TECHNICAL INFORM

Analysis of the impact of embodied emissions from renewable electricity on the carbon intensity of e-fuels under the IMO Zero or Near Zero Fuel (ZNZF) framework

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PUBLIC VALUE

EPE CONDUCTS STUDIES AND RESEARCH TO SUPPORT THE FORMULATION, IMPLEMENTATION, AND EVALUATION OF BRAZILIAN ENERGY POLICY AND PLANNING. E-FUELS ARE PROMISING ALTERNATIVES FOR THE DECARBONIZATION OF VARIOUS SECTORS, INCLUDING MARITIME TRANSPORT. THROUGH THIS REPORT, EPE PROVIDES A TECHNICAL ANALYSIS OF THE IMPACT OF THE GEOGRAPHIC LOCATION OF RENEWABLE ELECTRICITY GENERATION ON THE CARBON INTENSITY OF THESE FUELS, BASED ON REGIONAL INDICES OF WIND AND SOLAR POTENTIAL. THIS INFORMATION ENABLES THE REFINEMENT OF BRAZIL'S POSITIONS IN INTERNATIONAL AGREEMENTS, HELPING TO REDUCE ASYMMETRIES AND CONTRIBUTE TO THE ESTABLISHMENT OF INTERNATIONAL DECARBONIZATION FRAMEWORKS THAT ARE FAIR, COMPETITIVE, AND CAPABLE OF DELIVERING EFFECTIVE REDUCTIONS IN GLOBAL GREENHOUSE GAS EMISSION.

Summary

▪ Ilustration list

▪ Grafic list

1. Objective

The objective of this study is to analyze the decarbonization potential of e-ammonia and e-methanol as e-fuels, based on an assessment of the sensitivity of their full life-cycle carbon intensity (well-to-wake) to the embodied emissions in the renewable electricity used in their production. The study investigates how variations in wind generation capacity factors and solar irradiation levels for photovoltaic systems affect the final carbon intensity of these fuels.

Among the various sectors that could use low carbon e-fuels, the transport sector stands out, particularly those classified as hard-to-abate, such as aviation and maritime. The aviation sector has identified decarbonization pathways through improvements in aircraft efficiency and the maturation of sustainable aviation fuels (SAF), among which synthetic hydrocarbons are emerging as a promising option. The maritime sector faces different challenges, and the use of e-fuels may be one of the alternatives for its decarbonization, with particular emphasis on e-methanol and e-ammonia.

In this context, with a focus on presenting pathways for the maritime sector, this work seeks to identify the minimum energy performance thresholds and the geographic regions globally where the production of e-ammonia and e-methanol, based on solar photovoltaic and wind electricity, can meet the 19 g CO_2e/MJ limit defined by the International Maritime Organization (IMO) for classifying fuels as “zero or near-zero fuel” (ZNZF) over the period from 2028 to 2034. Additionally, the study provides quantitative inputs to support the discussion on the environmental viability of these fuels within the framework of international maritime decarbonization policies, contributing to a better understanding of the role of regional renewable generation conditions in determining the eligibility of e-fuels for incentive mechanisms established under the IMO regulatory framework.

2. Introduction

E-fuels are considered promising options for decarbonizing hard-to-abate transport. They are produced from hydrogen generated via water electrolysis using renewable electricity, meaning that the embodied emissions of this energy can significantly affect the magnitude of GHG emissions associated with the life cycle of these fuels. Factors such as the average annual irradiation of a given region (in the case of solar photovoltaic energy) and the capacity factor of generation (for wind energy) directly influence the impact that such embodied emissions have on the carbon intensity of the e-fuel produced, and are therefore key aspects in assessing the decarbonization potential of these fuels.

In the aviation segment, synthetic hydrocarbons stand out as promising e-fuel options. In the maritime segment, other alternatives have attracted significant interest from the international community, particularly e-ammonia and e-methanol. Within the net-zero framework established by the International Maritime Organization (IMO), a threshold of 19 g CO_2e/MJ was defined as the carbon intensity limit for classifying a fuel as a “zero or near-zero fuel” (ZNZF) for the period from 2028 to 2034, with ZNZFs being eligible to generate reward mechanisms for the use of low-carbon fuels. This measure covers the “well-to-wake” (WtW) scope, which includes fuel production, transport, storage, loading, and use onboard ships.

