Advancement and Assessment of Power-to-X Strategies as a Significant Contribution for the De-Fossilization of Economies

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Abstract: In order for the EU to achieve its 2050 climate objectives, transport-, power-, and industry sector, which heavily relies on fossil fuels, must significantly decrease their emissions. Green hydrogen and sustainable fuels, among them e-methanol, e-kerosene, and green ammonia, produced using the Power-to-X approach, have been recognised as viable alternatives to reduce emissions and support decarbonization. However, there are some techno-economic challenges in adopting sustainable fuels, particularly related to the higher costs compared to fossil fuels. The economic feasibility of sustainable fuels depends on the cost of green hydrogen and carbon capture technology. Large-scale deployment, improvements in electrolysis modes, and intensive implementation of point-of-source CO_2 capture technologies could make sustainable fuels cost-effective and competitive with fossil fuels by 2050. However, it seems improbable that e-fuels would become widely available at low cost in the near future. The prospective environmental performance of adopting e-methanol, e-kerosene, and e-ammonia is examined, highlighting the necessity of conducting a thorough investigation into the possible negative impacts on human health and ecosystems.

1 INTRODUCTION

Nowadays global concerns surrounding climate change have significantly escalated, with greenhouse gas emissions reaching ceiling. The combustion of fossil fuels contributes to elevation CO_2 and NOx concentrations, leading to the entrapment of thermal energy from the sun. The resultant global warming poses a critical threat to ecosystems, animals, and humanity. In response to this issue, the 2015 Paris Agreement has outlined pivotal objectives, aiming to limit the temperature rise to 1.5 °C and prevent it from exceeding 2 °C above pre-industrial levels[1]. Recognizing the importance of the situation, Germany has acknowledged the imperative need for mitigating carbon emissions and therefore decided in 2021 to strengthen the Climate Action Law in order to reach net greenhouse gas neutrality by 2045[2].

Various potential solutions have been deliberated, with a significant emphasis on transitioning to renewable energy sources for a sustainable future. Solar, hydro, wind, biomass, and biogas represent renewable energy alternatives that stand out for their abundance and continuous renewal [1,2], without affecting long-term environmental damage. There is strong negative correlation between rate of renewable energy usage in EU countries and CO_2 emission ($r<-0.9$, $p<0.001$, Figure 1). However, despite of the numerous advantages of solar energy and wind power, their intermittent nature presents a considerable challenge in maintaining a consistent and reliable energy supply [1]. The fluctuations in their output pose obstacles to achieving a stable energy provision. Addressing these challenges requires innovative solutions that go beyond mere energy generation.

To effectively harness the potential of renewable energy, surplus power generated by renewable energy systems must be efficiently stored or transformed into storable substances. Among the promising technologies addressing this need is Power-to-X (PtX), an emerging energy storage solution designed to alleviate the imbalances inherent in renewable energy sources [2]. PtX employs electrochemical

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[1] https://www.ipcc.ch/sr15/chapter/spm

[2] https://www.cleanenergywire.org/factsheets/germanys-climate-action-law-begins-take-shape

