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Environmental Life Cycle Analysis of an Ammonia-Ethanol Fueled Internal Combustion Engine (ICE) for Power Generation

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Abstract

Climate change and other environmental impacts have been an enormous worldwide concern in recent decades. Decarbonizing strategic and economic industries is mandatory. Using carbon-free fuels such as ammonia (NH_3) has been promoted as a promising solution for decarbonizing both energy and industrial sectors. The use of biofuels has also been encouraged as an attractive alternative to replace conventional petroleum-based fuels in transportation. Therefore, the present study evaluates the environmental profile of using ammonia-ethanol blends in internal combustion engines (ICE) for power generation systems through a life cycle assessment (LCA) framework using the OpenLCA v1.10.3 software. The experiments were conducted in a single-cylinder spark-ignition engine that employs direct injection using three different fuel compositions (in mole fraction) of ethanol/ammonia (75/25, 50/50, and 25/75), with two different intake pressures (0.5 and 1 bar) at 1000 rpm. The functional unit (FU) was set at 1 kWh. The GWP results for 0.5 bar of intake pressure are between 0.07 and 0.95 kg CO_2/kWh. The scenario running on Brazilian ethanol and green ammonia is the most environmentally friendly case. The carbon footprint for ethanol/ammonia-based ICE at 1 bar fluctuates between 0.052 and 0.68 kg CO_2/kWh. Similarly, regarding GWP, there is a slight difference in Fossil Depletion Potential (FDP) when using ethanol from Brazil and ethanol from Ecuador due to the lack of circular economy strategies in Ecuador's agriculture, compared to Brazil. Regarding the contribution analysis, for a 50% green ammonia – 50% ethanol scenario for power generation, ethanol production has the highest contribution for global warming, fossil depletion, and freshwater eutrophication potential impacts. Compared to the analysed environmental impacts, some of our proposed scenarios depict better performance than the average electricity production in the United Kingdom, France and Europe. Therefore, ethanol-ammonia fuel-based for power generating systems could be an important option to contribute to the decarbonization of the electric sector.

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Keywords: carbon footprint, life cycle assessment, power generation systems, ammonia-ethanol blend, electric sector.

Introduction

Climate change has been a significant worldwide concern in recent decades. From a global perspective, energy consumption is the most substantial origin of greenhouse gas (GHG) emissions from daily human activities [1]. Two-thirds of global GHG emissions are attributed to the combustion of fossil resources from human activities such as heating, electricity generation, transportation, and industrial processes [2]. The prevailing energy paradigm society has adopted revolves around the extraction and consumption of these resources. Since the early stages of the Industrial Revolution, the utilization of energy derived from fossil fuels has been consistently escalating [3]. Moreover, the global oil demand is anticipated to reach its zenith in the coming four years until 2028, when it is set to slow markedly due to more stringent fuel efficiency regulations, the expansion of the electric vehicle market, and fundamental shifts in global economies [4]. Thus, it is imperative that the world economy and our planet's sustainable development no longer rely on these finite fossil resources. Continued dependence on these resources would undeniably exacerbate global warming [5], leading to severe consequences like escalating sea levels, soil desertification, intensified extreme weather events, and heightened risks of floods [6,7].

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The global community is currently observing an increasing demand for cost-effective and enduring energy resources that align with sustainability principles. The seventh and thirteenth objectives among the Sustainable Development Goals (SDGs) established by the United Nations are dedicated to attaining sustainable energy for developmental purposes and essential measures to address climate-related concerns [8]. Thus, there is a need to increase the use of renewable energy sources, which are expected to increase globally as governments attempt to achieve their environmental and regulatory responsibilities [9]. The use of low-carbon fuels and biofuels (either partially or entirely) blended with fossil fuels in internal combustion engines [10–15] has been seen as an attractive alternative to replace conventional petroleum-based fuels to diminish greenhouse emissions in several sectors [16–18]. For instance, biofuels have a significant role in reducing carbon emissions in the transportation sector, while the transition to other renewable energy sources in this sector is presently slower than in other industries [19]. Altaie et al. analysed the effects on diesel engine performance by blending methyl oleate (MO) with palm oil methyl ester (PME). This research concluded that due to the low oxygen content of pure PME reflected in a decrease in soot emissions and brake-specific fuel consumption (BSFC) [14]. Costa et al. compared binary fuel combinations such as ethanol/gasoline or biogasoline/gasoline with ternary fuel blends consisting of ethanol/biogasoline/gasoline in terms of torque, power, fuel consumption, efficiency, and emissions. The results showed that using a blend of ethanol and biogasoline as additives, with a maximum inclusion rate of 10%, generally resulted in enhanced efficiency and reduced emissions, such as carbon monoxide (CO) and hydrocarbons (HC), compared to using pure gasoline [12]. Dhande et al. investigated the production of ethanol derived from discarded pomegranate and its impact on the performance of a spark-ignition engine under various ethanol-gasoline blends. The inclusion of ethanol resulted in improvements in volumetric efficiency and overall mechanical performance [15]. Recently, Pillai et al. evaluated the impacts of diethyl ether on performance parameters and emissions characteristics in a conventional variable compression ratio (VCR) diesel engine. The biodiesel was derived from rice bran oil and cotton seed oil, with the addition of diethyl ether, using four distinct blends. The findings revealed that incorporating 5% diethyl ether with biodiesel blends led to enhancements in brake thermal efficiency and reductions in brake-specific fuel consumption, carbon dioxide emissions, and oxides of nitrogen emissions [13].

Based on a mobility model result for the 2 °C scenario (2DS) reported by the International Energy Agency (IEA), it is projected that biofuels will account for approximately 30.7% of the overall consumption of transportation fuels by 2060 [20]. Bioethanol stands out as a highly appealing option due to its potential to replace conventional fuels [21–24]. Consequently, numerous nations, such as the United States [25–27], Brazil [28–31], China [32–34], Canada [35,36], India [37–40], Argentina [31,41], Ecuador [42,43] and several European Union member states [44–48], have already made official commitments to reduce the dependence on fossil fuels and increase the implementation of bioethanol. Nonetheless, large-scale bioethanol manufacturing encounters significant barriers in terms of shortage of feedstocks and production costs [20,49–51].

Carbon-free fuels such as hydrogen and ammonia (NH_3) are also being promoted as a promising solution for decarbonizing other sectors such as the energy and industrial sectors. Hydrogen stands as a promising eco-friendly energy carrier with the potential to supplant fossil fuels. The production of hydrogen can stem from various feedstocks and technological blends, leading to varying levels of greenhouse gas emissions throughout its lifecycle [52]. Nonetheless, the current storage and distribution issues associated with hydrogen pose a significant challenge to its implementation.