In this study, a sensitivity analysis was conducted to identify the capacity factor thresholds for these energy sources, based on wind intensity for wind power and solar irradiation for solar power, that enable the production of e-ammonia and e-methanol in compliance with the ZNZF limit, considering the impact of embodied emissions from each renewable source. Based on this, regions around the world where such opportunities are concentrated were identified.

3. Methodology

3.1. Life Cycle Analyses (LCA)

The WtW emissions of e-ammonia and e-methanol were calculated according to the methodology described in this section. The objective was to model processes that represent the global average emissions of these fuels.

3.1.1. Fuel Production

The e-ammonia production process comprises air purification for nitrogen separation, water electrolysis for hydrogen production, and the Haber–Bosch synthesis, in which the inputs react to produce ammonia. In this study, air purification is carried out using a cryogenic air separation unit, a technology recognized as the most suitable for achieving high purity levels (Aneke; Wang, 2015). For electrolysis, alkaline electrolysis was considered, as it is currently the most commercially mature technology and has the lowest investment cost (Ingwersen et al., 2025).

The e-methanol production process, in turn, includes alkaline water electrolysis for hydrogen production and methanol synthesis through a thermocatalytic process that reacts hydrogen with CO derived from CO_2. The CO_2 stream was treated as a direct input to the reactor. This CO_2 may originate from direct air capture (DAC) or from industrial gas capture. Furthermore, the stream was assumed to be emission-free, under the premise that it is renewable (in the case of DAC and/or biogenic carbon) or that the emissions associated with these streams have already been allocated to the upstream industrial process from which the CO_2 is sourced (in the case of fossil carbon).

The life cycle inventory of the processes was primarily based on previous life cycle assessment studies (D'Angelo et al., 2021; Hank et al., 2019), covering all the stages described. Electricity consumption for the air separation unit, specifically, was based on Aneke and Wang (2015). Electricity consumption for cooling water circulation was modeled based on Schulze et al. (2019) and Li and Flynn (2021).

Greenhouse gas emissions associated with inputs and utilities (excluding electricity) were obtained from the Ecoinvent 3.11 database, using global average values.

For electricity, greenhouse gas emissions were treated as a sensitivity parameter. Accordingly, the life cycle assessment was conducted by varying the embodied emissions associated with renewable sources (solar and wind) between 10 and 100 g CO_2e/kWh. This allowed for the derivation of correlations between total fuel emissions and the embodied emissions of electricity.

3.1.2. Transmission and Distribution

For e-methanol, the energy consumption associated with transmission and distribution was obtained from the Argonne National Laboratory GREET model (2023).

The transmission of e-ammonia, in the context of its use as a fuel, was assumed to occur intracontinentally via pipelines, barges, and rail, with respective average distances and loads calculated based on data from Bonnet-Cantalloube et al. (2023) and Kruse et al. (2012). For fuel distribution, the use of trucks was considered, with an average distance of 50 km.

The emissions associated with these transport modes were obtained from the Ecoinvent 3.11 database. For pipeline transport of e-ammonia, the value reported for oil transport was used as a proxy. Emissions associated with the use of natural gas and diesel were obtained from Intergovernmental Panel on Climate Change (2022). For coal, the value reported by the U.S. Energy Information Administration (2024) was used.

3.1.3. Storage and Loading

The energy consumption associated with the storage and loading of fuels onto ships was based on Bianchi et al. (2025), and the emissions associated with this energy use were obtained from the same sources described in the previous sections.

3.1.4. Fuel final use

The use of e-methanol in marine engines emits COx, NOx, and particulate matter (Brynolf; Fridell; Andersson, 2014). Similarly to what is described in Section 3.1, CO_2 was considered emission-neutral in this modeling, such that greenhouse gas emissions from the use phase of e-methanol were assumed to be zero.

For e-ammonia, N_2O formation results in emissions during use. A recent literature review study submitted to the International Maritime Organization (Pacific Environment; CSC; EDF, 2025) reports an average generation of 0.5 mg N_2O per g NH_3. However, engine manufacturers report significantly lower values (3 ppm or less), which would correspond to approximately 0.04 mg N_2O per g NH_3 (Wingd, 2025). In this study, these two cases were considered separately, in order to account for both the global average value and the best-case scenario based on good practices in engine design and manufacturing.