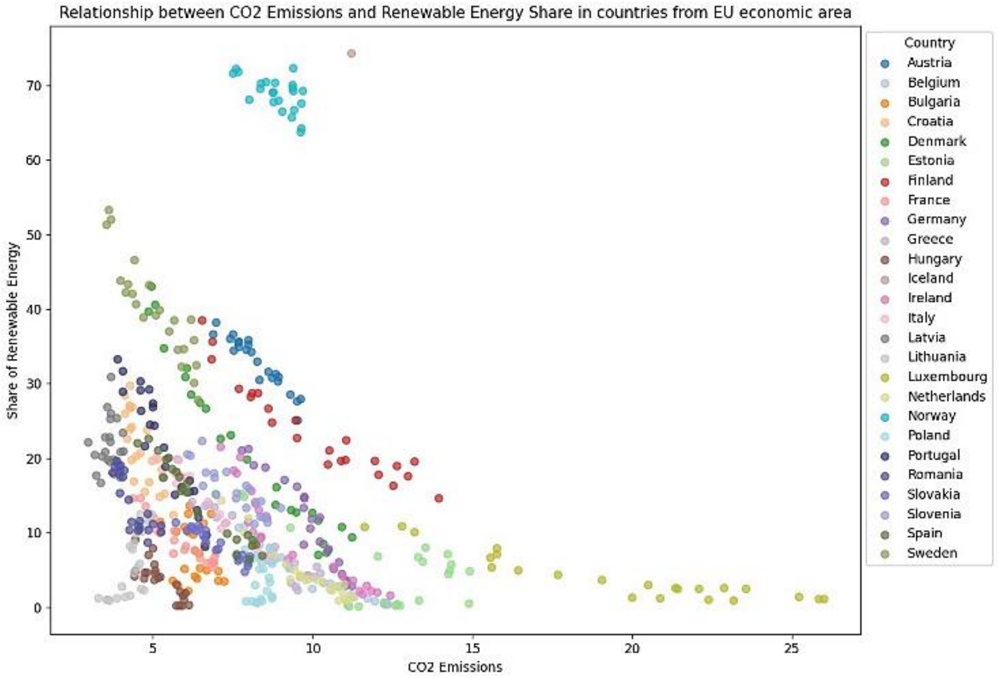

Figure 1: Clustering of relationship between CO_2 emission and rate of renewable energy implementation in EU countries[3].

reactions to convert excess renewable power into hydrogen, which is then combined with carbon molecules to generate a versatile substance referred to as “X”. It is worth noting that the number of publications regarding PtX within the last 10 years was increased in 5-10 times depends on the pathway, with the most promising power-to-gas (PtG) and power-to-liquids (PtL), based on the Scopus and WoS database.

Despite their promising potential, PtX technologies face challenges come from diverse pathways, economic uncertainties, inconsistent policies, and spatial and temporal variations [2, 3]. This analytical review explores these challenges, offering insights into the complexities of PtX technologies and their role in shaping the future of renewable energy storage. While the majority of research on e-fuels primarily concentrates on their economic aspects and disregarding their environmental impact and related expenses, we pay attention these critical issues as well.

2 METHODOLOGY

The methodology employed in this study involved a comprehensive search across the Scopus database and Google Scholar, using key terms such as “green hydrogen”, “wind energy”, and “Power to X”, with a primary focus on “'title, abstract, and keywords”. To refine the search and ensure relevance, filters were applied to restrict results to specific research disciplines, namely “Chemical Engineering”, “Energy”, “Environmental Sciences”. Further refinement included filtering by document type, with an emphasis on highly cited publications and review papers to track hydrogen trends over the preceding three-five years.

Data acquisition predominantly relied on the International Energy Agency (IEA), International renewable energy agency (IRENA) website, Statista, which recently updated its information on hydrogen policy and economy for nations worldwide. Official reports from entities such as the Germany’s Renewable Energy Agency (AEE), German Energy Agency (DENA), provided additional insights into regional policies. Insights into the current perspectives of hydrogen specialists were derived from news sources and press conferences.

To carried out meta-analysis of existed data Meta-Essentials macros for Excel was used [4]. Tornado and population graphs were plotted using GraphPad 9.0 in order to compare economic- and environment-related traits of conventional and e-fuels. Python was used to estimate the relationship between CO_2 emission and progress in renewable energy implementation.

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[3] based on open source data, https://ourworldindata.org

3. POWER-TO-X

3.1 E-Methanol

Methanol and its derivates serves as initial compounds for the manufacturing of several everyday products, including paints, carpets, plastics, and pharmaceuticals. Its versatility expands worldwide, being utilized in innovative ways to address the increasing energy demands, among them its implementation as environmentally friendly energy carrier and storage as well as a renewable fuel that can replace the fossil-derived analogues [5]. Also, switching to e-methanol might help significantly cut down on CO_2 emission (by 59%) [5] because production of grey and blue methanol is responsible for ~ 0.3 Gt CO_2 annually which accounts for almost 10% of the overall emissions from the chemical sector [6].

3.1.1 Techno-Economic Challenges and Putative Solution in E-Methanol Adoption

Power-to-Methanol employs a synergistic combination of hydrogen and CO_2 in 3:1 equimolar ratio over $CuO/ZnO/Al_2O_3$ at elevated pressure and temperature (200-300 °C) to synthesize methanol. This resulting methanol can be conveniently stored in liquid form and harnessed for energy generation through various processes, including hydrogen breakdown, direct utilization in fuel cells, or combustion or even transform into dimethyl ether, diesel, or jet fuel. Detail analysis of previous findings and predictions proved that the average expenses are in the range of 38 and 62 €GJ^{-1} which is almost two folds higher than for conventional methanol and, therefore, still remains economically uncompetitive, particularly in case of energy produced using onshore wind turbines [6]. It is anticipated that these prices will become economically feasible with a significant decrease in the cost of green hydrogen which significantly depends on the type of electrolysis (30–35% of the total levelized production costs) and energy mode (50–55% of the overall levelized production costs) and, on the other hand, carbon capture technology (IRENA). e-MeOH has the potential to be an effective rival to traditional MeOH derived from fossil fuels in the market, as long as the cost of H_2 is 2.5 €·kg^{-1} and the price of CO_2 reaches 120 €·t^{-1} [6]. A reduction of renewable electricity cost might be reach in terms of economies of scale, an increase in wind turbine (from MW to GW transition) and wind onshore/offshore capacity (IRENA).

