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Exergoeconomic analysis of a lean burn engine operating with ethanol and hydrogen addition

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ABSTRACT

This research applies exergy and exergoeconomic analyses to a turbocharged ethanol-fuelled engine enriched with hydrogen to operate in lean mixture conditions. Utilizing simulation data, the study examines the impacts of up to 6% of hydrogen fraction in the fuel for engine operation in the lean range from stoichiometric to fuel/air mixture equivalence ratio 0.7 are investigated. The exergy analysis revealed that hydrogen enrichment in lean operation can improve global exergy efficiency by nearly 30%. This improvement in efficiency was accompanied by significant reductions in exergy destruction and heat-based exergy transfer. The exergoeconomic evaluation indicated that hydrogen energy density and lean operation can reduce the fuel cost rate by up to 23%. The best operational scenario produced 29% decrease in specific exergoeconomic cost of electricity generation and 31% reduction in total losses.

1. Introduction

The capacity of developing countries to meet their nationally determined contributions (NDC) for greenhouse gas (GHG) emission targets is directly linked to finding alternative energy sources to replace fossil fuels. As an example, fossil fuels in Brazil accounts for 72% of energy demand in the transport sector and are responsible for 59% of carbon dioxide (CO_2) emissions [1]. In response to this, the Brazilian Government created the new national automotive policy, Rota 2030, and the new national biofuel policy, RenovaBIO. These policies were established to expand the adoption of biofuels in the energy matrix and establish efficiency and emission targets for automobiles. The country has a consolidated infrastructure that makes it the world's largest producer of ethanol fuel from sugar cane [2]. Together with the USA, Brazil is responsible for 85% of the global ethanol supply.

The Brazilian energy matrix is arguably a clean one, making the ideal scenario for the adoption of electric vehicles [3]. However, significant investment is required to adapt the electricity network and build the infrastructure to support the new demand [1]. A realistic scenario in the short and medium term is the deployment of flexible-fuel hybrid-electric vehicles, preferably using plug-in models and ethanol fuel instead of gasoline, as more plausible solution than the full replacement of conventional vehicles by pure electric vehicles [3].

One drawback of current ethanol engines is their lower energy density compared to gasoline. Adding hydrogen as a supplementary fuel can overcome this limitation due to its favourable properties like high lower heating value, flame speed, and knock resistance [4], thus promoting higher efficiencies and approximating the combustion process to the Otto cycle idealization of constant volume heat addition. While the high flame temperature of hydrogen might increase NO_X emissions [5], its broad flammability range enhances engine stability and enables combustion in lean or diluted regimes, thus offering better control over emissions [6].

Engine development with new technologies, fuels, or configurations requires extensive research. A multi-faceted approach including economics and technical overviews is essential for a comprehensive perspective [7]. This approach should not only focus on energy analysis but also aim for efficient technology application and energy resource conversion in society [8]. In this context, exergy analysis is an adequate approach as it takes into account system irreversibilities [9]. Exergy measures the maximum theoretical useful work a system can produce while interacting with its environment until equilibrium is reached [10]. This makes it a convenient indicator for assessing the environmental impact of a system [11].

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When hydrogen is used as fuel, it offers higher second-law efficiency than other fuels due to its higher compressibility, efficient combustion, and lower specific consumption [12]. If hydrogen is used as an additive, it can increase work availability potential [13,14] and reduce irreversibilities during combustion [15,16]. Lean operation with hydrogen offers benefits under the second law of thermodynamics, particularly when optimized for maximum brake torque (MBT) [15]. Hydrogen properties like high burn rate and shorter quenching distance contribute to reduce exhaust gas exergy and facilitate heat-based exergy transfer [16]. Moreover, turbocharging with hydrogen also presents significant potential for exergy recovery [17].