3.2. Assessment of Suitable Locations

The embodied emissions associated with electricity generation from solar photovoltaic and wind sources depend on a range of specific factors and can vary from 18 to 180 g CO_2e/kWh for solar PV and from 7 to 56 g CO_2e/kWh for wind (IPCC, 2014). Part of this variation is linked to regional differences in solar irradiation and wind availability.

The literature references used by the Intergovernmental Panel on Climate Change to estimate these emission values were reviewed in this study in order to identify correlations between annual solar irradiation and wind capacity factors, and the reported emission values.

For solar photovoltaic energy, the IPCC relies primarily on the review by Hsu et al. (2012), in which the authors harmonized LCA results from the literature considering parameters such as annual irradiation, panel efficiency, system performance, and lifetime. A similar approach was adopted in this study; however, the harmonization with respect to annual irradiation was not applied. This resulted in a scatter of data points correlating the annual irradiation considered in each study with the corresponding harmonized emission values.

For wind energy, the IPCC relies mainly on the work of Arvesen and Hertwich (2012), in which the authors reviewed a range of LCA studies. In this work, all studies considering turbines with installed capacity above 1 MW were reassessed, generating another set of data points that correlate the wind capacity factor assumed in each study with the corresponding emission values.

Based on these results, the minimum thresholds of annual irradiation and wind capacity factor required to produce e-ammonia and e-methanol with carbon intensity below the 19 g CO_2e/MJ limit were determined. This made it possible to assess which regions of the world effectively meet the ZNZF criteria.

4. Results

Figure 1 presents the results of the sensitivity analysis for estimating the carbon intensity of e-methanol and e-ammonia, according to the embodied emissions of the electricity used. It shows that low electricity carbon intensity values are required for these fuels to meet the threshold established for classification as ZNZF (14.07 g CO_2e/kWh for e-ammonia assuming average N_2O emissions; 26.95 g CO_2e/kWh for e-ammonia with best practices in engine manufacturing; and 28.74 g CO_2e/kWh for e-methanol). The production of e-methanol is less sensitive to electricity emission levels.