On the other hand, ammonia is a carbon-free carrier presently gaining significant attention from academic institutions, governmental entities, and industrial corporations alike. Ammonia is seen as an alternative fuel for both stationary power generation and for decarbonizing the international shipping sector due to the feasibility of implementing exhaust gas after-treatment [53]. The feasibility of employing ammonia in diverse power generation systems is currently being closely examined across varying scales of power generation [9]. Currently, ammonia is not massively employed as a vehicle fuel due to its production process, which heavily relies on natural gas, a non-zero-carbon fuel source. Moreover, prominent obstacles prevent ammonia from gaining traction as a fuel in the automotive sector, such as its limited flammability range, elevated ignition temperature, and elevated heat of vaporization. Recent research have analysed alternative solutions to these barriers, making a significant contribution to the global market while concurrently mitigating greenhouse gas emissions over the medium term in the automotive sector [54–59]. Nevertheless, the utilization of ammonia as a liquid fuel needs more investigation, especially when considering an integrated approach that allows for the impacts of different ammonia production methodologies. Hence, one of the objectives of this study is to consolidate these aspects within a life cycle assessment (LCA) framework, aiming to evaluate the environmental profile of using ammonia-ethanol blend in internal combustion engines (ICE) for power generation systems.

The Life Cycle Assessment is an extensively utilized instrument for evaluating the ecological efficiency of a product, procedure, or service throughout its entire life cycle. The environmental impacts of using ammonia as a fuel vector for private road transport [60,61] and other purposes have been evaluated from a life cycle perspective in a variety of works [62–66]. For instance, Bicer and Dincer [61] assessed the environmental profile of using ammonia as an energy carrier for passenger cars and plants power generation in power plant systems. The findings show that ammonia-powered vehicles emit less grams (100 g) of carbon dioxide per travelled kilometre than a gasoline-powered vehicle (270 g) and a diesel-powered car (230 g). Regarding power generation systems, the use of ammonia can decrease the global warming potential (GWP) if compared with natural gas power plants. Razon et al. examined the ecological implications of producing and burning methane and ammonia in a tangential swirl burner for heat generation [66]. The results depict that employing ammonia from conventional current methods would yield more adverse global warming potentials than using methane to generate an equivalent amount of heat.

As mentioned above, the use of ammonia in power generation systems, including fuel cells, internal combustion engines, and gas turbines, is being analysed at various power scales [9], with significant endeavours to address emissions and achieve dependable and consistent procedures [67]. Considerable advancements have been achieved in this area, resulting in the establishment of global initiatives to create innovative technologies to showcase ammonia's capacity for storing renewable energy generated from wind, solar, and marine resources [68]. Despite previous research, no LCA study has incorporated an operational emissions profile to determine the ecological consequences of using ammonia-ethanol blends in power generation systems. Therefore, this study aims to evaluate the environmental profile of ammonia-ethanol blend as a substitute fuel for internal combustion engines (ICE) for power generation systems from a comprehensive life cycle perspective. The analysis considers different fuel compositions of ethanol/ammonia with a homogeneous injection strategy at different intake pressures (0.5 and 1 bar).

Materials and Methods

This study is the first to offer insights into using ethanol blended with ammonia in a single-cylinder spark-ignition engine that employs direct injection. The experiments were conducted using three different fuel compositions (in mole fraction) of ethanol/ammonia: 75/25, 50/50, and 25/75. A homogeneous injection strategy was conducted with two different intake pressures, 0.5 and 1 bar at 1000 rpm. The scope of this work considers a cradle-to-gate approach, and the functional unit (FU) is set at 1 kWh (Fig. 1).

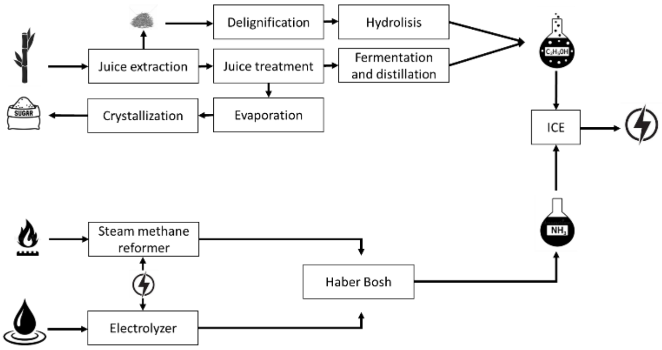

Fig. 1. System boundaries for the LCA of an ammonia-ethanol fuelled ICE for power generation (1 kWh).

This study considered green ammonia from renewable energy sources (wind, solar, and hydro) and grey ammonia produced from natural gas since resource extraction. The ammonia production processes inventory was obtained from Boero et al. [69], which considers Australia (AUS), Morocco (MR), Chile (CH), Brazil (BR), and the United Kingdom (UK) as countries with green and grey ammonia production facilities (Table 1). Green ammonia can be produced in Morocco, Chile, Brazil, Australia, and the United Kingdom. Grey ammonia is made in the United Kingdom. The ethanol production processes inventory was obtained from Arcentales et al. [43] and the Ecoinvent 3.7.1 database [70] for a case study in Ecuador and Brazil, respectively (Table 1). The internal combustion engine was from the Ecoinvent 3.7.1 database [70]. The emissions values of the ammonia-ethanol blend combustion are obtained from an experimental study conducted in a single-cylinder long-stroke spark-ignition engine with a flat piston and a pent-roof chamber [71]. The engine specifications are indicated in Table 2. The exhaust gases of the engine combustion were examined using a Gasmet Fourier Transform Infrared (FTIR) spectrometer to evaluate the levels of H_2O, CO_2, NO, CO and NH_3. The life cycle assessment was modeled using the OpenLCA v1.10.3 software, covering six environmental impacts from the

ReCiPe midpoint methodology through a hierarchical (H) perspective: global warming potential (GWP), fossil depletion potential (FDP), freshwater eutrophication potential (FEP), ozone depletion potential (ODP), terrestrial acidification potential (TAP), and photochemical oxidation formation potential (POFP), as shown in Table 3.

