Techno-economic Analysis of Green Methanol and Ammonia Production in Turkey

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Abstract: - This research examines two distinct power-to-fuel approaches for the sustainable synthesis of fuels (green methanol and green ammonia), considering their energetic and economic implications. Both methods involve a 10 MW alkaline electrolysis unit powered by renewable wind energy to generate high-purity green hydrogen. Subsequently, the study explores two processes for synthesizing two specific chemicals with market prices in Türkiye. In the initial scenario, hydrogen is combined with CO_2, sourced from an industrial facility, and captured by a biogas plant. The resulting gases are directed to a pressurized reactor for methanol synthesis. In the second scenario, hydrogen is mixed with N_2 obtained from an industrial air separation unit (ASU), and the mixture is sent to a reactor for ammonia synthesis. Both synthesis processes are conducted under elevated pressures and temperatures. The economic viability of the power-to-fuel plants is assessed in both cases. Methanol synthesis demonstrates a slightly higher efficiency compared to ammonia production, yet the two solutions exhibit similar economic impacts. The economic sustainability of both cases is further enhanced by the sale of major co-produced oxygen. This aspect, along with the anticipated reduction in electrolyser capital costs, proves to be crucial for achieving economic sustainability.

Key-Words: - Green hydrogen, green methanol, ammonia, alkaline electrolysis, power-to-fuel, fuel synthesis.

Received: October 19, 2024. Revised: April 22, 2025. Accepted: May 18, 2025. Published: June 3, 2025.

1 Introduction

Renewable methanol, derived from captured off-gas CO_2 and non-fossil hydrogen, has the potential to substitute fossil hydrocarbons in various industrial and domestic sectors, thereby advancing them closer to carbon neutrality. Predictions indicate that the global market for methanol as a fossil substitute will reach 500 Mt by 2050, [1]. Methanol is already extensively utilized due to its favorable characteristics, such as easy and safe transport and storage as a liquid at room temperature. It is biodegradable, serves as an efficient and clean energy carrier, and is commonly employed as a chemical feedstock in producing plastics, adhesives, construction materials, paints, solvents, and wastewater treatment, [2].

With a high Octane rating (109 RON), methanol surpasses gasoline and diesel in energy conversion. Various regions, including Europe and China, already use different blends of methanol with gasoline and diesel, with 3% and 15% adoption rates, respectively. China's authorities are actively promoting the use of M100 (100% methanol) in light vehicles, buses, and trucks. Methanol is gaining traction as a clean alternative to bunker fuel in marine transport [3] and is increasingly popular for industrial boilers and cook stoves, [2].

Renewable methanol, produced from captured CO_2 and non-fossil hydrogen, is positioned to replace fossil hydrocarbons on a large scale. Methanol boasts a Lower Heating Value (LHV) of 19.9 MJ/kg in mass terms and an energy density of 15.7 MJ/l. With about 100 kg of hydrogen contained in a cubic meter of methanol, renewable methanol is considered a valuable hydrogen carrier. Its ease of storage and transport, along with a higher hydrogen density than pure H_2 in an equivalent liquid volume, makes it a practical and economically viable solution. The demand for renewable methanol extends to diverse fuel applications and as a feedstock for the chemical industry, making it capable of reducing greenhouse gas emissions across significant sectors of the global economy.

Ammonia is an important basic raw material for inorganic and organic chemical industries.

Ammonia is also one of the main carriers of hydrogen energy. However, 98% of the feedstock for ammonia production comes from fossil fuels. Green ammonia production is where the process of producing ammonia is 100% renewable and carbon-free. One way of producing green ammonia is by using hydrogen from water electrolysis and nitrogen separated from the air, [4]. Ammonia is a gas at standard pressure and temperature, its liquefaction is quite easy, as it is liquid at ambient temperature and modest pressure (10 bar) or ambient pressure and temperature of -33°C. Ammonia is considered one of the most promising energy carriers for hydrogen: a cubic meter of ammonia contains about 145 kg of hydrogen.