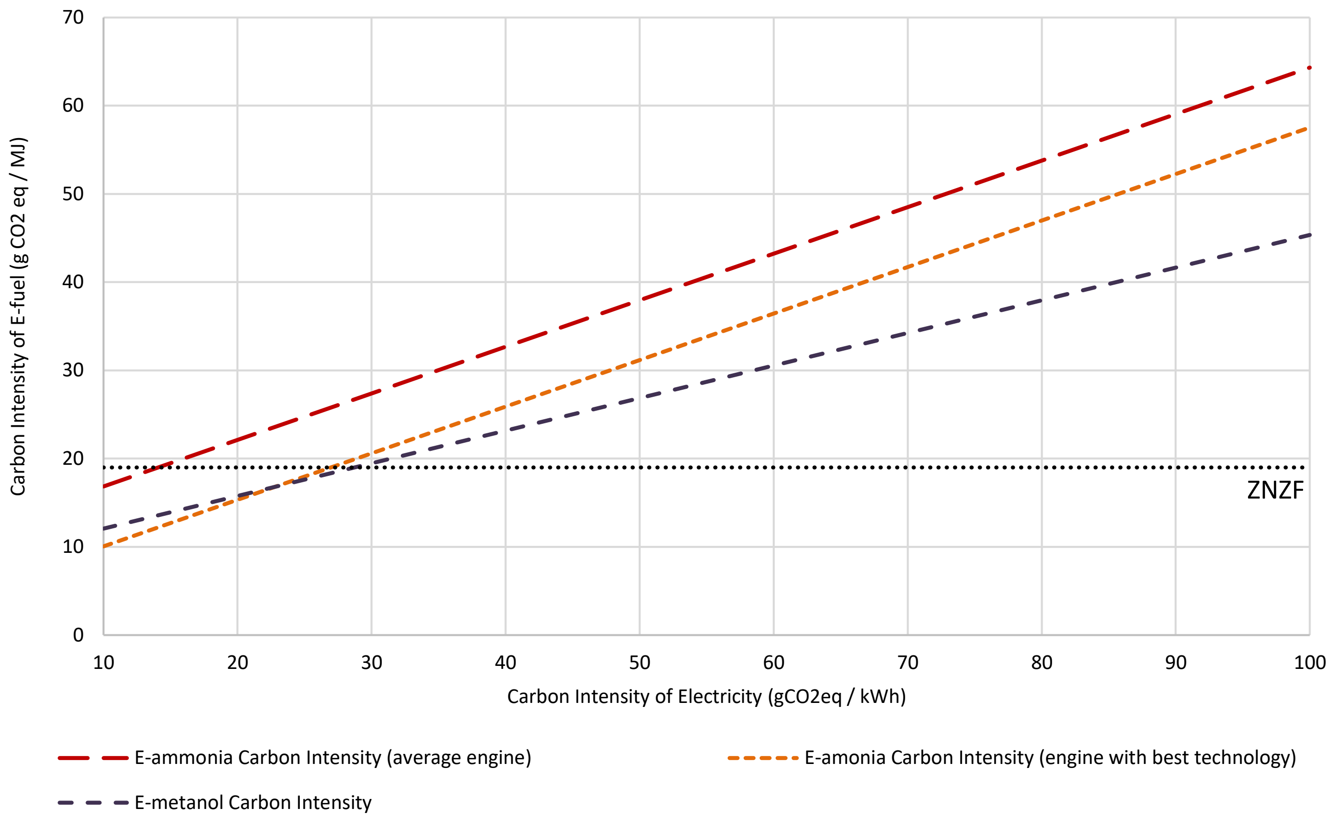

Figure 1 – Carbon intensities of e-ammonia (average use-phase emissions and best practices in engine manufacturing) and e-methanol as a function of the embodied emissions of the electricity used.

Source: Own elaboration

Figure 2 presents the carbon intensity of electricity as a function of annual irradiation (solar photovoltaic) reported in the literature. On average, it can be observed that, for e-methanol and for e-ammonia (under the best-case scenario for engine manufacturing), irradiation levels above approximately 2200 kWh/m²/year are required to produce ZNZFs, which translates into only a limited number of eligible regions, as shown in Image 1:

- South America: a large part of northeastern Brazil, the Atacama Desert region, and the coastal strip of Peru;
- North America: most of Mexico and the southwestern United States;
- Africa: most of the continent, except for a more equatorial belt;
- Asia: most of the Arabian Peninsula and parts of Iran, Pakistan, Afghanistan, and western China;
- Oceania: most of Australia.

In the case of e-ammonia with average use-phase emissions, the annual irradiation required for eligibility would exceed 2500 kWh/m²/year, further reducing the number of viable regions.