Table 1. Ammonia and ethanol production characteristics

Process	Color	Country	Description
Ammonia production	Green	United Kingdom	Power to ammonia via electrolysis process, electricity from wind.
		Chile	Power to ammonia via electrolysis process electricity from photovoltaics.
		Australia	Power to ammonia via electrolysis process, electricity from wind.
		Brazil	Power to ammonia via electrolysis process, electricity from hydropower.
		Morocco	Power to ammonia via electrolysis process, electricity from wind.
	Grey	United Kingdom	Methane to ammonia via steam methane reforming process
Ethanol production	NA	Ecuador	Ethanol from sugarcane juice mixed with molasses.
	NA	Brazil	Modern sugarcane mills processing sugarcane stalks for the production of ethanol and electricity

Table 2. Engine characteristics

Type of engine	SI (EPC LC)
Displaced volume (L)	0.535
Stroke (mm)	115
Bore (mm)	77
Compression ratio	11.75
Number of valves	4
Coolant and oil temperatures (°C)	80

Table 3. Midpoint impact indicators selected with their brief definition.

Midpoint impact indicator	Definition*
Global warming potential (GWP)	Cumulative radiative over a specified time horizon results from greenhouse gas emissions.
Fossil depletion potential (FDP)	Over-extraction of all fossil resources.
Freshwater eutrophication potential (FEP)	Freshwater quality degradation.
Ozone depletion potential (ODP)	Reduction in the density of the stratospheric ozone layer.
Photochemical oxidant formation potential (POFP)	Quantifies the photochemical reactions of volatile organic compounds causing adverse effects on human health.
Terrestrial acidification potential (TAP)	This impact measures the increase in the acidity of soil due to atmospheric pollutants such as SO2 and NOx.

*Impact categories definition were obtained from [72,73]

The scenarios are modelled as a function of two different intake pressures (0.5 and 1 bar), two different ammonia production (grey and green), and three different ethanol/ammonia blends (75/25, 50/50, and 25/75) as shown in Table 4. The performance and pollutant emissions were assessed across various fuel compositions while maintaining a constant indicated mean effective pressure (IMEP) as indicated in [71]. In the latter, the tests were conducted based on two injection methodologies to achieve homogeneous and stratified conditions, coupled with three varying intake pressures: 0.5, 1.0, and 1.5 bar. A complete input – output table for 25% ethanol Brazil - 75% ammonia UK blend scenario for an intake pressure of 0.5 bar can be seen in the supporting information.

Table 4. Proposed scenarios for the two different intake pressures analyzed with their respective ethanol/ammonia blends on the ICE and NH_3, NO_x, and CO_2 emissions at 1000 rpm and 80°C

Intake pres.	Ethanol Intake (mol/mol)	Ammonia intake (mol/mol)	Fuel consumption	NH_3	NO_x	CO_2
(bar)	(%)	%	g/kWh	g/kWh	g/kWh	g/kWh
0.5	75%	25%	438.71	0.978	27.00	768.63
0.5	50%	50%	471.4	3.42	31.95	672.02
0.5	25%	75%	607.69	18.28	32.16	539.0
1	75%	25%	331.75	0.653	27.85	636.32
1	50%	50%	349.73	1.89	32.63	557.87
1	25%	75%	438.18	5.69	29.87	413.91

Results and Discussions

Characterization analysis

The following results (Figs. 2-7) correspond to the homogeneous injection strategy at 0.5 and 1 bar. The variability in the results is associated with ethanol/ammonia compositions and their geographical production conditions, as seen in Figs. 2-7. The carbon footprint (GWP) of an ethanol/ammonia-based ICE at 0.5 bar fluctuates between 0.07 and 0.95 kg CO_2/kWh. The lowest impact is shown by the scenario using ethanol from Brazil and ammonia from the United Kingdom produced from renewable sources (wind) with 0.07 kg CO_2/kWh. The scenario using ethanol from Brazil and grey ammonia produced in the United Kingdom with a higher proportion of ammonia (75%) depicts the worst environmental performance regarding GWP impact. It is noteworthy that GWP impact is mainly affected by the ammonia production process when natural gas is used as a raw material to produce ammonia. When green ammonia is produced, ethanol production has a more significant impact on GWP. For comparison purposes, we ran a simulation to evaluate the GWP performance of the average electricity production mix in France, the United Kingdom, and Europe, showing values of 0.079, 0.31, and 0.39 kg CO_2/kWh, respectively. The latter shows that some of our scenarios depict GWP results below the value for electricity production in the United Kingdom. Regarding the GWP of an ethanol/ammonia-based ICE at 1 bar, the results fluctuate between 0.052 and 0.68 kg CO_2/kWh. There is a noticeable reduction in the results when the intake pressure is increased. Moreover, the GWP decreases with more ethanol proportion in the blend.

These results, which show that GWP is reduced with ethanol-ammonia mixtures, align with the results obtained by Yapicioglu et al. [74] and Al-Baghdadi [75]. The latter author found that introducing additional hydrogen into the ethanol-air blend would enhance the combustion process, decrease the specific fuel consumption, and reduce emissions of harmful pollutants. In the same way, Yapicioglu et al. [74] analyzed the performance of hydrogen and ammonia combustion with alternative fuels such as ethanol, methanol, and propane for power generation systems. They found that augmenting the proportion of clean fuel in the blend would decrease CO_2 emissions when combined with a combustion enhancer. On the other hand, in aspects related to transport systems, there are no studies on ethanol blended with ammonia. However, studies such as Boero et al. [59] and Arcentales et al. [76] analyze the use of ammonia and the use of ethanol-gasoline blends in road passenger vehicles, respectively. Boero et al. [59] found a significant reduction (70%) for GWP compared to a vehicle fueled with gasoline. Arcentales et al. [76] compared an ethanol-gasoline flex-fuel versus an electric vehicle and found that the environmental friendliness of the flex-fuel vehicle can vary depending on the percentage of renewable electricity used to charge the electric vehicle. Moreover, they found that the significance of the resource takes precedence over the energy carrier, mainly when the resource exhibits low carbon emissions. Another important aspect that can be noted from these results is the difference in GWP when using ethanol from Brazil and ethanol from Ecuador, even though the production processes are very similar. This difference is due to Ecuador's lack of precision agriculture and industrial symbiosis, compared to Brazil [43].