When it comes to electrolysers, alkaline electrolysis and proton exchange membrane electrolysers are the most favoured options to produce green H_2, with a majority of projects choosing AEC. Nevertheless, SOE and PEM electrolysers exhibit a discernible disparity in terms of development compared to AEC systems, notwithstanding their optimistic prospects, which proved by projecting of the average levelized costs of e-methanol. Based on meta-analysis it will have been by the 2030 around 4.2±0.68 €·kg^{-1} with the low level of publication biased (Figure 2).

However, this price is still far from the price for blue hydrogen, which costs ~1.6 EUR·kg^{-1} ([4] [9]). This price holds economic viability within specific sectors but lacks suitability for large-scale industrial supply. Moreover, some developers tend to believe that the costs of green hydrogen unlikely to fall dramatically in the near future because of increase in capex and shortages in electrolyser manufacturing capacity as was announced on the *Investing in Green Hydrogen* conference (London, 2023)[5]. It dictates the necessitates additional technological advancements and paramount importance of permanent intense search of smart solutions.

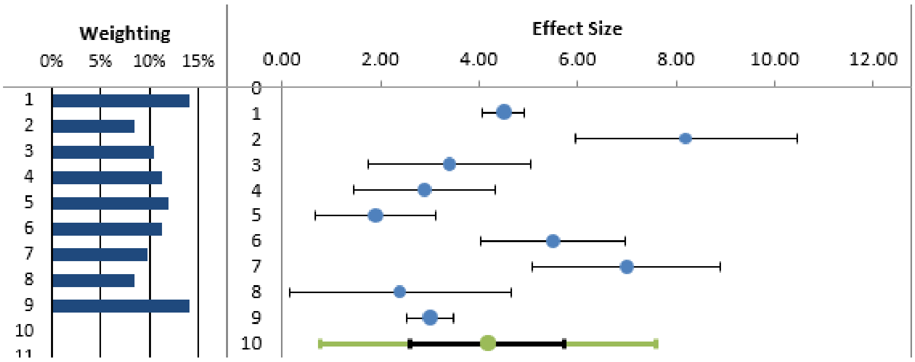

Figure 2: Meta-analysis of levelized costs for green hydrogen production (€·kg^{-1}) based on [5-8].

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[4] BloombergNEF

[5] www.hydrogeninsights.com

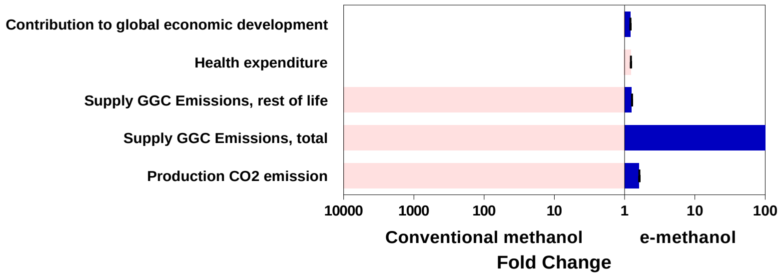

Figure 3: Comparative analysis of conventional and e-methanol related to environment and human health effects (based on data from [5-8, 10, [6]]).

3.1.2 Prospects for Environmental Performance Regarding E-Methanol Adoption

If conventional methanol production supports sky-rocketing CO_2 emission, e-methanol brings itself closing to zero-emission CO_2 [6], around 4.4 g $CO_{2\,eq}$/MJ (Figure 3). This indicates a reduction in emissions of almost 90% compared to conventional methanol. Green methanol also connected to a decrease in NOx emissions by up to 80% and totally eliminates SOx and particulate matter emissions. It might help humankind to decrease carbon footprint and tackle a problem of constantly increasing greenhouse gas emission and related global warming.

However, there is the trend to further transform e-methanol into dimethyl ether, which would be used as a sustainable diesel fuel replacement because it needs only minor engine modifications. PtX derived dimethyl ether in the case of partial oxidation might form formaldehyde, reactive carbonyl species, a recognised carcinogen. The emissions of formaldehyde during DME fuel production and combustion should be identified as the most important health-related issue in the whole life cycle of this fuel, and, therefore, has to be tightly controlled.