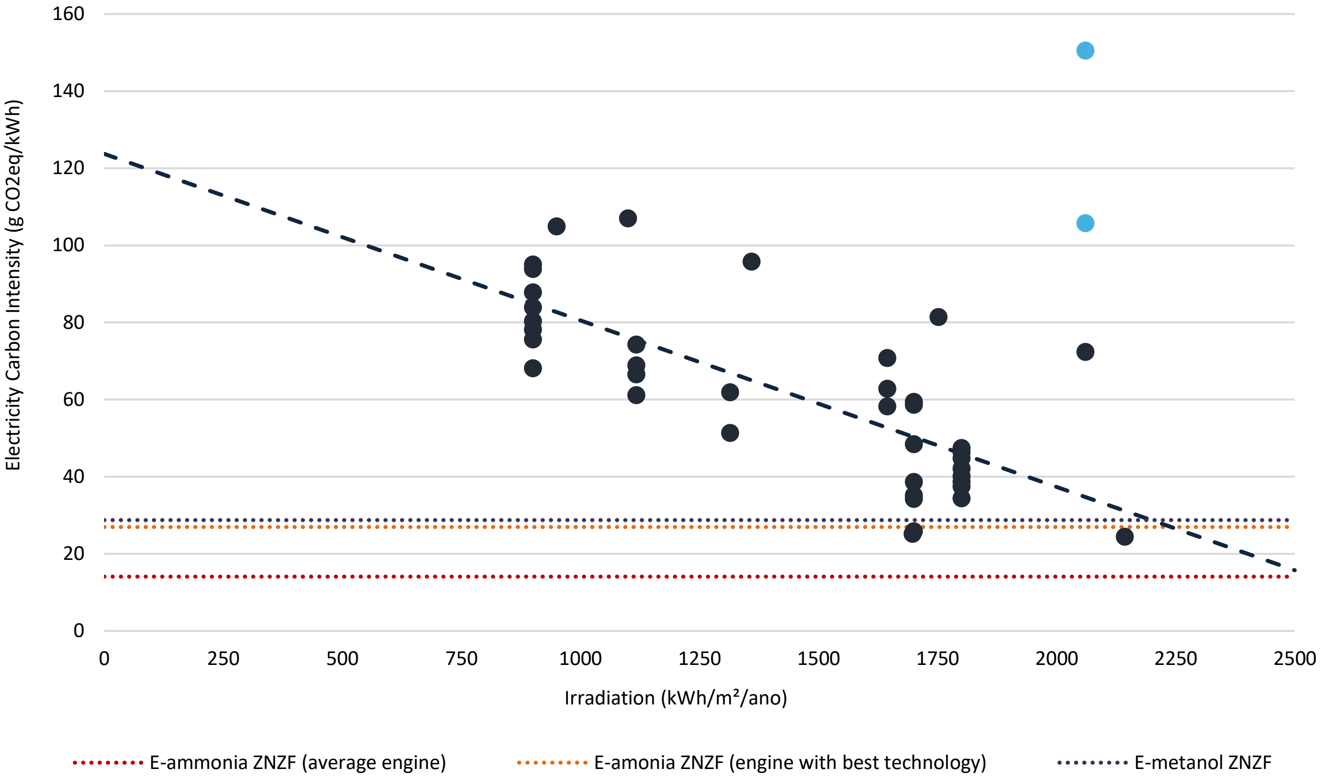

Figure 2 – Correlation between embodied emissions of solar photovoltaic energy and the irradiation factor reported in the literature.

Note: The horizontal lines represent the maximum electricity carbon intensity, calculated from Figure 1, for the fuels to meet the ZNZF thresholds. Light blue indicates literature values that were not included in the linear regression.

Source: Own elaboration based on Hsu et al. (2012)

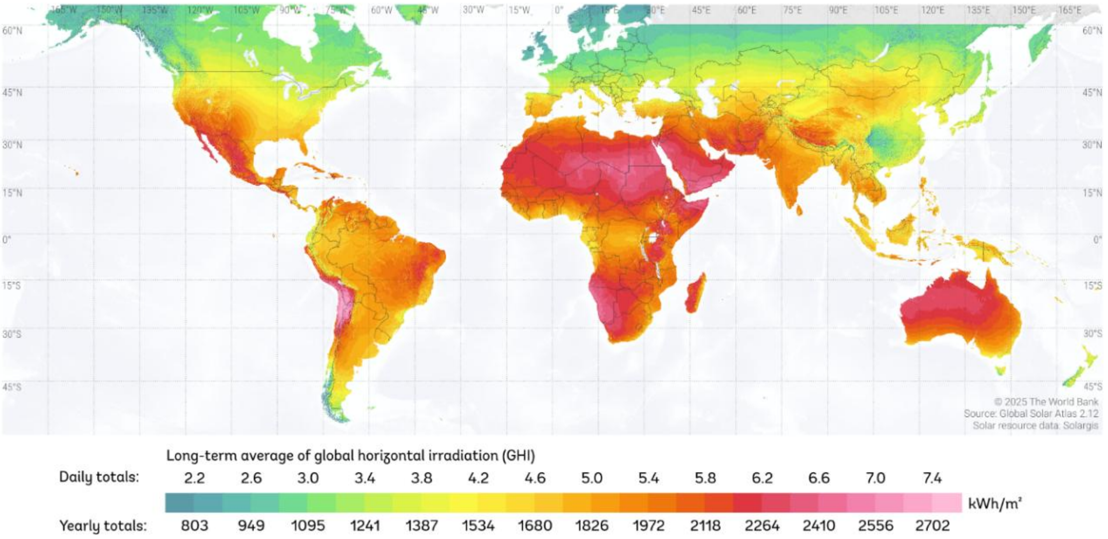

Image 1- Global Solar Irradiation

Source: Global Solar Atlas.

Figure 3 presents the carbon intensity of electricity as a function of the wind capacity factor reported in the literature. In this case, it can be observed that, on average, the criteria for ZNZF production are met worldwide for e-methanol and for e-ammonia (under the best-case scenario for engine manufacturing).

For e-ammonia with average use-phase emissions, however, wind capacity factors above approximately 13% are required for eligibility, excluding certain intertropical regions, inland areas of Europe and Asia, and the western part of North America, as shown in Image 2.