Regarding the FDP of an ethanol/ammonia-based ICE at 0.5 bar, the values range between 0.018 and 0.43 kg oil/kWh, as seen in Fig. 3. Similar to GWP results, the highest FDP impact is depicted by the scenario using ethanol from Brazil and grey ammonia produced in the United Kingdom with 0.43 kg oil/kWh. The best environmental FDP performance is shown by the system using ethanol from Brazil and green ammonia from the United Kingdom with 0.018 kg oil/kWh. The average electricity production mix in France, the United Kingdom, and Europe show values of 0.031, 0.14, and 0.12 kg oil/kWh, respectively. The FDP of an ethanol/ammonia-based ICE at 1 bar has a similar behaviour, and its results fluctuate between 0.013 and 0.31 kg oil/kWh, as seen in Fig. 3. Similarly to GWP, there is a slight difference in FDP when using ethanol from Brazil and ethanol from Ecuador. This difference could be related to the need for circular economy strategies in Ecuador's agriculture, compared to Brazil [43]. Although no studies analyze the fossil depletion potential in ethanol-ammonia blends for electricity generation, we can reference the study developed by Boero et al. [59]. They also showed a substantial reduction in FDP (almost 70%) when using ammonia as fuel compared with a gasoline engine vehicle for road transportation.

Considering the FEP results at 0.5 bar, the values range between 0.000032 and 0.00025 kg P/kWh as seen in Fig. 4. The worst FEP performance is depicted by the scenario using ethanol from Ecuador and green ammonia produced in Morocco (0.00025 kg P/kWh), followed by the scenario using ethanol from Ecuador and green ammonia from Chile (0.00022 kg P/kWh), both using an ethanol/ammonia blend of 25%/75%. The average electricity production mix in France and the United Kingdom shows a better FEP impact with values of 0.000016 and 0.000051 kg P/kWh, respectively. The FEP result for the average electricity production mix in Europe reports a value of 0.00043 kg P/kWh. Regarding the FEP of an ethanol/ammonia-based ICE at 1 bar, the values range between 0.000023 – 0.00016 kg P/kWh. Comparing the FEP results between Ecuadorian and Brazilian ethanol, it is observed, although minimal, a difference between the two countries despite having similar production processes. Again, this is due to the lack of precision and industrial symbiosis in Ecuadorian agriculture.

It is also important to notice that most of the scenarios where renewable energy is used for ammonia production have a higher FEP impact when the ammonia blend percentage is higher compared to the systems that use more proportion of ethanol. This could be related to the emissions of phosphates generated during waste treatment processes of copper, hard coal, and lignite mining in ammonia production, as concluded by Boero et al. [69].

The ODP values at 0.5 bar range between 1.04e-08 and 6.53e-08 kg CFC-11/kWh, as seen in Fig. 5 The worst ODP value is reported by the scenario using ethanol from Brazil and grey ammonia (natural gas) produced in United Kingdom (6.53e-08 kg CFC-11/kWh), followed by the scenario using ethanol from Ecuador and ammonia from Chile (3.81e-08 kg CFC-11/kWh), both scenarios using an ethanol/ammonia blend of 25%/75%. The best ODP performance is obtained by the scenario using ethanol from Brazil and green ammonia produced in the United Kingdom. The average electricity production mix in the United Kingdom, France, and Europe show values of 1.69e-08, 8.45e-09, and 1.74e-08 kg CFC-11/kWh, respectively. Regarding the ODP of an ethanol/ammonia-based ICE at 1 bar, the results fluctuate between 4.69e-09 - 2.72e-08 kg CFC-11/kWh. Thus, there is a noticeable reduction in the results when the intake pressure is increased. Based on the results, it is observable that those scenarios with ammonia produced from methane have higher ODP than those using ammonia based on electrolysis. This similar tendency is observed in the study by Boero et al. [69]. On the other hand, it is also noticeable that scenarios with a higher blend proportion of ethanol have a better environmental result. This aligns with Borrion et al. [77], who concluded that a higher use of ethanol-blended fuel offers an advantage concerning its impact on ozone depletion potential.

In the case of POFP, the values at 0.5 bar range between 0.032 and 0.047 kg NMVOC/kWh, as seen in Fig. 6. The scenarios with the highest POFP values are reported by ethanol from Ecuador and green ammonia produced in Chile (0.047 kg NMVOC/kWh) and ethanol produced in Ecuador and green ammonia from Morocco (0.047 kg NMVOC/kW), both scenarios using an ethanol/ammonia blend of 25%/75%. The best POFP performance is obtained by the scenario using ethanol from Brazil and grey ammonia produced in the United Kingdom with 0.032. The average electricity production mix in the United Kingdom, France, and Europe show values of 0.00061, 0.00022, and 0.00086 kg NMVOC/kWh, respectively. Regarding the POFP of an ethanol/ammonia-based ICE at 1 bar, the results fluctuate between 0.031 and 0.041 kg NMVOC/kWh. The ICE reported the best scenario using ethanol produced in Brazil and grey ammonia from the United Kingdom, with 0.031 kg NMVOC/kWh at 75%/25% ethanol/ammonia blend. For the respective analysis of the scenarios, it is observable that the higher the ammonia proportion, the greater the POFP. This correlates with the results obtained by Boero et al. [69], which state that nitrogen compound emissions are naturally associated with electricity generation using ammonia as a fuel source.

The TAP values at 0.5 bar range between 0.022 and 0.069 kg SO_2/kWh as seen in Fig. 7. The scenarios with the highest TAP values are reported by ethanol from Ecuador and green ammonia produced in Chile (0.069 kg SO_2/kWh) and ethanol produced in Ecuador and green ammonia from Morocco (0.069 kg SO_2/kWh), both scenarios using an ethanol/ammonia blend of 25%/75%. The system with the best environmental performance is obtained using ethanol from Brazil and grey ammonia produced in the United Kingdom with 0.022 kg SO_2/kWh using an ethanol/ammonia blend of 75%/25%. The average electricity production mix in the United Kingdom, France, and Europe show values of 0.00077, 0.00031, and 0.00163 kg SO_2/kWh, respectively. Regarding the TAP of an ethanol/ammonia-based ICE at 1 bar, the results fluctuate between 0.020 – 0.035 kg SO_2/kWh. The TAP performance of this ICE at 1 bar is likely as 0.5 bar, obtaining the highest result in the scenario with ethanol from Ecuador and green ammonia produced in Chile (0.035 kg SO_2/kWh). Based on these results, it is important to notice that those scenarios with less ammonia proportion reflect a better environmental impact. The latter conclusion is aligned with the results by Boero et al. [69], who indicated that small-scale production ammonia is preferred compared to a large-scale production because it eliminates any ammonia emissions associated with storage and transportation, consequently increasing TAP.

