Model Development for the Optimization of Green Ammonia Value Chain in Tunisia

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ABSTRACT – This paper develops an integrated techno-economic optimization model for Tunisia's green ammonia value chain using OSeMOSYS. The model captures interactions between renewable electricity, electrolysis, ammonia synthesis, and resource constraints over a 25-year horizon. Results show wind energy as the dominant electricity source, supported by solar PV, enabling ammonia production to reach 1,600 kt by 2050. The Levelized Cost of Ammonia is estimated at 880 USD/ton, driven primarily by capital investments in wind and electrolysis. Sensitivity analysis highlights the importance of declining renewable costs and diversified generation. Findings support strategic planning for Tunisia's emerging green ammonia sector.
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1. INTRODUCTION

Tunisia is undergoing a critical energy transition as declining domestic fossil fuel resources and rising demand deepen structural imbalances. By 2023, the country's energy independence rate had fallen to 48%, with oil and natural gas still supplying around 72% of primary energy and renewables contributing only 2% (Ministry of Industry, Mines and Energy, 2024). Natural gas production declined by 9%, while the electricity sector consumed 73% of available gas, requiring imports to meet 11% of national demand. Electricity generation remains dominated by natural gas (95%), with renewables representing just 4.3% of the grid mix (STEG, 2022). These trends highlight the urgency of diversifying supply and strengthening system resilience.

Despite these challenges, Tunisia possesses strong renewable energy potential, including more than 3,000 hours of sunlight annually and significant wind resources exceeding 8,000 MW (IRENA, 2018). National strategies target carbon neutrality by 2050, 8,530 MW of renewable capacity by 2035, and a 36% reduction in CO_2 emissions by 2030 (Government of Tunisia, 2023). However, severe water scarcity complicates the deployment of water-intensive technologies such as green hydrogen production (FAO, 2021; World Bank, 2023).

Green hydrogen is increasingly recognized as a key decarbonization vector (IEA, 2023; IRENA, 2020), and Tunisia's national strategy envisions producing up to 8.3 million tonnes by 2050 (Ministry of Industry, Mines and Energy, 2023). Within this context, green ammonia has emerged as a promising derivative due to its high energy density, established transport infrastructure, and suitability for both fertilizer use and clean energy applications (IEA, 2019; IRENA, 2022; Valera-Medina et al., 2018).

This study develops an integrated techno-economic optimization model of Tunisia's green ammonia value chain. By capturing interactions between renewable energy availability, water constraints, hydrogen production, and ammonia synthesis, the model provides insights to guide cost-effective and sustainable deployment aligned with national energy and climate strategies.

2. METHODOLOGY

2.1 Modelling Framework

The analysis uses OSeMOSYS, an open-source, long-term energy systems optimization model, implemented through the MoManI web interface. This framework allows for the development of a detailed techno-economic model of Tunisia's green ammonia production system over a 25-years period (2025–2050). OSeMOSYS is used for assessing capacity expansion options, operational dispatch, and investment choices under cost-minimization goals. The model aims to minimize total system costs, including capital expenditures (CAPEX), fixed and variable operational costs (OPEX), as well as fuel and resource costs. All technologies are described with explicit techno-economic parameters, such as efficiencies, lifetimes, capital expenses, operational costs, and capacity factors. The temporal setup includes multiple time slices to account for seasonal and daily variations in renewable energy availability.

2.2 System Components and Technology Representation

The modeled green ammonia value chain includes:

- Electricity generation: onshore wind and solar PV
- Hydrogen production: alkaline electrolysis (AE), proton-exchange membrane (PEM), and solid oxide electrolysis (SOEC)
- Nitrogen production: air separation units (ASU)
- Ammonia synthesis: Haber–Bosch process
- Storage**:** hydrogen, nitrogen, and ammonia storage
- Final output: ammonia for domestic use or export

Each technology is characterized by investment cost, efficiency, operational constraints, and availability profiles. Wind and solar PV are modelled with Tunisia-specific capacity factors derived from national renewable resource assessments.

Wind energy is modelled as the primary electricity source due to its high capacity factors in coastal and southern regions. Solar PV complements wind generation by providing daytime stability and reducing reliance on storage.

2.3 Temporal and Spatial Resolution

The model uses a multi-period structure with annual investment decisions and intra-annual time slices to represent hourly and seasonal variability. This temporal granularity captures fluctuations in renewable output and their impact on electrolyzer utilization, storage requirements, and ammonia synthesis operations.

Spatial differentiation is incorporated through region-specific renewable resource profiles and technology potentials, reflecting Tunisia's heterogeneous wind and solar conditions.