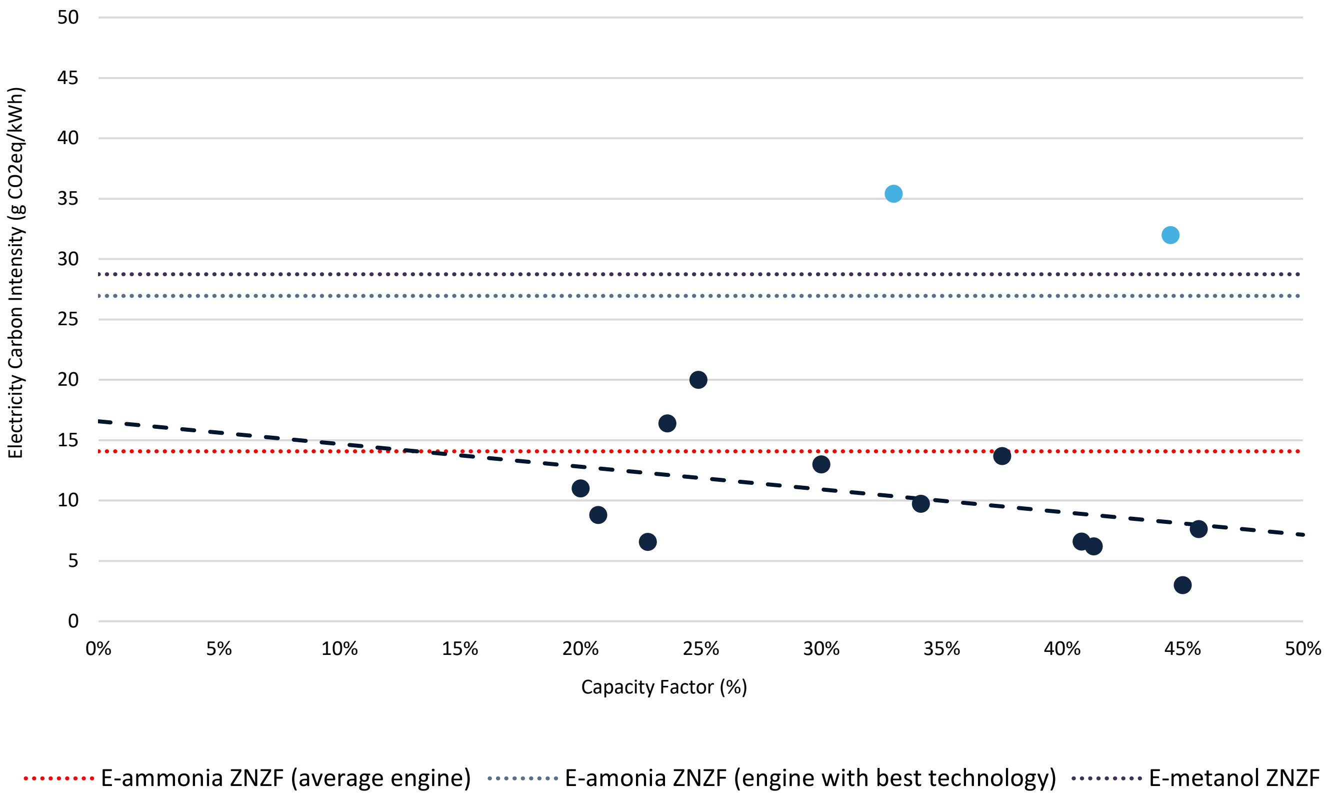

Figure 3 – Correlation between embodied emissions of wind energy and the capacity factor reported in the literature.

Note: The horizontal lines represent the maximum electricity carbon intensity, calculated from Figure 1, required for the fuels to meet the ZNZF thresholds. Light blue indicates literature values that were not included in the linear regression.

Source: Own elaboration based on Arvesen e Hertwich (2012)