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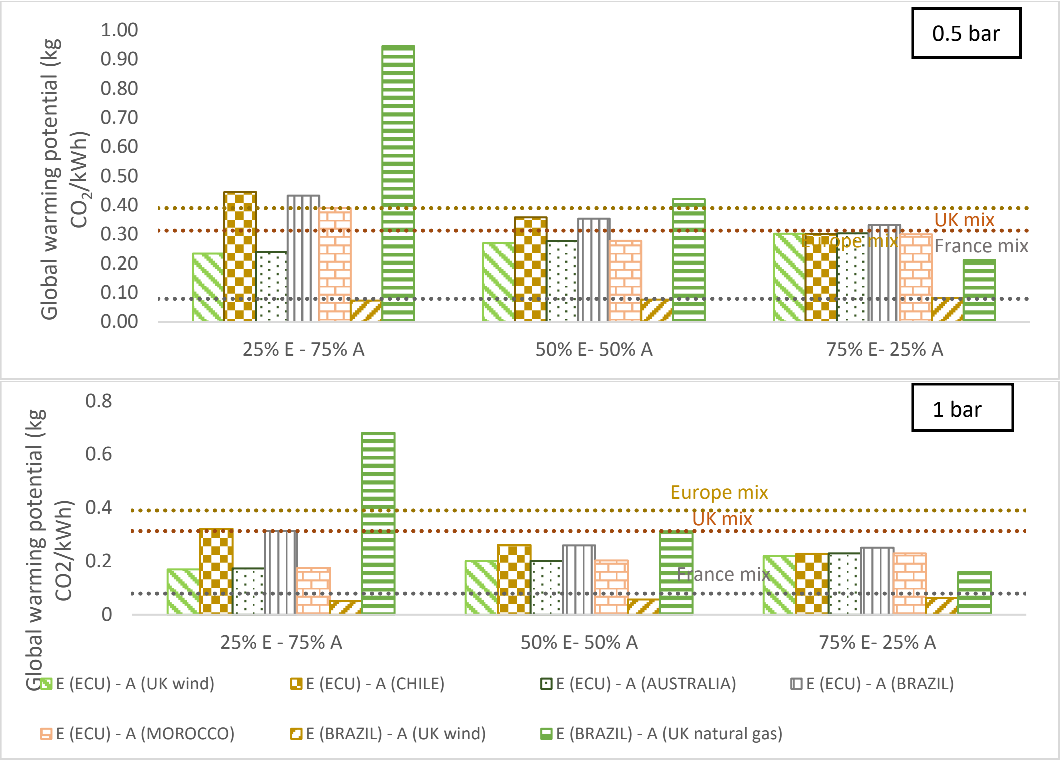

Fig. 2. Global warming potential results for different ethanol/ammonia compositions at 0.5 and 1 bar of intake pressure for an ICE power generation system.

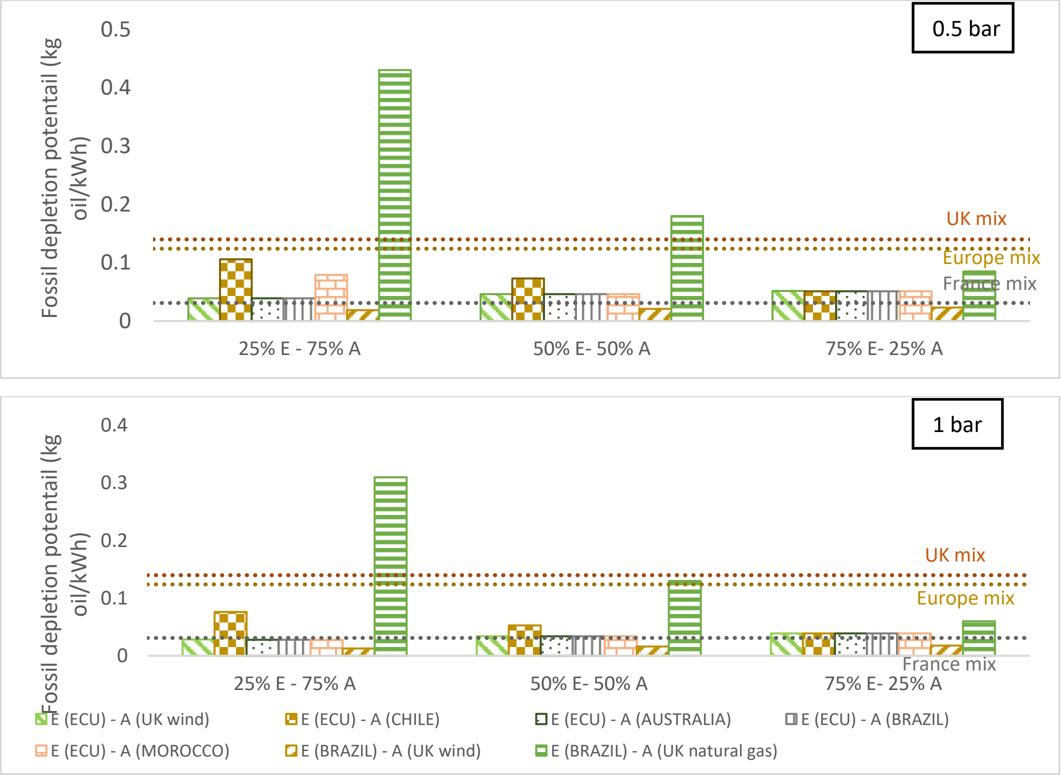

Fig. 3. Fossil depletion potential results for different ethanol/ammonia compositions at 0.5 and 1 bar of intake pressure for an ICE power generation system.