Also, social life-cycle portrait of e-methanol respect for forced labour and healthcare costs among others, shows some disadvantages when compared to conventional methanol [10]. The heightened complexity of the supply chain inside the green methanol system might be the fundamental reason of these issues. Unfortunately, environmental aspects and social life-cycle portrait of e-methanol are still overlooked and, therefore, have to be deep analyse.

3.2 Sustainable Aviation E-Fuels

By 2022, aviation contributed 2% of the world's energy-related CO_2 emissions, counted 800 Mt CO_2, seeing a more rapid growth compared to rail, road, and shipping in recent decades[7]. Therefore, the projected carbon emissions from 2021 to 2050, assuming no changes in current practices, amount to around 21.2 gigatons of CO_2[8]. Following medium and long-term objectives, ReFuelEU Aviation advocates for the utilization of e-fuels, known as well as sustainable aviation fuel, e.g. e-kerosene, blended with conventional fuels at a rate of 2% in 2025, gradually escalating to 70% by the year 2050 in order to significantly decrease the emissions intensity of aviation or even reach net zero emissions by 2050.

Nevertheless, in 2019, their share in the overall aviation fuel market was less than 0.01% according to the International Energy Agency (IEA, 2019). In 2021, Germany established a goal to utilise e-kerosene for 0.5% of aviation fuel by 2026, with a further increase to 2% by 2030 [11]. To favour these goals, Lufthansa has indicated its intention to procure a minimum of 25000 L e-kerosene per year over the next five years[9]. However, the costs of these fuels are currently three to six times higher than those of traditional fossil-fuel-based aviation fuel.

3.2.1 Particular Techno-Economic Challenges of E-Fuel Production Related to CO_2 Capture Technologies

E-fuel, consists of high-molecular alkanes, is produced by green hydrogen, generated through water electrolysis utilizing renewable energy, with CO_2 sourced from industrial outlets, biogenic sources, or directly captured from the atmosphere or just before its emission to atmosphere in terms of the Fischer-Tropsch synthesis or Methanol-to-Jet synthesis technique. Because of main steps of manufactured process, it is predicted that a substantial proportion of the cost of e-fuel is attributed to the expenditure related to renewable power follow by > synthesis and conversion > CO_2 supply > electrolysis > H_2 storage [12]. It is worth mentioning, that the cost fraction of green energy is pretty the same for production of e-fuel and e-methanol (see 3.1.) [IRENA, 12] and

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[6] www.methanol.org

[7] https://www.iea.org/energy-system/transport/aviation

[8] https://www.iata.org/en/programs/environment/flynetzero

[9] Lufthansa Group, 2021

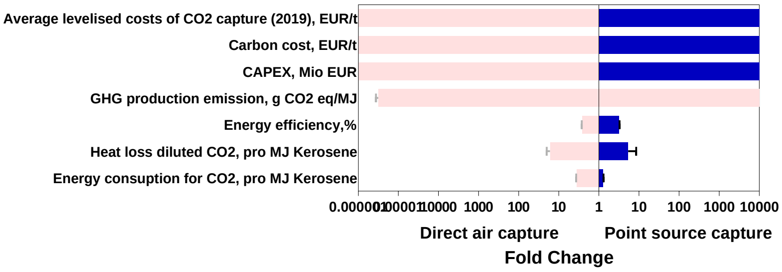

Figure 4. Comparative analysis of direct air capture and point source capture techniques of CO_2 takeover based on data from [12]. [10, 11]

the activities intended to decrease its price, have been mentioned in 3.1, might be universal, we would pay more attention to CO_2 supply.

Although Direct air capture (DAC) appears as a highly promising way of removing CO_2 from the atmosphere because of its space effectivity, it belongs to the most cost-demand technology in comparison to alternative methods, e.g. point source capture[10].

The cost-effectiveness of collecting CO_2 from industrial systems, among them cement manufacturing and particularly natural gas coal to chemicals processing, exceeds that of DAC because of the greater volume fraction of CO_2 involved, leading to a more economical value. Furthermore, the gaseous stream produced by industrial emissions is found to have a higher purity of CO_2 compared to the surrounding air. This contributes to a more efficient and economical method of concentrating CO_2. It is projected that point of source capture might allow not only optimise energy consumption during the production pathway of e-kerosene, but also support an increase in energy efficiency (44% vs 52%) and environment decarbonization alongside lower CAPEX and levelized cost (up to 300%) (Figure 4). When consider industrial and renewable energy capacities some Asia and South America countries attract attention on that purpose. As an example Taiwan and Brazil possess leading position into cement manufacturing around the world[12] and at the same time have abundant green power resources, among them high off- and onshore wind capacities what makes them secure players on the e-fuel marketplace.