Ammonia is essential in chemical fertilizers, pharmaceuticals, oil refining, soda ash, synthetic fibers, synthetic plastics, and nitrogen-containing inorganic salts. It is anticipated to be a zero-carbon energy carrier in the future, serving as fuel for automobiles, ships, aircraft, and engines, and replacing gas/oil in industrial boilers or stoves. With the pressing need for green alternatives due to global warming and environmental concerns, achieving low energy consumption, low emissions, and sustainable ammonia production becomes imperative. Green ammonia production, utilizing hydrogen from water electrolysis and nitrogen from the air, is a crucial step in this direction, [5], [6], [7], [8], [9], [10].

While renewable methanol production exhibits an efficiency of approximately 52%, renewable ammonia production is slightly lower at 50%, attributed to higher compressor energy consumption. Ammonia's superiority as a hydrogen carrier, with the capacity to store a significant amount of H_2, contrasts with methanol's advantage in utilizing a considerable amount of CO_2 in its production process, leading to positive environmental impacts, [11]. Although production costs exceed market values for both renewable ammonia and methanol, selling co-produced O_2 and reducing hydrogen electrolyser capital costs can enhance the economic feasibility of these production processes. In both cases, electricity constitutes the most significant production cost, accounting for over 65% in Türkiye. Synthesis units for ammonia are comparatively more expensive than methanol, primarily due to lower single-pass conversion necessitating higher operating pressure, temperature, and recirculation rates.

This study investigates two distinct power-to-fuel solutions for sustainable fuel synthesis, considering energetic, environmental, and economic perspectives. Both solutions involve a pressurized alkaline electrolysis section powered by a wind farm, producing high-purity green hydrogen. In the first case, hydrogen is combined with CO_2 from a biogas plant and captured by a carbon capture system (CCS), with the gases directed to a pressurized reactor for methanol synthesis. In the second case, hydrogen is mixed with N_2 obtained from an industrial air separation unit (ASU), and the mixture is sent to a reactor for ammonia synthesis. Both processes occur under high pressures and temperatures, prompting a thermodynamic analysis to calculate overall efficiencies. Economic evaluations of the power-to-fuel plants are conducted, revealing that utilizing green hydrogen for methanol and ammonia synthesis significantly reduces carbon emissions compared to fossil fuel-based production methods. The assessment employs a life cycle analysis (LCA) to quantify the environmental footprint, considering factors such as energy consumption, raw material utilization, waste generation, and emissions throughout the production processes.

2 Plant Layout

The methanol and ammonia production plant from green hydrogen planned to be established in Osmaniye is a pilot project to realize the interaction of various elements and to be a model for other regions of Türkiye (Figure 1). Existing renewable energy power plant (wind farm) with a power of 70 MW, a 10 MW electrolyser unit, and a 10 MW methanol reactor to generate either 2,000 kg/h green methanol or 10 MW N_2 production and ammonia synthesis unit to generate 2,100 kg/h green ammonia within the scope of the Osmaniye pilot plant (Figure 2). The flow diagram of the green hydrogen production process is shown in Figure 3.

The approximated investment cost is €29,180,000 (excluding the existing wind power plant with a power of 70 MW), and the installation period of the pilot plant is foreseen as 24 months. The CO_2 required for green methanol production is planned to be supplied from the biogas plant to be built in Toprakkale/Osmaniye or the existing Osmaniye Garbage Power Plant. The pilot plant is expected to operate for 7,500 full load hours annually, produce 2,175 tons of green hydrogen, and save 23,200 tons of CO_2 by being fed from a 70 MW wind farm. The electrolyser unit with a power of 10 MW in the facility has produced 2,000 Nm^3/h of H_2 and approximately 1,000 Nm^3/h of O_2.

The estimated installed electrical power of the pilot plant is 15.125 MWA, the specific energy consumption is 1.106 kWh/Nm^3 with ±1% deviation

(DC), and the specific energy consumption electrolyser (AC) nominal load is approximately 1.17 kWh/Nm^3 with ±1% deviation. The availability of the plant is 95% and the total life expectancy of the plant is predicted to be 20 years (Table 1).