However, technological advancements should also be economically feasible, making exergoeconomic analysis essential for low-cost system design and operation [18]. A study by Aghbashlo et al. [19] applied the Specific Exergy Cost (SPECO) methodology to engines operating on diesel blends with 5% biodiesel emulsified with water, with or without added nanoparticles. The study revealed that load variation impacts exergoeconomic factors more significantly than the fuel mixture. While exergy analysis suggested an optimal fuel blend, exergoeconomic analysis favoured a different blend, pointing out a gap between theoretical and actual techno-economic performance. Another investigation using SPECO methodology on a diesel engine-based cogeneration system found that varying ambient temperatures and compression ratios had mixed effects on exergetic efficiency and heat production, underscoring the complex relationship between system parameters and evaluation criteria [20].

Abusoglu and Kanoglu [21] performed an exergoeconomic analysis on a diesel engine-powered cogeneration system and concluded that the low cost of diesel oil and minimal plant investment made electricity generation relatively economical. They also suggested that reducing the cost of exergy destruction could make the system more profitable, even if investment costs increase. Aghbashlo et al. [22] conducted both exergoeconomic and exergoenvironmental analyses on diesel and biodiesel blends. They found that increased load reduced specific exergoeconomic costs and environmental impact, without significant differences between the blends in these respects.

Cavalcanti [23] researched the effects of exhaust gas recirculation (EGR) and load in a diesel engine, observing that increased EGR led to reduced exergetic efficiency and increased costs. These findings suggest that while EGR may not result in positive exergetic and exergoeconomic outcomes, the inclusion of environmental considerations can justify its use.

A study comparing biodiesel and a mixture of 5% biodiesel in diesel fuel (B5) found that low biodiesel concentrations had the lowest exergoeconomic cost, but pure biodiesel was better in terms of exergoenvironmental factors [24]. These findings contradict the investigation of Caliskan and Mori [25], which favoured B100 in both respects. Karagoz et al. [26] observed that diesel-biodiesel mixtures doped with aluminium oxide nanoparticles achieved the best performance from exergy, exergoeconomic, and sustainability perspectives.

Doğan et al. [27] explored the impact of titanium dioxide (TiO_2) and silver oxide (Ag_2O) nanoparticles on biodiesel engines, focusing on thermal and exergy efficiency. While nanoparticle inclusion improved efficiency and reduced total exergy losses, it also elevated the cost per unit of exergy, mainly due to the high cost of nanoparticles. Ağbulut et al. [28] combined diesel, ethanol, and nanoparticles, finding that such blends improved energy and exergy efficiencies. However, the lowest exergoeconomic cost was still achieved with pure diesel, indicating that more cost-effective alternatives should be considered.

Herrera et al. [29] examined a diesel engine cogeneration system that used diesel and hydrogen blends. They found increased exergetic efficiency with higher hydrogen content but lower exergoeconomic costs with pure diesel, primarily due to the higher price of hydrogen compared with diesel fuel. The results suggest that thermodynamic gains may not be economically viable, but an exergoeconomic analysis aids in decision-making. A subsequent study by the same group [30] explored the use of natural gas instead of hydrogen. They found that natural gas increased the engine exergetic efficiency due to more efficient pre-mixed phase combustion. The cost per exergetic unit and the exergoeconomic cost of cold production both decreased with higher fractions of natural gas in the mixture. Unlike hydrogen, natural gas proved less effective in reducing the cost of cold production but allowed higher energy replacement rates without major engine modifications. These findings signify the complex trade-offs inherent in fuel choices and underline the necessity for an exergoeconomic approach.

Kaya et al. [31] evaluated diesel fuel and natural gas in a compression ignition engine, and found that mechanical load greatly impacted performance. At full load, the addition of 20% natural gas to diesel fuel provided the best results from both an exergetic and exergoeconomic standpoint. The authors also noted that when the cost of emissions is considered, CO_2 cost becomes a dominant factor. This has implications for the use of CO_2-neutral biofuels like ethanol and carbon reduction strategies such as lean operation and hydrogen enrichment.

Dogan et al. [32] researched the use of 1-heptanol as an additive in diesel engines. They found it comparable to diesel in terms of energy and exergy efficiency but with lower CO_2 costs at the highest substitution levels. Another work by the same authors found that blends of fusel oil in diesel had lower costs for power generation and CO_2 emissions [33]. Despite the lower cost and higher efficiency of diesel fuel, its environmental impact is expected to make it less viable in the future.