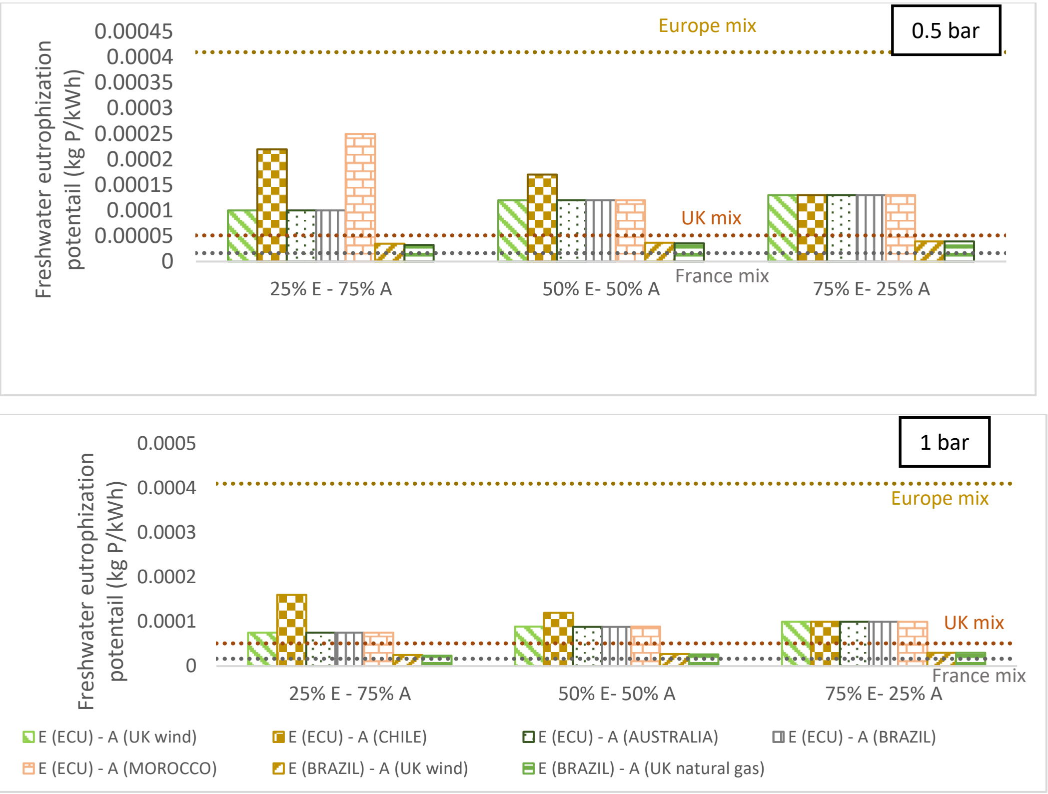

Fig. 4. Freshwater eutrophication potential results for different ethanol/ammonia compositions at 0.5 and 1 bar of intake pressure for an ICE power generation system.

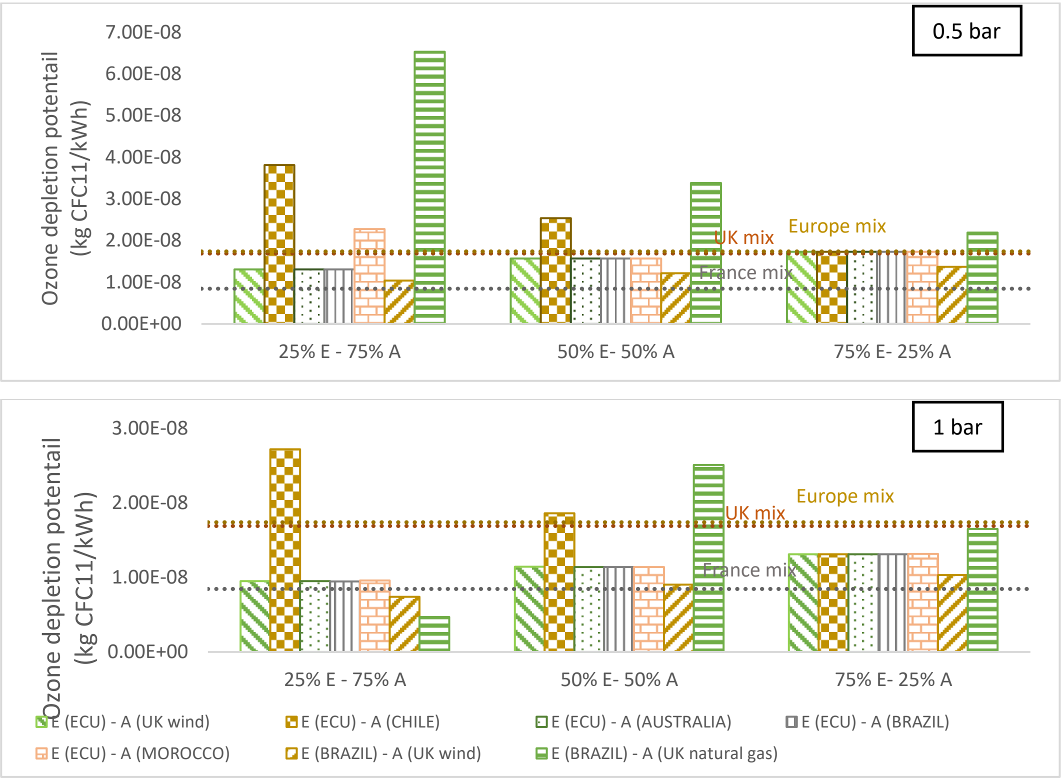

Fig. 5. Ozone depletion potential results for different ethanol/ammonia compositions at 0.5 and 1 bar of intake pressure for an ICE power generation system.