Fig. 1: Location of methanol and ammonia production pilot plant from green hydrogen

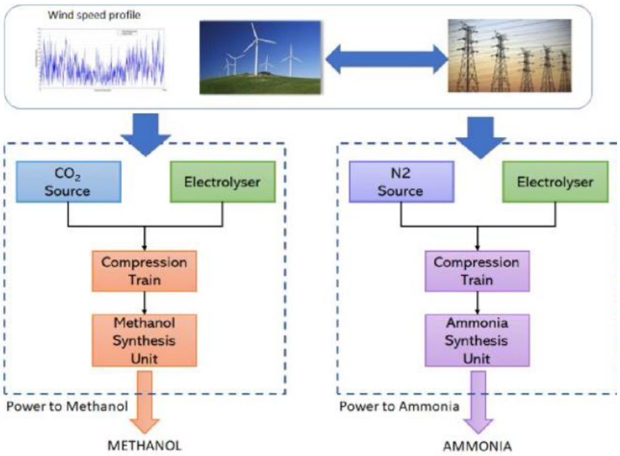

Fig. 2: Schematic diagram of methanol and ammonia production from green hydrogen

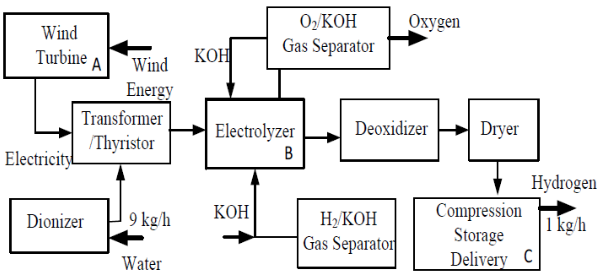

Fig. 3: The flow diagram of the green hydrogen production process

The grid balance for the Wind Farm/Electrolyser ratio in Osmaniye is calculated as 6:1. A 10 MW Alkaline Electrolyser (AE) is required for green H_2 production, therefore existing 70 MW wind farm is sufficient. The electrolyser units use process water for electrolysis and cooling water. KOH is needed for the electrolyte in the system. The system includes a transformer, thyristor, electrolyze unit, feed water demineralizer, hydrogen scrubber, gas holder, two compressor units to 30 bar, deoxidizer, and twin tower dryer. The electrolyser has energy efficiencies (57%-75%) based on a Higher Heating Value (HHV) and 50-60% based on a Lower Heating Value (LHV). The typical current density is 100-300 mA/cm^2.

The economic assumptions of Osmaniye green methanol and ammonia pilot plant are given in Table 2.

Table 1. Technical assumptions of Osmaniye green methanol and ammonia production plant

Plant lifetime	20 years	Methanol Unit		Ammonia Unit	
Plant availability	95%	Operating temperature	210 °C	Operating temperature	450 °C
Electrolyser		Operating pressure	80 bar	Operating pressure	200 bar
Nominal power	10 MW	$H_2 : CO_2$ molar ratio	3:1	$H_2 : N_2$ molar ratio	3:1
Operating pressure	30 bar	Single pass conversion	0.36	Single pass conversion	0.25
Specific energy consumption	4.7 kWh/Nm^3	Overall conversion	0.98	Overall conversion	0.95
Stack replacement	80,000 heq	Electric energy cons. auxiliaries	3% AE Cons.	Electric energy cons. auxiliaries	5% AE Cons.

Table 2. Economic assumptions of Osmaniye green methanol and ammonia pilot plant

Weighted average cost of capital (WACC)	6%	Methanol Unit	
Electric energy cost	0.06 €/kWh	Capital expenditure (CAPEX)	26,548 $(M_{prod})^{0.65}$ €
Electrolyser		Operating expenses (OPEX)	2% of CAPEX
Capital expenditure (CAPEX)	1,000 €/kW	CO_2 cost	15 €/ton
Stack replacement	50% of CAPEX	Ammonia Unit	
Number of stack replacement	1	Capital expenditure (CAPEX)	50,890 $(M_{prod})^{0.65}$ €
Operating expenses (OPEX)	45 €/kW	Operating expenses (OPEX)	2% of CAPEX
KOH cost	500 €/ton	N_2 cost	10 €/ton