A study comparing diesel and microalgae biodiesel (MAB) [34] showed that the exergetic efficiency of diesel fuel was only slightly higher than MAB, but diesel fuel performed worse in exergoeconomic terms. Adding hydrogen to diesel-MAB mixtures could offer a more sustainable future alternative.

The existing literature underscores the value of exergoeconomic analysis but primarily focuses on the role of hydrogen addition to diesel fuel with few exceptions. Notably, there is a research gap for the assessment of ethanol-fuelled engines and their combined potential with hydrogen enrichment and lean operation. Thus, this research aims to utilize exergy and exergoeconomic analyses to evaluate a turbocharged ethanol engine enriched with hydrogen and operating lean. The simulation results for the ethanol engine [35] are used as basis for the exergy and exergoeconomic evaluations in this investigation.

2. Exergy analysis

The total exergy (Ex) can be categorized into thermomechanical (Ex^{tm}) and chemical (Ex^{q}) exergy as [36]:

$$Ex = Ex^{tm} + Ex^{q} \tag{1}$$

The thermomechanical exergy corresponds to the maximum work obtained by an interacting system until it reaches thermal and mechanical equilibrium with the environment. Considering kinetic and potential energy as negligible, the specific thermomechanical exergy on molar basis of a mixture of ideal gases in a closed system, $\overline{ex}^{tm}$ (kJ/kmol), is [36]:

$$\overline{ex}^{tm} = (\overline{u} - \overline{u}_0) + P_0(\overline{v} - \overline{v}_0) - T_0(\overline{s} - \overline{s}_0) \tag{2}$$

where $\overline{u}$ is the mixture specific internal energy on molar basis (kJ/kmol); $\overline{u}_0$ is the mixture specific internal energy on molar basis at the reference temperature (kJ/kmol); $\overline{v}$ is the mixture specific volume on molar basis (m^3/kmol); $\overline{v}_0$ is the mixture specific volume on molar basis at the reference temperature (m^3/kmol); $\overline{s}$ is the mixture specific entropy on molar basis (kJ/kmol.K); and $\overline{s}_0$ is the mixture specific entropy on molar basis (kJ/kmol.K) at the reference temperature T_0 (K) and pressure P_0 (kPa).

If a control volume is considered, the specific thermomechanical flow exergy on molar basis of an ideal gas mixture, $\overline{ex}_f^{tm}$ (kJ/kmol), becomes [37]:

$$\overline{ex}_f^{tm} = (\overline{h} - \overline{h}_0) - T_0(\overline{s} - \overline{s}_0) \tag{3}$$

where $\overline{h}$ is the mixture specific enthalpy on molar basis (kJ/kmol); and $\overline{h}_0$ is the mixture specific enthalpy on molar basis at the reference temperature (kJ/kmol).

In cases where the chemical composition remains constant, the exergy variation is solely thermomechanical. For changes in chemical composition, such as in incomplete combustion in internal combustion engines, chemical exergy must also be considered. The specific chemical exergy on molar basis of an ideal gas mixture ($\overline{ex}^q$) is calculated by Ref. [37]:

$$\overline{ex}^q = \sum_i y_i \overline{ex}_i^q + \overline{R} T_0 \sum_i y_i \ln y_i \tag{4}$$

where $\overline{ex}_i^q$ is the standard chemical exergy for substance i in the mixture (kJ/kmol).

Standard chemical exergy values for the substances used in this work can be found in Ref. [38]. The specific chemical exergy of an ideal gas mixture on mass basis, ex^q (kJ/kg), is calculated in a way similar to other thermodynamic properties [37]:

$$ex^q = \frac{\overline{ex}^q}{M} \tag{5}$$

where M is the average molecular weight of the mixture (kg/kmol).