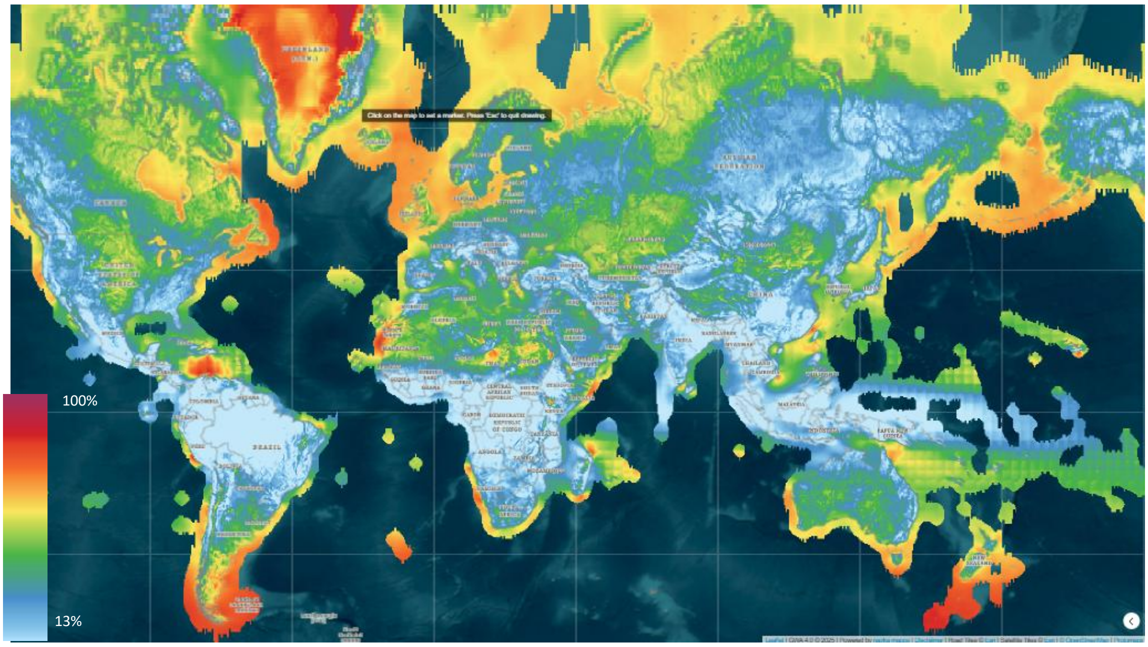

Image 2 – Global wind capacity factor for IEC Class III turbines.

Fonte: Generated from the Global Wind Atlas.

5. Final Considerations

The results presented in this study show that factors such as annual irradiation (especially) and wind capacity factor significantly affect the carbon intensity of e-fuels produced from renewable electricity. To meet the minimum threshold established for the eligibility of e-ammonia and e-methanol as ZNZFs, it is necessary to take these parameters into account in order to avoid regional distortions. It is therefore recommended that the definition of minimum regional average parameters for the eligibility of these fuels be addressed within the scope of guideline discussions in international programs.

It should be noted that the results presented here are simplifications based on linear correlations between the analyzed parameters and embodied emissions. In this sense, this document is not intended to be prescriptive regarding the exact numerical values of annual irradiation or wind capacity factor thresholds to be adopted, but rather to highlight the relevance of these factors in calculating the carbon intensity of e-fuels, demonstrating the need for the topic to be explored in greater depth in future discussions.

6. References

ANEKE, Mathew; WANG, Meihong. Potential for improving the energy efficiency of cryogenic air separation unit (ASU) using binary heat recovery cycles. Applied Thermal Engineering, *[S. l.]*, v. 81, p. 223–231, 2015. DOI: 10.1016/j.applthermaleng.2015.02.034.

ARVESEN, Anders; HERTWICH, Edgar G. Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs. Renewable and Sustainable Energy Reviews, 2012. DOI: 10.1016/j.rser.2012.06.023.

BIANCHI, Fiammetta Rita; RISSO, Riccardo; CARDONA, Lucia; BOVE, Dario; CANNIZZARO, Fabio; BONARDI, Luca; PALMISANI, Ezio; BOSIO, Barbara. Feasibility analysis of e-Hydrogen, e-Ammonia and e-Methanol synthesis compared with methane to fuel production. Fuel, *[S. l.]*, v. 384, 2025. DOI: 10.1016/j.fuel.2024.133938.

BONNET-CANTALLOUBE, Bastien; ESPITALIER-NOËL, Marie; FERRARI DE CARVALHO, Priscilla; FONSECA, Joana; PAWELEC, Grzegorz. Clean Ammonia in the Future Energy System. [s.l: s.n.]. Disponível em: https://hydrogeneurope.eu/wp-content/uploads/2023/03/2023.03_H2Europe_Clean_Ammonia_Report_DIGITAL_FINAL.pdf?utm_source=chatgpt.com. Acesso em: 24 ago. 2025.