3 Analysis

Annual Fixed Cost (AFC) is calculated as the annual rate of Total Capital Investment (TCI) over 20 years of plant lifetime (n), using a 6% WACC as rate (r), as follows:

$$AFC = TIC * \frac{r*(1+r)^n}{(1+r)^{n-1}} [€] \quad (1)$$

Annual Variable Costs (AVC) include the sum of the OPEX of each plant component, CO_2 and H_2 costs, and electrical energy costs.

$$AVC = \Sigma_i OPEX_i + CO_{2\,cost} + \text{Elec. Ener. Cost } [€] \quad (2)$$

Fuel Production Cost (FPC) is the specific cost of the product over the total annual costs. It is calculated in terms of:

(i) the amount of product (€/ton),
(ii) the energy content in the product (€/MWh),
(iii) the amount of H_2 contained in the product, as follows:

$$FPC_{€/ton} = \frac{AFC+AVC}{Annual\ Production\ [ton]} \quad (3)$$

$$FPC_{€/MWh} = \frac{AFC+AVC}{Annual\ Prod.Energy\ Content\ [MWh]} \quad (4)$$

$$FPC_{€/MWh} = \frac{AFC+AVC}{Annual\ Prod.H2.Content\ [kg\ of\ H2]} \quad (5)$$

4 Energy Efficiency Comparison

In both scenarios, the predominant sources of energy losses stem from electrolysers, which also account for the highest electrical energy consumption, constituting over 95% of the total input in both instances. Additional losses are attributed to compressors, heat exchangers, and synthesis reactors. When comparing overall efficiencies, it is noteworthy that methanol synthesis demonstrates a higher efficiency at 52%. In contrast, ammonia synthesis, utilizing the Haber-Bosch process at elevated pressures and temperatures, requires a greater energy input, resulting in a slightly lower efficiency of 50% compared to methanol synthesis.

Taking into account a plant operability rate of 95%, equivalent to approximately 8,320 operational hours per year, the energy inputs amount to 85.8 GWh/year required for producing 8,100 tons/year of methanol and 87.6 GWh/year required for producing 8,510 tons/year of ammonia. In both cases, the primary energy consumption is attributed to alkaline electrolyser, accounting for 83 GWh/year. In methanol production, approximately 11,600 tons/year are utilized for the synthesis process, while in ammonia production, about 7,400 tons/year are required. Despite the similar mass flows and energy content of the two produced fuels, ammonia exhibits a hydrogen (H_2) content approximately 50% higher than that of methanol (1,502 tons/year compared to 1,012 tons/year), highlighting ammonia's significance as a hydrogen carrier. In both configurations, the electrolyser co-generates pure oxygen at a rate of 12,600 tons/year, providing a potential opportunity for storage and sale in the market.

5 Energy Efficiency Comparison

The investment expenses associated with green methanol and ammonia production systems, each featuring a 10 MW electrolyser, were approximately 30 million Euros (excluding existing the 70 MW wind farm) in Osmaniye. Notably, a substantial portion of these costs, amounting to 14 million Euros can be attributed to electrolyser, encompassing stack replacement. The distribution of annual fixed and variable costs exhibits notable similarities between the two configurations. Electricity cost emerges as the predominant factor, constituting 66.5% of green methanol and 65.5% of green ammonia production. The electrolyser costs follow closely behind, contributing around 27%, with other expenses, including the methanol unit (3%) and ammonia unit (6%), making up the remaining portion. The significance of both wind turbines and electrolyser technologies is evident in shaping the economic viability of these systems. Concerning the synthesis units, ammonia production proves to be more costly than methanol, primarily due to higher operating pressure and temperature, as well as a lower single-pass conversion ratio.

5.1 Electrolysis (Hydrogen Production)

The electrolysis of water is an energy-intensive process, requiring substantial electrical input. To produce 1 ton of H_2 with 100% theoretical efficiency necessitates 39.4 MWh of electricity (33.3 MWh/t for the LHV of H_2); however, practical efficiency is approximately 50 MWh/t. This electrolysis process involves the splitting of water through electrical energy to obtain hydrogen and oxygen, with hydrogen purity reaching almost 100% at the cathode, [12].