The mixture specific total flow exergy on both molar basis, $\overline{ex}_f$, and a mass basis, ex_f, are obtained by Ref. [37]:

$$\overline{ex}_f = \overline{ex}_f^{tm} + \overline{ex}^q = (\overline{h} - \overline{h}_0) - T_0(\overline{s} - \overline{s}_0) + \overline{ex}^q \tag{6}$$

$$ex_f = (h - h_0) - T_0(s - s_0) + ex^q \tag{7}$$

The relationship between the total exergy and total flow exergy is depicted [37]:

$$\overline{ex} = \overline{ex}_f + T\overline{R}\left(\frac{P}{P_0} - 1\right) \tag{8}$$

$$Ex = m\frac{\overline{ex}_f}{M} \tag{9}$$

$$Ex_f = \frac{\overline{ex}_f}{M} \tag{10}$$

where m is the mixture mass inside the control volume (kg).

The exergy variation between two states 1 and 2, ΔEx, is given by Ref. [37]:

$$\Delta Ex = Ex_1 - Ex_2 = Ex_I - Ex_g + Ex_Q - Ex_W - Ex_D \tag{11}$$

where Ex_1 is the exergy at state 1 (kJ); Ex_2 is the exergy at state 2 (kJ); Ex_I is the exergy following the flow into the control volume (kJ); Ex_g is the exergy following the flow exiting the control volume (kJ); Ex_Q is the exergy transfer via heat between the system and the reference environment (kJ); Ex_W is the exergy converted into work (kJ); and Ex_D is the exergy destruction due to irreversibilities (kJ).

The exergy transfer via heat is given by Ref. [37]:

$$Ex_Q = Q_S\left(1 - \frac{T_0}{T_S}\right) \tag{12}$$

where Q_S is the heat exchanged through the cylinder walls (kJ); T_S is the cylinder wall temperature (K).

The exergy converted into work is defined as the difference between the shaft work and the surrounding work [37]:

$$Ex_W = W - W_{atm} = \int_1^2 (P - P_0)dV \tag{13}$$

where W is the shaft work (kJ) and W_{atm} is the surrounding work (kJ).

The exergy destroyed due to irreversibilities is given by Ref. [37]:

$$Ex_D = Ex_I - Ex_g + Ex_Q - Ex_W - \Delta Ex \tag{14}$$

In transient condition, the exergy balance in the control volume is rewritten as a function of the crankshaft angle (θ) [37]:

$$\dot{E}x_D = exf\frac{dm}{d\theta} + \dot{E}x_Q - \dot{E}x_W - \frac{dEx}{d\theta} \tag{15}$$

Equations (16)–(19) present the terms in the exergy balance as ratios of the incoming exergy, expressed in percentages [37]:

$$Ex_W = \frac{Ex_{W,HP}}{Ex_I} 100\% \tag{16}$$

$$Ex_Q = \frac{Ex_{Q,HP}}{Ex_I} 100\% \tag{17}$$

$$Ex_g = \frac{Ex_{g,HP}}{Ex_I} 100\% \tag{18}$$

$$Ex_D = \frac{Ex_{D,HP}}{Ex_I} 100\% \tag{19}$$

where the terms *HP* correspond to the parameters calculated during the closed phase of the engine operating cycle.

3. Exergoeconomic analysis

Addressing the need for efficient and environmentally friendly systems is vital, especially due to limited natural resources. Exergoeconomic analysis serves as an effective tool for this purpose by combining exergetic and economic principles [39]. It does this by assigning a monetary value to exergetic flows [40]. In this research, the focus is on converting chemical exergy into shaft power in internal combustion engines and evaluating the value of these flows at each stage of production. The valuation process relies on cost equations derived from a cost balance. Calculating the cost in monetary terms follows the same methodology as in exergetic terms. This calculation should account for factors like investment, operation, and maintenance in the overall analysis. The cost balance equations between the incoming (subscript I) and outgoing (subscript O) cost rates are demonstrated as follows [32]:

$$\sum_O \dot{C}_j^i - \sum_I \dot{C}_j^i = \dot{Z}_i \tag{20}$$

$$\dot{C}_j^i = c_j^i \dot{E}x_j \tag{21}$$

$$\sum_O c_j^i \dot{E}x_j - \sum_I c_j^i \dot{E}x_j = \dot{Z}_i \tag{22}$$

where $\dot{C}_j^i$ is the exergoeconomic cost rate of stream j, in component i ($); c_j^i is the specific exergoeconomic cost of stream j, in component i ($/kJ); $\dot{Z}_i$ is the cost rate associated with acquisition, operation, maintenance, *etc.*, of component i ($/h); and $\dot{E}x_j$ is exergy flow rate due to stream j (kJ/h).

