 (Catalyst development): theory-guided catalyst development, eco-design criteria, synthesis and physico-chemical characterization.
- WP2 (Structuring and kinetics): catalytic screening and kinetic studies; model-based design of structured internals; transport-property assessment; functionalization/wash-coating of structured catalysts.
- WP3 (Demonstrator): screening and selection of NH_3 adsorption materials; design and commissioning of the AEHB module; 400 h validation under 0-100% load variation, including safety (FAT/HAZOP/SOPs) and on-line analytics.
- WP4 (Modeling, TEA, LCA, policy): multi-scale process modeling and optimization; techno-economic assessment; environmental and socio-economic impact analysis; policy and regulatory barriers and drivers.
- WP5 (Dissemination and exploitation): stakeholder engagement, market intelligence, and white-paper updates alongside exploitation planning.
- WP6 (Coordination): strategic/technical coordination, quality and risk management, IPR management.

1.5 Target performance metrics

Key quantitative targets include: (i) catalysts with activities >= $1x10^{-2}$ mol NH_3 g_{cat}^{-1} h^{-1} at < 250 °C and <50 bar; (ii) structured catalyst beds and absorption struts delivering >= 50% enhancement in heat transport compared to powder beds; (iii) TRL4 demonstration at 0.25 kg NH_3/day for 400 h under 0-100% load variation with < 10% productivity drop; and (iv) cradle-to-cradle sustainability assessment consistent with European environmental and social standards and the EU 'do no significant harm' principle (EU Taxonomy Regulation).

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Key challenges addressed by FASTER

1.6 Decentralization and downscaling

Conventional Haber-Bosch is optimized for very large plants. Downscaling introduces disproportionate energy penalties, particularly from compression and recycle. FASTER lowers operating pressure and temperature via AEHB equilibrium shifting and high-activity catalysts.

1.7 Flexibility under variable renewable energy

Dynamic operation (ramping, partial load, cycling) is difficult in conventional packed-bed systems due to heat-transfer limits, hotspots, and slow thermal transients. FASTER uses conductive structured internals to shift heat transfer toward conduction and enable faster, more stable operation.

1.8 Catalyst performance at mild conditions without critical materials

Highly active catalysts at mild conditions often rely on scarce noble metals. FASTER targets non-noble systems supported on electron-donating materials (hydrides/amides/nitrides) to facilitate nitrogen activation and stabilize active phases.

1.9 Integrated separation and sorbent stability

AEHB relies on cyclic absorption and desorption. Sorbent kinetics, thermal management, and stability under repeated swings are key risks. FASTER develops supported metal halide sorbents and structured absorbers to mitigate sintering and enhance heat transfer.

1.10Safety, permitting, and social acceptance

NH_3 toxicity and corrosivity create safety and regulatory hurdles for distributed production and bunkering. FASTER integrates safety-by-design, HAZOP-informed engineering, and regulatory studies to support deployment-ready designs.

1.11Verified sustainability claims

Market uptake depends on credible certification of GHG performance. FASTER embeds life cycle assessment and policy analysis to align technical development with emerging EU and international standards.

Current findings and progress (as of January 2025 - Jan 2026)

FASTER's early technical progress spans catalyst modeling, experimental screening, and process and absorber modeling. The results below reflect initial HOP-ON and preparatory activities supporting the first TRL4 demonstrations.

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1.12 Catalyst modeling: DFT and data-driven discovery

Hybrid DFT and machine-learning workflows are being developed to accelerate catalyst discovery across relevant metal/support families. As of December 2025, more than 140 surface energies had been computed for candidate nitride surfaces and facets. Early insights indicate that nitrogen vacancy formation energies do not correlate directly with facet surface energy, and that vacancy formation energies for N-terminated facets are frequently closest to zero - suggesting potentially favorable Mars-van Krevelen-type pathways for nitrogen activation.

1.13 Preliminary catalyst screening: TPR with hydrogen

Early TPR experiments indicate that NH_3 can be synthesized at temperatures below 400 C on supported catalyst family 'A' for multiple supports (except SiO_2). Three dominant reduction temperature regions (~280 C, ~380 C, and >500 C) were observed, and support 'B' showed the greatest NH_3 formation below 300 C. Addition of promoter metals facilitated surface-nitrogen bond dissociation and lowered the temperature required for NH_3 evolution. Comparative productivity trends under identical screening conditions highlighted enhanced low-temperature NH_3 productivity for the B-supported catalyst and further gains with metal promotion.

1.14 Process and reactor modeling: scaling, operating windows, and intensification

System studies and example flowsheets have been developed to link catalyst requirements, separation performance, and balance-of-plant design. A representative 100 tNH_3/day conceptual design would require about 42 MW of electrolyzer stack capacity (assuming 70% efficiency) to supply about 17.5 tH_2/day. Example calculations at 350 C and 40 bar with 95% NH_3 removal by sorbents support the feasibility of reduced-pressure operation, and illustrate how high-activity catalysts can enable operation down to about 20 bar. These studies also inform sizing of laboratory and pilot reactors for the 0.25 kg NH_3/day TRL4 demonstrator.