Alongside with DAC and point source capture technique, there are some others, such as Visible-Light-Driven CO_2 Reduction [13], that might be useful in CO_2 capture and processing, however they are on the juvenile stage and its large-scale implementation is pretty murky.

3.2.2 Prospects for Environmental Performance Regarding Green Kerosene Adoption

Presently, the most reliable approach involves the use of emission factors that establish the relationship between the quantity of fuel consumed and the pollutants produced (e.g., in grams of pollutant per gram of fuel burned). However, the standards for incorporating fossil kerosene and e-kerosene into a blend are often disregarded, as evidenced by numerous references, among them [14]. While e-jet fuels typically exhibit a lower global warming potential [15, 16] and are less scarce in comparison to fossil jet fuels, they might adversely affect human health and ecosystem quality. This implies a shift in the balance of negative effects from resource scarcity towards concerns related to human health and the quality of ecosystems. It is believed that the environmental impacts of Power-to-Liquid kerosene varied significantly across the production pathways and the layout using high-temperature electrolysis, low-temperature Direct Air Capture and electricity from wind power pretends to be the most environmental-friendly [16]. Although various materials that were suggested for Direct Air Capture, including metal hydroxide-based absorption and amine-supported materials, they might provoke specific toxicity due to potential leakage of target chemicals into milieu, among them pH effect (alkalisation), hypercalcemia, skin and respiratory track irritations. Eliminating environmental threats by using green sorbents, in other words bioregenerative materials and Ionic liquids, e.g. mesoporous chitosan-SiO_2 nanoparticles with a capacity of 193.16 mg of CO_2 per gram of sorbent and superhydrophobic PVDF/Si-R hollow fiber membrane [17]. A scarcity of findings regarding the environmental impacts of e-kerosene, as a desirable fuel option in the future within the context of potential hazards for humankind, underscores the importance for an in-depth study into its plausible adverse effects.

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[10] www.iea.org

[11] https://kth.diva-portal.org/smash/get/diva2:1520216/FULLTEXT01.pdf

[12] https://www.globalcement.com/magazine/articles/822-top-75-global%20cement%20companies

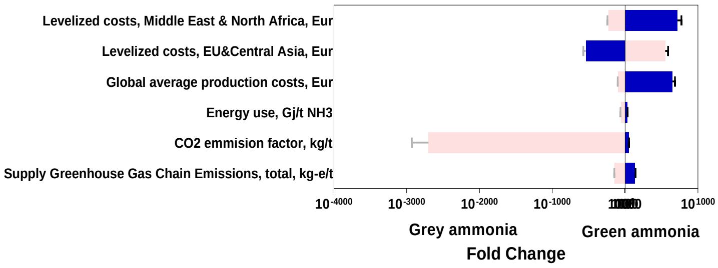

Figure 5: Comparative analysis of grey and green ammonia based on data from [19].[13, 14]

3.3 Green Ammonia

Approximately 70% of global ammonia production is conveyed for fertilizer synthesis, among them ammonium nitrate, with the remaining proportion finding applications across diverse industrial sectors, including the production of plastics, explosives, and synthetic fibers. Nowadays, the USA, China, Russia belong to the main producers of ammonia. The current trajectory of the ammonia industry is considered unsustainable because of unstable geopolitical situations, massive CO_2 emission (~450 Mt CO_2, 1.8% overall global CO_2 emissions) and energy (~4% of the sector's energy inputs) demand (ww.iea.org), since predictions suggest a nearly 40% increase in output by 2050 under the Stated Policies Scenario, driven by economic development and population expansion. While the potential of ammonia as a clean energy source is acknowledged, its current integration into energy systems remains in its nascent stages.

3.3.1 Techno-Economic Challenges of Green Ammonia Production

Ammonia should be synthesized using iron-based catalytical Haber-Bosch reaction. Although ammonia possesses a lower heating value of 18.6 $MJ \cdot kg^{-1}$, which is about 40% of the energy density of petrol, it pretends to be the important player on the marketplace. Ammonia is particularly noteworthy due to its remarkable gravimetric hydrogen content of 17.8%, which places it among the energy carriers with the greatest levels, transportability and potential for decarbonization of NH_3. The existing infrastructure of a comprehensive liquid ammonia transport network, mostly used in the fertilizer sector, offers a readily available basis for its global transportation. Once delivered, ammonia can be catalytically decomposed back into hydrogen or used directly as a fuel, thus making a substantial contribution to the worldwide effort to achieve sustainable energy solutions. To this end it is worth mentioning that its production and decomposition of ammonia require less energy than liquefying hydrogen, favouring its use as an efficient method of storing hydrogen.