The term $\dot{Z}_i$ is given by Ref. [32]:

$$\dot{Z}_i = \frac{Z_i\ CRF\ \varphi_m}{n_H} \tag{23}$$

and the capital recovery factor (*CRF*) is calculated as [32]:

$$CRF = \frac{i_j\left(1 + i_j\right)^{n_y}}{\left(1 + i_j\right)^{n_y} - 1} \tag{24}$$

where Z_i is the equipment purchase cost ($); CRF is the capital recovery factor; φ_m is the maintenance factor; n_H is the number of annual operating hours for the equipment (h); i_j is the interest rate; and n_y is the equipment's useful life, in years.

If a cost balance is applied to the exergy balance of a spark ignition engine operating with ethanol and hydrogen, the following equation is obtained [19,22,32]:

$$c_f\left(\dot{m}_{H_2}ex^q_{H_2} + \dot{m}_{EHC}ex^q_{\mathrm{EHC}}\right) + c_a\dot{E}x_a + \dot{Z}^e = c_W\dot{E}x_W + c_Q\dot{E}x_Q + c_g\dot{E}x_g \tag{25}$$

where subscript a refers to intake air; subscript g refers to engine exhaust gases; subscript W refers to brake mechanical power; subscript Q refers to wall heat transfer; superscript e refers to the engine; EHC e H_2 refer to ethanol fuel and hydrogen, respectively.

This research employs the SPECO methodology to tackle the cost allocation issue, breaking down exergy into physical and chemical components [41]. The method comprises three steps: (i) system exergetic analysis, (ii) definition of fuel and product for each component, and (iii) application of cost equations. Fuel and product are defined through a set of equations that adhere to the F–P principles based on their exergetic contributions, and auxiliary equations are used to obtain unique solutions [41].

In the context of Internal Combustion Engines (ICE), the goal is to generate power [32]. Based on the F principle, the exergoeconomic costs of heat losses and exhaust gases are considered equal to the fuel cost [19,22,32,41]. The exergoeconomic cost of air is deemed zero. Eqs. (26) and (27) show these relationships [19,22]:

$$c_f = c_Q = c_g \tag{26}$$

$$c_a = 0 \tag{27}$$

Finally, $\dot{E}_W$ can be considered equal to the product. In this case, the product can be either the engine brake mechanical power ($\dot{W}_m$) or the electric power output produced by a generator coupled to the engine ($\dot{W}_{el}$). These two parameters are related to one another through the generator electrical efficiency (η_{el}) as [32]:

$$\dot{W}_{el} = \eta_{el}\dot{W}_m \tag{28}$$

For an engine without a generator, taking Eqs. (26) and (27) into Eq. (25) one can obtain [19,22,32]:

$$c_f\left(\dot{m}_{H_2}ex^q_{H_2} + \dot{m}_{EHC}ex^q_{\mathrm{EHC}}\right) + \dot{Z} = c_W\dot{W}_m + c_f\dot{E}_Q + c_f\dot{E}_g \tag{29}$$

When an engine-generator setup is examined the following equation is obtained, where the purchase cost of the electrical generator is included in the $\dot{Z}^{m,g}$ term [19,22,32]:

$$c_f\left(\dot{m}_{H_2}ex^q_{H_2} + \dot{m}_{EHC}ex^q_{\mathrm{EHC}}\right) + \dot{Z}^{m,g} = c_{el}\dot{W}_{el} + c_f\dot{E}_Q + c_f\dot{E}_g \tag{30}$$

The exergy destruction flow rate is the difference between the fuel exergy flow rate entering the engine and the outgoing exergy flow rates, as shown by Refs. [19,22,32]:

$$\dot{E}_D = \dot{m}_{H_2}ex^q_{H_2} + \dot{m}_{EHC}ex^q_{\mathrm{EHC}} - \dot{E}_g - \dot{W}_{el} - \dot{E}_Q \tag{31}$$