1.15 Absorption/separation: TSA and regeneration strategy

For metal-halide-based NH_3 capture, regeneration can be supported by temperature (and pressure) swing and, optionally, by sweep gas. Using minimal N_2 sweep gas, NH_3 purity levels up to about 72 mol% have been reported at regeneration temperatures around 200 C, with most NH_3 release occurring within minutes. Such results motivate reactor-absorber integration strategies that minimize energy consumption while maintaining product quality.

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EU policy and regulatory landscape for renewable and low-carbon ammonia

The regulatory landscape for ammonia is shaped by two roles: (i) ammonia as a chemical commodity (fertilizers, industrial feedstock) and (ii) ammonia as a potential energy carrier (storage, shipping fuel). EU rules influencing renewable and low-carbon ammonia therefore span climate targets, energy and fuel sustainability rules, product and safety regulation, market-based carbon pricing, and evolving certification frameworks.

1.16Climate targets and strategic direction

The European Climate Law makes the EU's climate-neutrality objective by 2050 legally binding and sets an intermediate target of reducing net GHG emissions by at least 55% by 2030 (relative to 1990). These targets underpin the Fit for 55 package, shape public funding priorities, and drive industrial decarbonization pathways relevant to ammonia production and use.

1.17Renewable ammonia: RED III and RFNBO delegated acts

RED III (Directive (EU) 2023/2413) strengthens renewable energy targets and the role of renewable fuels in transport and industry. For hydrogen-based fuels and derivatives, the RFNBO framework is central. Commission Delegated Regulation (EU) 2023/1184 sets detailed conditions under which electricity used to produce RFNBOs can be considered renewable, including rules for additionality and temporal and geographical correlation between renewable generation and electrolysis. Commission Delegated Regulation (EU) 2023/1185 specifies a methodology for assessing lifecycle GHG emissions savings for RFNBOs and recycled carbon fuels. Renewable ammonia claims intended for EU markets increasingly need auditable evidence of compliance with these criteria.

1.18Low-carbon ammonia: gas market package and low-carbon fuels methodology

In addition to renewable fuels, the EU is building a framework for low-carbon hydrogen and fuels through the Hydrogen and Decarbonised Gas Market Package (Directive (EU) 2024/1788 and Regulation (EU) 2024/1789). A delegated act adopted in 2025 (Commission Delegated Regulation (EU) 2025/2359) lays out the methodology for assessing lifecycle GHG emissions savings from low-carbon fuels, including low-carbon hydrogen. This is relevant for blue ammonia pathways insofar as ammonia's upstream hydrogen may qualify as low-carbon and as EU guidance clarifies how hydrogen derivatives are treated under the low-carbon framework.

1.19Demand-side drivers and carbon pricing

Key EU instruments shaping market demand and competitiveness include:

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- EU ETS and maritime inclusion: maritime emissions are being phased into the EU ETS, creating carbon costs that increase the value of low-GHG fuels and energy carriers.
- FuelEU Maritime (Regulation (EU) 2023/1805): sets progressively stricter well-to-wake GHG intensity limits for energy used onboard ships and includes an RFNBO sub-target, supporting uptake of renewable hydrogen derivatives, including ammonia, where they meet eligibility criteria.
- CBAM (Regulation (EU) 2023/956): applies carbon accounting requirements to imports of certain carbon-intensive goods (including fertilizers and hydrogen), supporting fair competition and increasing the need for verified product emissions data.

1.20Safety, permitting, and product rules

Distributed NH_3 production and storage must comply with EU and national safety and environmental regulation. Key EU frameworks include the Seveso III Directive (2012/18/EU) for major-accident hazards; REACH and CLP for chemical safety and classification; Industrial Emissions and permitting rules; and transport rules for dangerous goods (ADR/RID/IMDG). For fertilizer markets, Regulation (EU) 2019/1009 sets harmonized rules for placing EU fertilising products on the market.

1.21Policy summary table

Table 2. Summary of the main policies in EU on NH_3.[1-18]

Instrument	What it governs	Relevance to renewable/low-carbon ammonia
Regulation (EU) 2021/1119 (European Climate Law)	EU-wide climate-neutrality and 2030 targets	Sets overarching decarbonization trajectory and investment signal
Directive (EU) 2023/2413 (RED III)	Renewable energy targets and fuel sustainability rules	Legal basis for RFNBO qualification of renewable H_2 derivatives such as ammonia
Reg. (EU) 2023/1184 and 2023/1185 (RFNBO delegated acts)	Electricity sourcing rules and lifecycle GHG methodology for RFNBOs	Defines how renewable ammonia must be verified (additionality/correlation + GHG accounting)
Directive (EU) 2024/1788 and Reg. (EU) 2024/1789 (Gas and Hydrogen package)	Internal market rules and definitions for hydrogen/low-carbon gases	Creates a pathway for low-carbon hydrogen and, potentially, derivatives in EU markets
Reg. (EU) 2025/2359 (low-carbon fuels methodology)	Lifecycle methodology for low-carbon fuels	Enables comparable GHG accounting for blue/low-carbon pathways