The main differentiating aspect among modern ammonia manufacturing methods is the hydrogen generation pathway. Currently, more than 96% of the hydrogen used worldwide in the production of ammonia comes from fossil fuel sources, what, however, in turn related to releasing 2.5-2.9 kg of CO_2 eq$\cdot kg^{-1}$ of ammonia produced (Figure 5) [18]. In order to follow Green Deal politic, grey/blue hydrogen needs to be substitute with green H_2. However, because of high price for green hydrogen, the present price of green ammonia produced by an integrated plant that combines renewables, hydrogen, and ammonia variated in the range of 540- 810 EUR per t vs an average cost for convential ammonia of less than 200 US $ based on the natural gas price before 2022. However, considering the peak price of natural gas in 2022, the grey ammonia price reached sky-high 1.500 US $, what bears witness to the favour of green NH_3[15].

It is expected, however, that in some countries, among them Australia, Central Asia and Middle East [20], with a favourable combination of solar and wind resources, as well as economic conditions that support low capital costs (capital cost < 8%), the projected cost of producing green ammonia will have been 360 Euro/t NH_3 by 2030 (Figure 5) [19]. It is worth noting, that in particular cases the cost of producing green ammonia keep up with the cost of producing grey ammonia, placing them in direct competition.

It is believed that the synthesis of green ammonia might be a feasible and economically advantageous substitute for the conventional Haber-Bosch method. This belief holds true when considering improvements in the energy efficiency of electrolyzers, reductions in the prices of water electrolyzers, and decreases in the levelized cost of electricity for renewable energy. Some findings in the frame of Techno-Economic Analysis and Life Cycle

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[13] https://www.futurebridge.com/industry/perspectives-energy/green-ammonia-an-alternative-fuel

[14] https://www.mckinsey.com/industries/agriculture/our-insights/from-green-ammonia-to-lower-carbon-foods

[15] https://www.eia.gov/todayinenergy/detail.php?id=52358

Assessment have emphasized the potential advantages of Solid Oxide Electrolysis for producing green H_2 as the feedstock for ammonia synthesis. When compared with conventional Alkaline Water Electrolysis and promising Proton Exchange Membrane electrolysis of water, Solid Oxide Electrolysis demonstrated significant cost rate of 0.9372 $/s with an exergy efficiency of 13.15 % and the least amount of CO_2 emissions [21, 22]. This is mainly due to its reduced energy requirements compared to other electrolysis methods. Meanwhile, all these methods demonstrate more valuable traits related to energy demands and CO_2 emission in the future than conventional ammonia (Figure 5). The Ammonia Energy Association has projected the production costs for NH_3 in 2030 (0.48 USD per kg) and 2050 (0.32 USD kg^{-1})[16], which in relation to CO_2 tax appear more economically valuable than the conventional Haber-Bosch NH_3 prices (with and without a CO_2 tax: 0.3 and 0.6 USD kg^{-1} NH_3, respectively) [21].

Considering the projected 37% increase in global ammonia production by 2050 and the associated concerns about CO_2 emissions, the adoption of green ammonia emerges as a valuable contributor to global economic growth, thanks to its low carbon footprint. While the substantial costs linked to ammonia make it unlikely to become a primary player in the global energy supply, there are niche applications where it can prove beneficial. One such use is as a transitional fuel in existing equipment, facilitating the transition to renewable energy sources. Moreover, ammonia may find relevance in scenarios where the feasibility of renewable energy is limited, such as in the shipping industry. In these specialized fields, green ammonia can play a strategic role in advancing sustainability goals and mitigating environmental impact.

3.3.2 Environmental Challenges Regarding Green Ammonia Adoption

Green ammonia has the potential to serve as a substitute for fossil fuels on a large scale in challenging-to-decarbonize regions of the energy and transportation sectors. Nevertheless, it is important to acknowledge potential drawbacks associated with its adoption, which should be prevented. The potential reduction in CO_2 emissions achieved by using ammonia may be completely negated by the release of nitrogen oxides (NO_X) and nitrous oxide (N_2O) emissions during its burning. It is tightly connected to potential adverse outcomes (Figure 6), among all respiratory system disorders, inflammation and immune disorders in human and acid rain and ozon depletion in frontline in environment [23].

It is worth noting that only in China NOx emission will have reached 45.5 Mt by 2030 under baseline scenario with an average annual growth rate of 1.84% [24]. It is however expected that this amount should be exceeded because of additional emission of NOx by e-ammonia adoption. To prevent this, it is necessary to decrease flame temperature or employ highly efficient post-treatment technologies, e.g. denitrification technology, to reduce the release of unintended emissions.