The exergoeconomic cost rate of total losses ($\dot{C}_{tl}$) is calculated by considering the specific exergoeconomic cost of exergy destruction equal to that of fuel (c_f) [19,22,32]:

$$\dot{C}_{tl} = c_f\left(\dot{E}_D + \dot{E}_g + \dot{E}_Q\right) \tag{32}$$

This way, it is possible to define the exergoeconomic factor (f_{ex}) as [19,22,32]:

$$f_{ex} = \frac{\dot{Z}}{\dot{Z} + \dot{C}_{tl}} \tag{33}$$

This parameter allows one to assess the proportion of investment, operational, and maintenance costs in the total system costs. A high value for this factor suggests that reducing equipment costs could improve exergoeconomic performance. Conversely, low values indicate that reducing inefficiencies and losses through more efficient technology can improve exergoeconomic performance, even if it necessitates investing in more costly equipment.

4. Numerical method

The characteristics of the turbocharged engine used in this research is described in Table 1 [4]. Since this study involves the use of both ethanol and hydrogen as fuel, Eq. (34) defines the fuel-air mixture equivalence ratio ∅ considering the properties of each fuel component [4]:

$$\varnothing = \frac{1}{\lambda} = \frac{\rho_{H_2}\dot{V}_{H_2}(A/F)_{s,H_2} + \dot{m}_{EHC}(A/F)_{s,EHC}}{\rho_{Air}\dot{V}_{Air}} \tag{34}$$

where λ is the air excess ratio; ρ is density (kg/m^3); $\dot{m}$ is mass flow rate (kg/s); $(A/F)_s$ is the stoichiometric air/fuel ratio; and $\dot{V}$ is volumetric flow rate (m^3/s). The subscripts H_2, EHC and Air represent hydrogen, ethanol, and air, respectively.

The amount of hydrogen in the engine is quantified as [4]:

$$H_2(\%) = \left(\frac{\dot{V}_{H_2}\rho_{H_2}LHV_{H_2}}{\dot{V}_{H_2}\rho_{H_2}LHV_{H_2} + \dot{m}_{EHC}LHV_{EHC}}\right) \bullet 100 \tag{35}$$

where $H_2(\%)$ is the hydrogen energy substitution percentage; LHV_{H_2} is hydrogen lower heating value (kJ/kg); and LHV_{EHC} is ethanol lower heating value (kJ/kg).

Seven cases of varying percentages of hydrogen in the fuel from 0 to 6% and mixture equivalence ratios from stoichiometric (1.0) to lean at 0.7 have been examined, as depicted in Fig. 1. The choice of 6% as upper limit for hydrogen addition was based on experimental studies on this engine under stoichiometric conditions [4], while 0.7 was chosen as lower equivalence ratio limit based on previous studies that explored lean operation of hydrogen enriched ethanol engines [2,35]. Turbocharging was used to achieve the rated power output when the engine was operated lean. At an equivalence ratio of 0.7, the engine struggled to achieve the required 74 kW output with up to 3% hydrogen due to unstable combustion [35]. However, raising the hydrogen content to 6% enabled stable operation and the desired output level.

The numerical procedure consisted of the following steps: engine cycle model definition, model calibration, and exergy and exergoeconomic analyses. Details about these steps are available at previous publications [35,37,42]. Upon calibration, the engine cycle model generated the output data required for the exergy analysis performed using Wolfram Mathematica software and the exergoeconomic analysis employing the specific exergy costing (SPECO) methodology. The exergoeconomic costs were calculated in U.S. Dollars, with the costs of hydrogen and ethanol set at specific rates based on global averages and

Table 1
Specifications of the engine used in this research.