The proposed plant envisions the use of alkaline electrolyser operating at 40 bars, although recent studies indicate that while alkaline electrolysers remain the most cost-effective solution, PEM electrolysers have witnessed a considerable cost reduction, making them a viable option. Despite the advantages of compactness and rapid response to load variations associated with PEM electrolysers, their economic drawback lies in a lower lifetime, necessitating stack replacement and resulting in a cost increase of approximately 50%.

The alkaline electrolyser (AEL) stands as the oldest electrolyser technology, widely employed since the early 1900s, and still predominantly used for commercial purposes. AEL is characterized by simplicity and durability, with a lifespan ranging from 20 to 30 years or 60,000 to 100,000 hours of operation. Operating temperatures typically range from 40-90°C, commonly around 60-90°C.

The term "alkaline" in alkaline electrolyser refers to the alkaline media serving as the electrolyte, typically potassium hydroxide (KOH) or less commonly sodium hydroxide (NaOH). Over the years, cell designs have evolved towards a zero-gap configuration, departing from classical systems where the oxygen and hydrogen electrodes were combined with interconnects in a dense nickel plate. Modern systems utilize a zero-gap design where the oxygen and hydrogen electrodes are separate components elevated from the bipolar plate and pressed against the diaphragm, enabling a doubling of current densities to 400-500 mA/cm^2, [13], [14], [15], [16], [17], [18], [19].

In the Osmaniye green methanol and ammonia production pilot plant, the electrolyser accounts for the highest energy consumption (83 GWh/year). The KOH consumption in the electrolysis unit is estimated at approximately 1 mg/Nm^3 H_2. The water requirements for the pilot plant include 80 l/Nm^3 H_2 for cooling and 160 m^3/h per 10 MW electricity clusters with an additional 16 m^3/h as tap feed water. The plant's availability is projected at 95%, with an expected total plant life of 20 years. The Osmaniye region's ample freshwater resources mitigate water management concerns, making it a less critical prerequisite for environmentally friendly hydrogen and methanol production. A 10 MW electrolyser unit in the facility produces 2,000 Nm^3/h of H_2 and approximately 1,000 Nm^3/h of O_2, thereby contributing positively to the environment if the produced O_2 is released into the atmosphere.

5.2 CO_2 Source (Biogas Plant)

The CO_2 required for green methanol production is planned to be supplied from the biogas plant to be built in Toprakkale/Osmaniye. The composition of the biogas considered is 40% CO_2 and 60% CH_4. In stoichiometric conditions, methanol synthesis requires 7.33 kg CO_2/kg H_2. The Osmaniye green methanol pilot plant is expected to operate for 7,500 full load hours annually, produce 2,175 tons of green hydrogen, and save 23,200 tons of CO_2 by being fed from a 70 MW wind farm. The biogas plant capacity in Osmaniye is around 1,128.85 kW; therefore it would be appropriate to establish a biogas plant with a capacity of 832.88 kW in Toprakkale/Osmaniye. There is another alternative CO_2 source is Osmaniye Garbage Power Plant with an installed capacity of 3.2 MW. This plant is operated by Ariş Enerji A.Ş. and landfill gas and CO_2 are produced, then the landfill gas is converted to electricity. Produced CO_2 is released into the atmosphere and this useless CO_2 can also be used Osmaniye pilot plant.

5.3 Green Methanol Production

The production of methanol through the catalytic conversion of CO_2 and hydrogen represents an emerging environmentally friendly technology capable of yielding clean methanol and water. The current catalysts exhibit high selectivity and possess a prolonged lifespan, operating under mild conditions in terms of pressures and temperatures, thereby significantly reducing energy requirements. These intensified processes also have minimal footprint requirements. The electricity demand is relatively low and can be sourced from renewable energy. The thermal energy released during the slightly exothermic reaction in the reactor will be utilized for the separation of methanol and water. Generally, each CO_2 molecule entering the process exits as a methanol molecule. However, for each CO_2 molecule, three molecules of H_2 are required, leading to the production of one molecule of water for every methanol molecule. To produce one ton of methanol, approximately 1.373 tons of CO_2 and 0.188 tons of H_2 (equivalent to around 1.7 tons of water) are necessary. The production of one ton of green methanol requires about 10-11 MWh of electricity, with the majority allocated to water electrolysis (approximately 9-10 MWh), [13].