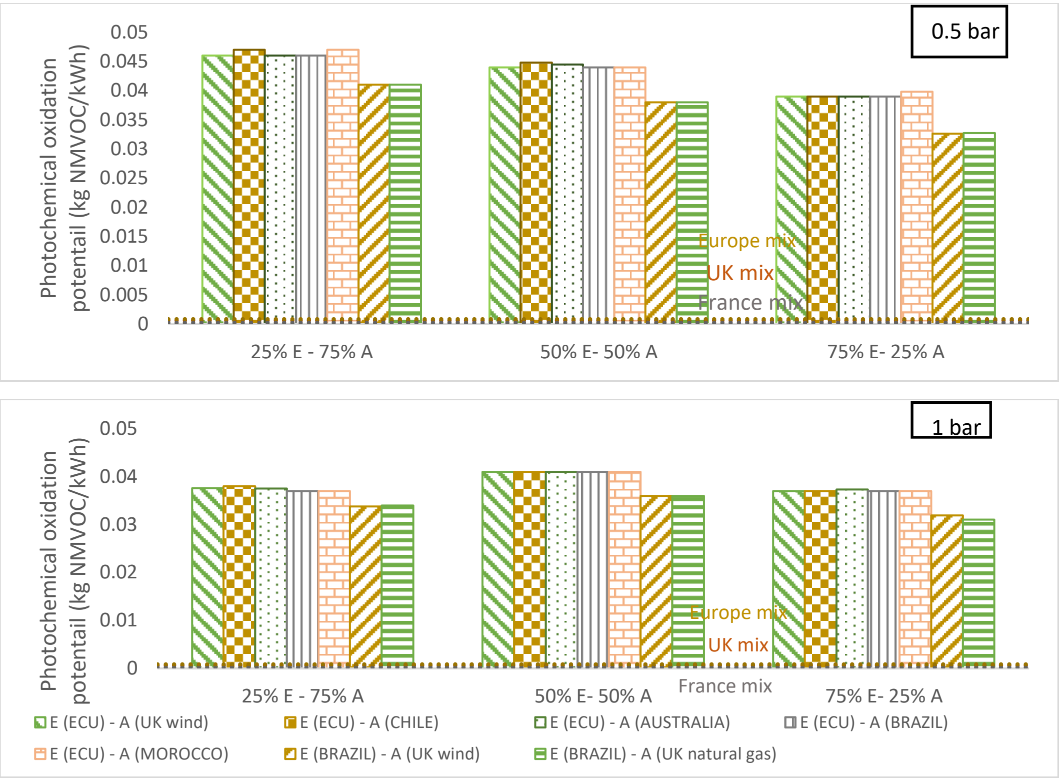

Fig. 6. Photochemical oxidant formation potential results for different ethanol/ammonia compositions at 0.5 and 1 bar of intake pressure for an ICE power generation system.

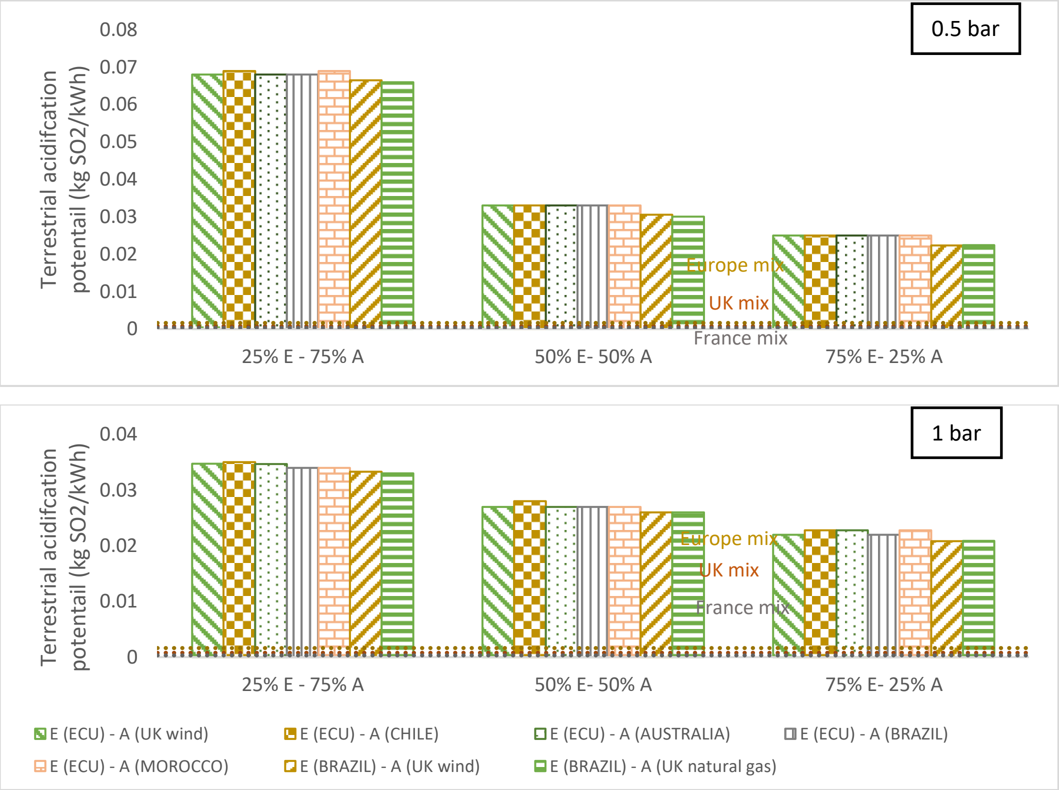

Fig. 7. Terrestrial acidification potential results for different ethanol/ammonia compositions at 0.5 and 1 bar of intake pressure for an ICE power generation system.

Contribution analysis

For the contribution analysis, a 50% grey ammonia – 50% ethanol scenario versus a 50% green ammonia – 50% ethanol scenario was taken into consideration. It is important to mention that ethanol from Brazil was used in this analysis based on its better environmental results compared to the scenarios where ethanol from Ecuador was used. Six environmental impacts were analysed: GWP, FDP, FEP, ODP, POFP, and TAP, as seen in Fig.8. In terms of GWP, FDP, FEP, and ODP impacts for a 50% green ammonia – 50% ethanol scenario for power generation, ethanol production has the highest contribution with 90.8%, 95.5%, 91.3%, and 98.1%, respectively; followed by the ammonia production with 6.7%, 2.1%, 6.7%, and 1.2%. The ICE construction and ICE operation are considered negligible for these four impacts. The latter results could be related to the lack of good field practices in the agricultural sector, the lack of agricultural precision, and the lack of industrial symbiosis in the sugarcane industry. Regarding the POFP and TAP impacts, it is noteworthy that the ICE operation has the highest contribution, with 93.7% and 85.9%, respectively, followed by the ethanol production with 6.2% and 13.9%. This latter result is due to the NO_x emissions found in the exhaust of ammonia combustion. The ammonia production and ICE construction have negligible contributions for these latter impacts. Regarding the 50% grey ammonia – 50% ethanol scenario for power generation systems, the GWP and FDP show that ammonia production has the highest contribution to these impacts, with 83% and 86%, respectively, followed by ethanol production, with 16% and 11%. This is due to using non-renewable resources for the steam methane reforming process. The latter results are in line with the reviewed literature [69]. Considering the POFP and TAP impacts, similar to the green ammonia–ethanol scenario, the ICE operation has the highest contribution with 93.1% and 85.5%, respectively, followed by the ethanol production with 6.2% and 13.9%. The ammonia production and ICE construction processes show insignificant contributions. Finally, for the FEP impact, the highest contribution is attributed to ethanol production at 93.5%, followed by ammonia production at 4%. This latter result is mainly related to the use of agrochemicals in sugarcane cultivation and the significant nitrogen and phosphorous content found in the distillation process for ethanol production, as seen in [43].