BRYNOLF, Selma; FRIDELL, Erik; ANDERSSON, Karin. Environmental assessment of marine fuels: Liquefied natural gas, liquefied biogas, methanol and bio-methanol. Journal of Cleaner Production, *[S. l.]*, v. 74, p. 86–95, 2014. DOI: 10.1016/j.jclepro.2014.03.052.

D'ANGELO, Sebastiano Carlo; COBO, Selene; TULUS, Victor; NABERA, Abhinandan; MARTÍN, Antonio José; PÉREZ-RAMÍREZ, Javier; GUILLÉN-GOSÁLBEZ, Gonzalo. Planetary Boundaries Analysis of Low-Carbon Ammonia Production Routes. ACS Sustainable Chemistry and Engineering, *[S. l.]*, v. 9, n. 29, p. 9740–9749, 2021. DOI: 10.1021/acssuschemeng.1c01915.

EIA. Carbon Dioxide Emissions Coefficients. 2024.

Argonne National Laboratory. GREET model. 2023.

HANK, Christoph; LAZAR, Lukas; MANTEI, Franz; OUDA, Mohamed; WHITE, Robin J.; SMOLINKA, Tom; SCHAADT, Achim; HEBLING, Christopher; HENNING, Hans Martin. Comparative well-to-wheel life cycle assessment of OME3-5 synfuel production via the power-to-liquid pathway. Sustainable Energy and Fuels, *[S. l.]*, v. 3, n. 11, p. 3219–3233, 2019. DOI: 10.1039/c9se00658c.

HSU, David D.; O'DONOUGHUE, Patrick; FTHENAKIS, Vasilis; HEATH, Garvin A.; KIM, Hyung Chul; SAWYER, Pamala; CHOI, Jun Ki; TURNEY, Damon E. Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation: Systematic Review and Harmonization. Journal of Industrial Ecology, *[S. l.]*, v. 16, n. SUPPL.1, 2012. DOI: 10.1111/j.1530-9290.2011.00439.x.

INGWERSEN, Anna; HAHN MENACHO, Alvaro J.; PFISTER, Stephan; PEEL, Jonathan N.; SACCHI, Romain; MORETTI, Christian. Prospective life cycle assessment of cost-effective pathways for achieving the FuelEU Maritime Regulation targets. Science of the Total Environment, *[S. l.]*, v. 958, 2025. DOI: 10.1016/j.scitotenv.2024.177880.

IPCC. Climate change 2014: mitigation of climate change. Working Group III contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. [s.l.] : Cambridge University Press, 2014.

IPCC. Climate Change 2022: Mitigation of Climate Change. Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Mitigation of Climate Change. [s.l: s.n.]. Disponível em: www.ipcc.ch.

KRUSE, C. James; PROTOPAPAS, Annie; OLSON, Leslie E.; DONELAN, Mike; HUTSON, Nathan. Current Operating Environment. *Em*: Marine Highway Transport of Toxic Inhalation Hazard Materials. Washington: National Cooperative Freight Research Program, 2012.

LI, Shuo; FLYNN, M. R. Cooling tower plume abatement and plume modeling: a review. Environmental Fluid MechanicsSpringer Science and Business Media B.V., , 2021. DOI: 10.1007/s10652-021-09790-w.

PACIFIC ENVIRONMENT; CSC; EDF. Review of current literature on tank-to-wake nitrous oxide emissions from ammonia-fueled engines. [s.l] 2025. Disponível em: https://cleanshipping.org/wp-content/uploads/2025/02/MEPC-83-7-23-Review-of-current-literature-on-tank-to-wake-nitrous-oxide-emissions-fromammonia-fueled-en.-Pacific-Environment-CSC.pdf. Acesso em: 24 ago. 2025.

SCHULZE, Christine; THIEDE, Sebastian; HERRMANN, Christoph. Life Cycle Assessment of Industrial Cooling Towers. *Em*: Sustainable Production, Life Cycle Engineering and Management. [s.l.] : Springer, 2019. p. 135–146. DOI: 10.1007/978-3-319-92237-9_15.

WINGD. WinGD delivers exceptional results in full-load X-DF-A ammonia engine test. 2025. Disponível em: https://wingd.com/news-media/news/wingd-delivers-exceptional-results-in-full-load-x-df-a-ammonia-engine-test. Acesso em: 24 ago. 2025.