PARAMETER	SPECIFICATION
Engine type	Ethanol fuelled spark ignition engine
Bore x Stroke mm	86 × 86
Total displacement cm^3	1.998
Combustion chamber geometry	Pent roof
Number of cylinders	4
Mechanism and number of valves	DOHC/8 intake and 8 exhaust valves
Compression ratio	10
Maximum power kW/rpm	113/6000
Nominal operating power kW/rpm	74/3500
Maximum torque Nm/rpm	198/4250
Fuel injection system	Port fuel injected
Ignition system type	Electronically controlled ignition
Air intake	Air cooled turbocharging

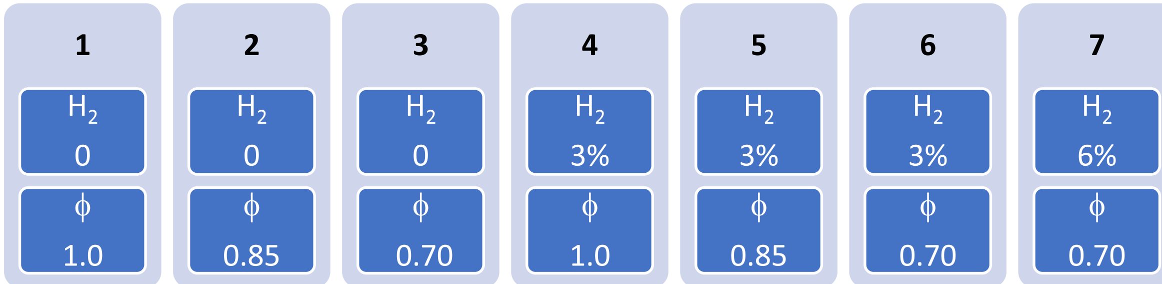

Fig. 1. Simulation matrix of exergy and exergoeconomic analyses for lean engine operation with hydrogen addition at 3500 RPM, 74 kW brake power, full load.

local conditions. The exergoeconomic cost parameters are provided in Table 2.

The ethanol-fuelled engine-generator set was dimensioned to charge a battery with a capacity of 350 kW h, which can allow a hybrid-electric bus to achieve a driving range of 300 km [43]. Battery acquisition costs were not included in this analysis, as the engine-generator set was the system of interest. If the battery capacity (B_{ch}) is known, the charging time (t_{ch}) can be determined assuming a daily charging cycle so that t_{ch} corresponds to the engine operating time per day [44]:

$$t_{ch} = \frac{B_{ch}}{\eta_b \, \eta_{ch} \, \dot{W}_{el}} \tag{36}$$

where B_{ch} is the battery charge capacity (kW.h); η_b is the battery energy efficiency; η_{ch} is the charger efficiency; and $\dot{W}_{el}$ is the electric power (kW).

The engine is estimated to operate 365 days a year for 7.5 years [45].

5. Results and discussion

Fig. 2 consolidates multiple aspects of fuel exergy distribution – converted into work (Ex_W), transferred via heat (Ex_Q), lost in exhaust gases (Ex_S), and destroyed (Ex_D) – while varying hydrogen concentration in stoichiometric and lean operation. Both increasing hydrogen concentration and lean operation enhance the engine conversion of exergy into work compared to the base case of stoichiometric operation with no hydrogen addition. In general, fuel exergy converted into work is increased with increasing hydrogen addition for all mixture strengths investigated. This result aligns with findings for syngas and natural gas, suggesting that lean operation coupled with hydrogen enrichment is generally favourable [13,14]. However, this trend should not necessarily be followed with further increase of hydrogen in the fuel, as the conversion efficiency starts to deteriorate from some point due to reduced volumetric efficiency [5,6].

As the engine operates with leaner mixtures a reduction in the fuel

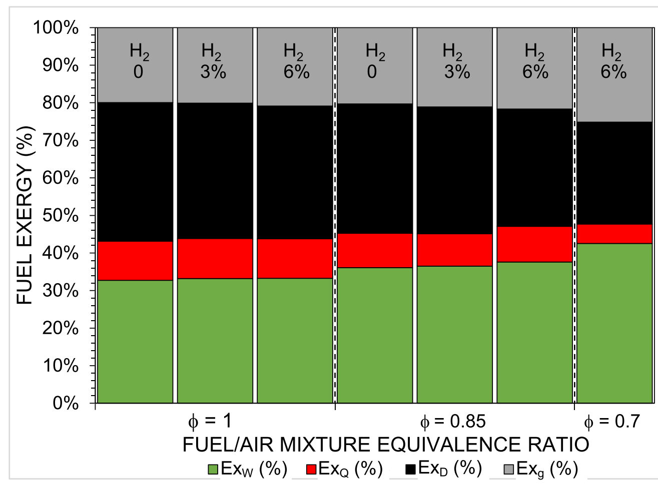

Fig. 2. Variation of fuel exergy converted into work (Ex_W), transferred via heat (Ex_Q), lost in exhaust gases (Ex_g), and destroyed (Ex_D) with hydrogen addition at lean operation.