2.4 Cost Optimization and Key Assumptions

The objective function minimizes the discounted total system cost over the planning horizon. Key assumptions include:

- Discount rate applied to all future investments
- Technology-specific CAPEX and OPEX based on international and regional cost databases
- Electrolyzer efficiencies: AE (baseline), PEM, and SOEC (future-ready alternatives)
- Ammonia demand trajectory aligned with Tunisia's national hydrogen strategy

Capital investment dominates system costs, particularly for wind power infrastructure and electrolyzers. Wind accounts for approximately 80% of total investment, followed by electrolysis (10%) and smaller contributions from PV, Haber–Bosch units, and air separation.

2.5 Electrolyzer Technology Analysis

Three electrolyzer technologies are modelled:

- Alkaline Electrolysis (AE): lowest CAPEX, mature, reliable
- PEM Electrolysis: higher efficiency, higher cost
- SOEC: high-temperature, high efficiency, early-stage technology

AE emerges as the cost-optimal option under current cost assumptions. PEM and SOEC are included in sensitivity scenarios to assess future competitiveness as technology costs decline.

3. RESULTS AND DISCUSSION

3.1 Energy Supply and System Operation

The model results show that wind energy becomes the backbone of Tunisia's green ammonia system, supplying approximately 85% of total electricity generation by 2050. This dominance is driven by Tunisia's favourable wind profiles and comparatively high-capacity factors, particularly in coastal and southern regions. Solar PV plays a complementary role, providing daytime generation that smooths variability and reduces reliance on storage. The combined wind–solar portfolio ensures stable electricity provision for continuous electrolyzer and Haber–Bosch operation.

Production trajectories indicate a steady and coordinated scaling of hydrogen, nitrogen, and ammonia output over the 25-year horizon. By 2050, ammonia production will reach 1,600 kilotons per year, consistent with Tunisia's long-term green hydrogen and ammonia ambitions. Hydrogen and nitrogen production expand proportionally, reflecting the stoichiometric requirements of the Haber–Bosch process and the increasing availability of renewable electricity.

3.2 Cost Structure and Investment Requirements

Cost analysis reveals that the economics of green ammonia in Tunisia are dominated by capital expenditures, which account for 76% of the Levelized Cost of Ammonia (LCOA). Operational costs represent the remaining 24%, reflecting the low marginal cost of renewable electricity once infrastructure is installed.

The resulting LCOA is approximately 880 USD/tonne, placing Tunisia within the current global cost range for renewable ammonia production. This value is strongly influenced by the scale of investment required for renewable generation and electrolysis.

Investment allocation is heavily skewed toward wind power, which absorbs 80% of total capital spending due to its central role in electricity supply. Electrolysis accounts for 10%, while the remaining investments are distributed across solar PV, Haber–Bosch units, and air separation systems. These results highlight the capital-intensive nature of early-stage green ammonia deployment and the importance of reducing upfront costs to enhance competitiveness.

3.3 Electrolyzer Technology Performance

The electrolyzer technology assessment shows that alkaline electrolysis (AE) is the most cost-effective option under current cost and efficiency assumptions. AE's technological maturity and lower capital cost make it the preferred choice for large-scale deployment in Tunisia.

However, PEM and SOEC electrolysis offer potential advantages in efficiency, operational flexibility, and integration with variable renewables. Although these technologies are currently more expensive, the model indicates that future cost reductions could shift the optimal technology mix. Their inclusion in sensitivity scenarios demonstrates that Tunisia's long-term strategy should remain open to technological diversification as global electrolyzer markets evolve.

4. CONCLUSION

This study provides an integrated assessment of Tunisia's green ammonia potential, showing that the country's strong renewable resource base can support large-scale, low-carbon ammonia production. By combining contextual analysis, technology review, and long-term optimization using OSeMOSYS, the work demonstrates that green ammonia can play a central role in Tunisia's energy transition, contributing simultaneously to climate objectives, economic diversification, and energy security.

The results confirm that Tunisia's strategic location and high-quality wind and solar resources position it well to become a competitive producer and exporter of green ammonia. Realizing this potential requires addressing key structural needs, including investment in transmission, port infrastructure, and desalination, as well as strengthening domestic technical capacity.

The analysis highlights several strategic priorities for sector development:

- Investment incentives to reduce high upfront capital costs, especially for wind and electrolysis.
- Regulatory clarity on permitting, grid access, and export frameworks to attract private and international investment.
- Infrastructure development to enable large-scale production and export.
- Capacity building to support long-term operational and industrial growth.

Overall, the findings show that Tunisia has the resource endowment and strategic positioning to establish a competitive green ammonia industry. Coordinated policy support, targeted investments, and continued technological innovation will be essential to unlock this opportunity and advance Tunisia's pathway toward a carbon-neutral economy by 2050.

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