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Reg. (EU) 2023/1805 (FuelEU Maritime)	Well-to-wake GHG intensity limits for shipping energy	Creates demand pull for RFNBO fuels, including renewable ammonia, if compliant and safe
Reg. (EU) 2023/956 (CBAM)	Carbon border measure for imports of listed goods	Increases competitiveness of low-carbon EU production and emphasizes verified emissions data
Directive 2012/18/EU (Seveso III)	Major-accident hazard control	Key safety/permitting driver for distributed NH_3 plants and storage
Reg. (EU) 2019/1009 (Fertilising Products)	Fertiliser product rules for EU market	Relevant to decarbonizing fertilizer supply chains and labeling requirements

Standards and certification: ISO, IMO, and emerging requirements

Standardization influences how carbon intensity is calculated, how products are audited, and how safety is assured in new applications such as bunkering. For ammonia, several standard families matter simultaneously: (i) lifecycle and carbon footprint standards used in certification, (ii) hydrogen-specific GHG standards that often underpin ammonia accounting, and (iii) safety and terminology standards for ammonia as a fuel.

1.22 ISO standards underpinning carbon accounting and climate claims

ISO 14040 and ISO 14044 define LCA principles and requirements, while ISO 14067 specifies requirements for quantifying and reporting the carbon footprint of products. ISO/TS 19870:2023 provides a methodology for determining GHG emissions associated with the production, conditioning, and transport of hydrogen. Because renewable and low-carbon ammonia are derived from hydrogen, ISO/TS 19870 can support robust accounting of the hydrogen component and comparability across certification schemes. ISO 14068-1:2023 provides principles and guidance for demonstrating carbon neutrality, relevant to 'carbon-neutral ammonia' claims and to alignment with emerging restrictions on offset-based green claims.

1.23 Ammonia as marine fuel: IMO guidelines and emerging ISO terminology

Where ammonia is used as fuel, international maritime safety guidance is critical. The IMO has issued interim safety guidelines for ships using ammonia as fuel (MSC.1/Circ.1687). ISO has also

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initiated terminology harmonization for ammonia fuel systems for ships (ISO/DIS 23397), aligned with IMO guidance. Fuel quality and sampling standards for ammonia bunkering are still emerging; industry guidance notes the lack of a specific standardized method for ammonia bunkering quality verification and anticipates future ISO or internationally accepted procedures.

1.24Implications for certification of green, blue and grey ammonia

In EU markets, green and blue ammonia claims must become auditable and comparable. A credible approach typically requires: (i) a classification linked to EU law (e.g., RFNBO qualification for renewable ammonia), (ii) a lifecycle GHG methodology consistent with EU delegated acts and, where appropriate, ISO methods, and (iii) traceability mechanisms (mass balance or book-and-claim) suitable for multi-node supply chains. FASTER's work package on life cycle analysis and policy is designed to support this evolving claim-verification ecosystem.

How FASTER supports EU climate-neutrality pathways?

FASTER contributes to EU climate-neutrality through enabling renewable electricity integration and decarbonizing ammonia value chains:

- Long-duration energy storage: decentralized NH_3 synthesis enables conversion of surplus renewable electricity into storable chemical energy for days-to-months time scales.
- Industrial decarbonization: mild-temperature, lower-pressure synthesis supports electrified operation and can reduce energy intensity at small and medium scale, supporting fertilizer decarbonization.
- Maritime fuels and ports: proximity production near ports can support FuelEU Maritime compliance where renewable ammonia meets RFNBO criteria, while aligning with evolving IMO/ISO safety standards.
- Energy security and resilience: distributed production reduces reliance on imported fossil-based ammonia and natural gas, improving robustness of supply for both energy and agriculture.
- Innovation and competitiveness: TRL4 demonstration and multi-scale modeling create a bridge from lab catalysts to investable engineering designs and bankable performance data.

Recommendations and outlook

FASTER's near-term focus is on de-risking TRL4 operation under realistic dynamic conditions and generating high-quality datasets for design optimization, techno-economics and LCA. In parallel, several policy and standards priorities can accelerate deployment of renewable and low-carbon ammonia in Europe:

(i) Clarify certification treatment of hydrogen derivatives: ensure RFNBO and low-carbon methodologies explicitly address ammonia and enable mutual recognition across Member States.

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(ii) Translate safety requirements into deployable templates: develop guidance that maps Seveso and permitting requirements to practical design templates for containerized, decentralized plants and port installations.
(iii) Accelerate standards for ammonia fuel quality and bunkering: build on IMO interim guidelines and ISO terminology work to create testing, sampling, and contamination specifications for fuel applications.
(iv) Value flexibility and long-duration storage: market designs should reward curtailment reduction, balancing, and seasonal storage so power-to-ammonia can capture system benefits.
(v) Support first-of-a-kind demonstrations: targeted support can reduce cost barriers and establish reference plants and verified emissions performance.

With these elements in place, FASTER's AEHB pathway can become an enabling technology for a European renewable ammonia economy that is both climate-aligned and industrially competitive.

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