5.4 Green Ammonia Production

The generation of green hydrogen for ammonia synthesis has emerged as a prospective strategy to alleviate the environmental consequences associated with traditional hydrogen production methods. Ammonia, a pivotal chemical compound, is conventionally synthesized through the Haber-Bosch process, predominantly utilizing hydrogen derived from fossil fuels. The shift towards employing green hydrogen, produced via electrolysis powered by renewable energy sources, presents a promising pathway for achieving sustainable ammonia production. Nevertheless, a comprehensive analysis of the environmental implications is imperative to grasp the overall sustainability of this approach. The primary advantage of green hydrogen production lies in its dependence on renewable energy sources during electrolysis, which substantially reduces carbon emissions compared to hydrogen derived from fossil fuels. However, factors such as electrolysis efficiency, energy losses during production, and the origin of the renewable energy employed significantly influence the overall environmental impact.

5.5 Integrated Processes from Renewable to Green Methanol and Green Ammonia

The comprehensive integration of the four previously examined individual processes yields numerous environmental advantages. When these optimized processes, designed for enhanced environmental performance, are implemented and strategically integrated on the same site, additional efficiencies in overall energy and water consumption can be realized. However, if these processes are situated in distant locations, the transportation of compressed H_2 or CO_2 may result in associated greenhouse gas (GHG) emissions. The energy efficiency of the pilot plant is determined by the ratio of the total energy content of the produced green methanol and ammonia to the energy consumption for the entire process. The total energy requirement for the pilot plant is calculated as 10.3 MWh, with approximately 35.6% allocated to the electrolyser, 3% to the compressors, 7.1% to the reactions, and 2.2% to the conversion. This results in a net energy input of 5.4 MWh for green methanol production and 5.2 MWh for green ammonia production. Predominantly, the electrolyser accounts for most of the energy losses and is the primary consumer of electrical energy (10.3 MWh power input, over 95% of the total). The Osmaniye plant aims to supply 2,000 kg/h of green methanol to the maritime transportation sector and 2,100 kg/h of green ammonia to the chemical sector, particularly for fertilizer production. Doubling the electrolyser capacity and sourcing the remaining electrical energy from the national grid would allow the simultaneous production of methanol and ammonia in the Osmaniye plant, leading to a significant reduction in production costs.

6 Conclusion

The efficiency of renewable methanol production stands at approximately 52%, while renewable ammonia production exhibits a slightly lower efficiency of 50%, attributed to increased energy consumption in compressors. Ammonia's superiority as a hydrogen carrier becomes evident due to its capacity to store a significant amount of H_2 in its structure. Conversely, the described process for methanol production allows for the utilization of a substantial quantity of CO_2, contributing positively to environmental considerations. Despite production costs exceeding market values for both renewable ammonia and methanol, the option of selling co-produced O_2, coupled with a reduction in hydrogen electrolyser capital costs, has the potential to significantly enhance the economic viability of green ammonia and methanol production.

Since the Osmaniye is very close to the Mediterranean coast, it has been determined that it is much more appropriate and economical to produce green methanol instead of ammonia and sell it to ships sailing in the region to achieve zero carbon targets. The utilization of green hydrogen in the production of methanol and ammonia holds substantial promise for reducing carbon emissions and fostering sustainability in the chemical and maritime transportation sectors. The techno-economic analysis highlights the feasibility of transitioning to these environmentally friendly processes, taking into account both initial investments and ongoing operational expenses.

To achieve its zero-emission targets, Türkiye must prioritize the production of alternative fuels using green hydrogen technologies and expand their usage. Failure to do so may result in significant economic challenges for the country's leading sector, manufacturing, especially considering the potential implementation of carbon taxes in the coming years in Türkiye.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.