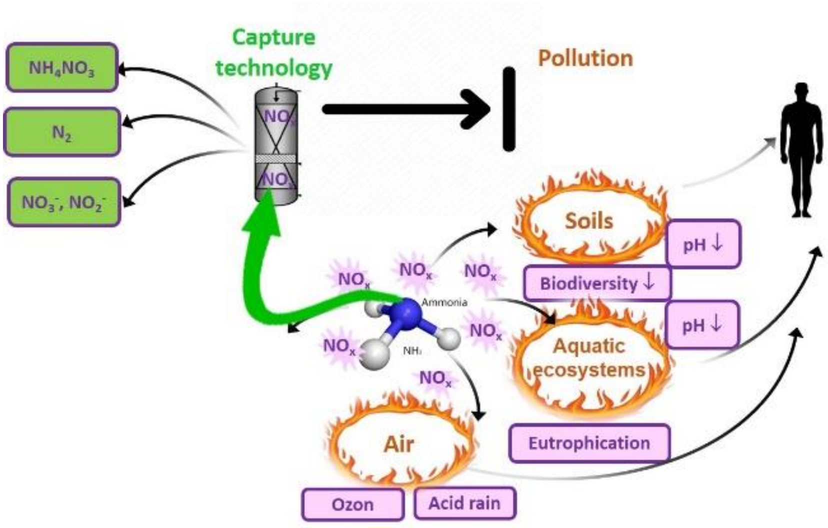

Figure 6: Exploring the potential adverse outcomes of NO_x emissions in relation to Green Ammonia and proposed solutions for mitigation.

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[16] https://www.ammoniaenergy.org/articles/the-cost-of-co2-free-ammonia

The selective catalytic (using Mn-based catalyst) or selective non-catalytic reduction [25] appear promising that allow to convert NO_X to N_2 which is actually the initial reagent of Haber-Bosch synthesis of ammonia and NH_4NO_3, fertilizer and just NH_3, correspondingly (Figure 6). Due to our knowledge, there is no approved NOx reduction emission strategy but only Nitrogen Oxides (NOx) Control Regulations by US EPA. However, the growing emphasis on NOx-related issues encourages proactive efforts to prune down on emissions and support the smooth adoption of green ammonia and sustainable development of the environment.

4 CONCLUSIONS

In conclusion, the adoption of green fuels, including e-methanol, e-kerosene, and green ammonia, synthesized through Power-to-X technique, holds promise in addressing environmental challenges and reducing carbon emissions in various sectors. These green fuels present opportunities for a sustainable energy transition, but a balanced approach is crucial to address economic, environmental, and social considerations. Effectively integrating e-fuels and PtX approach into various economic sectors requires addressing paramount challenges related to techno-economic aspects and environmental factors. In the foreseeable future, extending beyond 2035, there seems to be no defined role for storage of the mentioned derivatives. This is due to the ongoing high cost of Green Hydrogen, making it a precious primary energy source. Any re-transformation, such as converting green NH_3 back into green Hydrogen, results in notable efficiency and energy yield losses.

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REFERENCES

[1] P.A. Owusu and S. Asumadu-Sarkodie, "A review of renewable energy sources, sustainability issues and climate change mitigation," Cogent Engineering, vol. 3, 2016.

[2] A.R. Dahiru, A. Vuokila, and M. Huuhtanen, "Recent development in Power-to-X: Part I - A review on techno-economic analysis," J. Ener. Stor., vol. 56, pp. 105861, 2022.

[3] B.S. Zainal, P.J. Ker, H. Mohamed, H.C. Ong, et. al., "Recent advancement and assessment of green hydrogen production technologies," Renew. Sustain. Energ. Rev., vol. 189(A), pp. 113941, 2024.

[4] R. Suurmond, H. van Rhee, and T. Hak, "Introduction, comparison and validation of Meta-Essentials: A free and simple tool for meta-analysis," Res. Synth. Meth., vol. 8, pp. 537-553, 2017.

[5] S. Sollai, A. Porcu, V. Tola, F. Ferrara, and A. Pettinau, "Renewable methanol production from green hydrogen and captured CO2: A techno-economic assessment," J. CO2 Utiliz., vol. 68, pp. 102345, 2023.

[6] Y. Rahmat, S. Maier, F. Moser, M. Raab, et. al., "Techno-economic and exergy analysis of e-methanol production under fixed operating conditions in Germany," Applied Energy, vol. 351(C), pp. 121738, 2023.