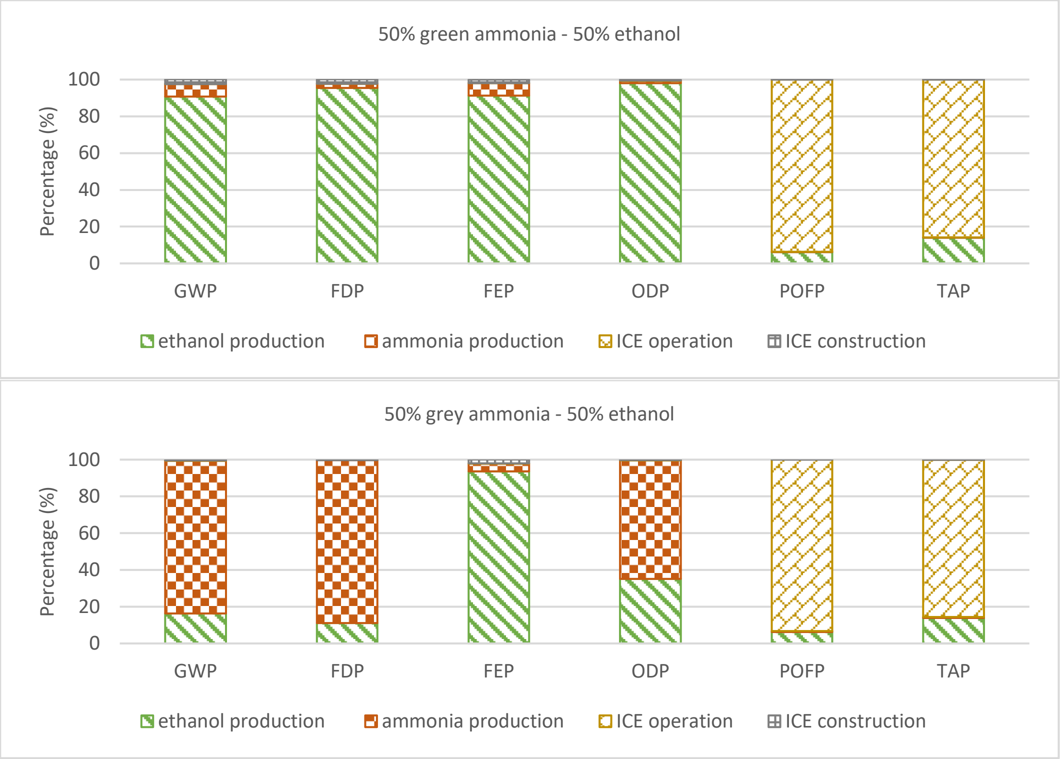

Fig. 8. Contribution analysis by process for GWP, FDP, FEP, ODP, POFP, and TAP impacts for a 50% green ammonia – 50% ethanol and a 50% grey ammonia – 50% ethanol scenario for power generation systems.

Conclusions

Various power generation systems are currently being investigated for their potential to utilize ammonia. This study aims to assess the environmental characteristics of an ammonia-ethanol blend as a potential alternative fuel for internal combustion engines (ICEs) used in power generation systems, considering its entire life cycle. The ethanol-ammonia injection model was conducted with two different intake pressures, 0.5 and 1 bar:

- The GWP results depict that using an internal combustion engine running on Brazilian ethanol and green ammonia is the most environmentally friendly scenario.
- The scenario using ethanol from Brazil versus ethanol from Ecuador obtained lower GWP results due to the lack of agricultural precision in the latter country.
- Regarding the FDP, similarly to GWP impact, there is an insignificant difference in FDP when using ethanol from Brazil and from Ecuador, based on the need for circular economy strategies in Ecuador's agriculture, compared to Brazil.
- Considering the FEP, most of the cases where renewable energy is used for ammonia production have an increased FEP when the ammonia proportion is higher, compared to the systems that use a superior proportion of ethanol.
- The ODP values show that scenarios with ammonia produced from methane have a greater ODP impact than those using ammonia based on electrolysis.
- Scenarios with less ammonia proportion reflect a higher TAP environmental result.
- Regarding the contribution analysis for a 50% green ammonia – 50% ethanol scenario for power generation, the production of ethanol has the highest contribution for GWP, FDP, FEP, and ODP impacts.
- For POFP and TAP impacts, the operation of the ICE has the greatest contribution due to the NO_x emissions present in the exhaust of ammonia combustion.
- For the 50% grey ammonia – 50% ethanol scenario, the GWP and FDP depict that the ammonia production has the highest contribution to these impacts due to using non-renewable resources for the steam methane reforming process.
- Compared to the analysed environmental impacts, some of our proposed scenarios show better environmental performance than the average electricity production in the United Kingdom, France, and Europe.

Therefore, ethanol-ammonia fuel-based for power generating systems could be an important alternative to contribute to the decarbonization of the electric sector.

Towards future work, it will be noticeable to perform a sensitivity analysis to study how different blending scenarios along with different intake pressures could influence the environmental profiles. It is important to remark that all the analysed scenarios with 1 bar of intake pressure show better environmental profiles than using 0.5 bar. For example, for the 25% ethanol – 75% ammonia blend, the GWP ranges from 0.052 – 0.68 kg CO_2/kWh at 1 bar; at 0.5 bar it ranges from 0.07-0.95 kg CO_2/kWh. This sensitivity analysis could be also performed even with an additional intake pressure (1.5 bar) besides the two already studied (0.5 and 1 bar). Finally, engine conditions using ammonia are still under development, with expectations to reduce fugitive emissions in the near future as technology develops.

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Conflicts of Interest

The authors declare no conflict of interest.

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Supporting information

Inputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Ammonia, anhydrous, liquid	0.322	kg	Product flow	Ecoinvent [78] market for ammonia production, steam reforming | APOS, U - GLO
Ethanol without water, in 95% solution state	0.286	kg	Product flow	Ecoinvent [78] market for ethanol production, from fermentation | APOS, U - GLO
Marine engine	5.000 e-07	item	Product flow	Ecoinvent [78] market for marine engine construction | APOS, U - GLO
Outputs				
Flow	Amount	Unit	Flow type	Life cycle inventory source
Mechanical power	1	kWh		-
Nitrogen dioxide	0.00512	kg	Elementary flow	-
Nitric oxide	0.02705	kg	Elementary flow	-
Ammonia	0.01829	kg	Elementary flow	-
Carbon monoxide fossil	0.00465	kg	Elementary flow	-
Hydrocarbons aromatic	0.01696	kg	Elementary flow	--
Nitrogen oxides	0.03217	kg	Elementary flow	-