[7] S. Pratschner, F. Radosits, A. Ajanovic, and F. Winter, "Techno-economic assessment of a power-to-green methanol plant," J. CO2 Utilization, vol. 75, pp. 102563, 2023.

[8] N. Heimann, R.-U. Dietrich, M. Raab, N. Wulff, R. Moser, and T. Francisco, "Standardized techno-economic analysis for the production of e-fuels in Germany," 11th International Conference "Fuel Science: From Production to Propulsion" 2023, Deutschland, 2023.

[9] F. Ueckerdt, P. Verpoort, R. Anantharaman, C. Bauer, F. Beck, T. Longden, and S. Roussanaly, "On the Cost Competitiveness of Blue and Green Hydrogen," Joule, 2024.

[10] D. Iribarren, R. Calvo-Serrano, M. Martín-Gamboa, A. Galán-Martín, and G. Guillén-Gosálbez, "Social life cycle assessment of green methanol and benchmarking against conventional fossil methanol," Sci. Total Environ., vol. 824, pp. 153840, 2022.

[11] K. Appunn, "CO2 reduction and biofuels in Germany’s transport sector-Implementing the RED II directive," Clean Energy Wire, 2021.

[12] E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050, Concawe, 2022, [Online]. Available: https://www.concawe.eu/wp-content/uploads/Rpt_22-17.pdf.

[13] S. Roy, and E. Reisner, "Visible-Light-Driven CO2 Reduction by Mesoporous Carbon Nitride Modified with Polymeric Cobalt Phthalocyanine," Angewandte Chemie, vol. 58, pp. 12180-12184, 2019.

[14] F.D. Ordóñez, T. Halfdanarson, C. Ganzer, N. Shah, N.M. Dowell, and G. Guillén-Gosálbez, "Evaluation of the potential use of e-fuels in the European aviation sector: a comprehensive economic and environmental assessment including externalities," Sustain. Energy Fuels., vol. 6(20), pp. 4749-4764, 2022.

[15] Deutsche Energie-Agentur (Publisher) (dena, 2022) "E-Kerosene for Commercial Aviation, From Green Hydrogen and CO2 from Direct Air Capture – Volumes, Cost, Area Demand and Renewable Energy Competition in the United States and Europe from 2030 to 2050".

[16] M. Micheli, D. Moore, V. Bach, and M. Finkbeiner, "Life-Cycle Assessment of Power-to-Liquid Kerosene Produced from Renewable Electricity and CO2 from Direct Air Capture in Germany," Sustainability, vol. 14(17), pp. 10658, 2022.

[17] Y. Abdullatif, A. Sodiq, N. Mir, Y. Bicer, et. al., "Emerging trends in direct air capture of CO2: a review of technology options targeting net-zero emissions," RSC Adv., vol. 13, pp. 5687-5722, 2023.

[18] P. Mayer, A. Ramirez, G. Pezzella, B. Winter, S.M. Sarathy, et. al., "Blue and green ammonia production: A technoeconomic and life cycle assessment perspective," iScience, vol. 26, pp. 107389, 2023.

[19] D. Saygin, H. Blanco, F. Boshell, J. Cordonnier, K. Rouwenhorst, et. al., "Ammonia Production from Clean Hydrogen and the Implications for Global Natural Gas Demand," Sustainability, vol. 15, pp. 1623, 2023.

[20] J. Egerer, V. Grimm, K. Niazmand, and P. Runge, "The economics of global green ammonia trade – 'Shipping Australian wind and sunshine to Germany'," Appl. Energy., vol. 334, pp. 120662, 2023.

[21] B. Lee, L.R. Winter, H. Lee, D. Lim, H. Lim, and M. Elimelech, "Pathways to a Green Ammonia Future," ACS Energy Lett., vol. 7, pp. 3032-3038, 2022.

[22] M.M. Nejadian, P. Ahmadi, and E. Houshfar, "Comparative optimization study of three novel integrated hydrogen production systems with SOEC, PEM, and alkaline electrolyzer," Fuel., vol. 336, pp. 126835, 2023.

[23] W. de Vries, "Impacts of nitrogen emissions on ecosystems and human health: A mini review," Cur. Opinion Environ. Sci. Health, vol. 21, pp. 100249. 2021.

[24] L. He, B.B. Wang, W. Xu, Q. Cui, and H. Chen, "Could China's long-term low-carbon energy transformation achieve the double dividend effect for the economy and environment?" Environ. Sci. Pollut. Res. Int., vol. 29, pp. 20128-20144, 2022.

[25] Z. Zhu and B. Xu, "Purification Technologies for NOx Removal from Flue Gas: A Review," Separations, vol. 9, pp. 307, 2022.