exergy transfer via heat if observed (Fig. 2). This is because lean combustion increases the flame quenching distance and reduces combustion chamber temperatures, thus reducing heat transfer [6]. Elsewhere, it has been found that increased hydrogen concentration in the fuel increases the amount of fuel exergy transferred via heat [16,17] but this trend is not clearly seen here as fuel exergy transferred via heat hardly changes with hydrogen fraction since a shorter variation range is considered.

Fig. 2 also indicates an increase in the percentage of fuel exergy lost in the exhaust gases with increasing hydrogen concentration in the fuel. Previous studies [46–48] have found opposite trends, and the likely reason for this is the different approach to combustion phasing in this work. Those works defined combustion phasing by adjusting the timing for maximum brake torque (MBT), which is altered when hydrogen is added, leading to earlier peaks. In this research, combustion pressure was adjusted to produce the peak cylinder pressure (CA_{pp}) at 14°ATDC, chosen as a typical value for efficient engine operation [42]. The exergy lost in the exhaust gas shows a modest increase when the mixture equivalence ratio is changed from stoichiometric to lean at 0.85 but rises more significantly for leaner mixtures at $\varphi = 0.7$.

Exergy destruction is consistently decreased with increasing hydrogen concentration in the fuel. This result agrees with previous findings [14], and is attributable to the simpler structure of hydrogen molecules [13]. Lean operation is here seen to result in less exergy destruction, contrary to some predictions [47,49]. This discrepancy can be attributed to the increase in manifold air pressure from the use of turbocharging for lean mixtures in this work, which impacts in the irreversibility production [50].

Fig. 3 shows that both hydrogen enrichment and lean operation result in increased global exergy efficiency. Notably, the highest efficiency is obtained at the leanest equivalence ratio of 0.7. These

Table 2
Values for the exergoeconomic analysis parameters.

PARAMETER	VALUE
Cost of ethanol ($/l)	0.76
Cost of hydrogen ($/kg)	1.5
Base engine cost ($)	15500.00
Turbocharging kit cost ($)	1914.20
Hydrogen injection adaptation kit ($)	1225.00
ECU ($)	1498.68
Generator cost ($)	7175.00
Total system cost without hydrogen addition ($)	26087.88
Total system cost with hydrogen addition ($)	27312.88
Charging time (h/day)	5.39
Annual operating hours for the equipment (h)	1936
Equipment useful life (years)	7.5
Maintenance factor (−)	1.08
Interest rate (%)	10
Electric efficiency of generator (%)	97

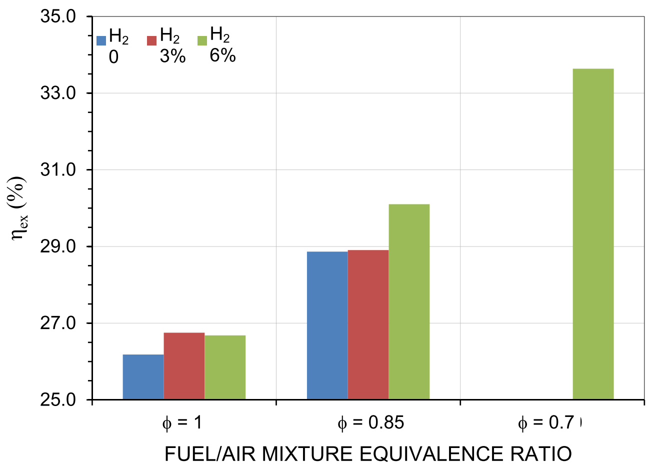

Fig. 3. Variation of engine global exergetic efficiency (η_{ex}) with hydrogen addition at lean operation.

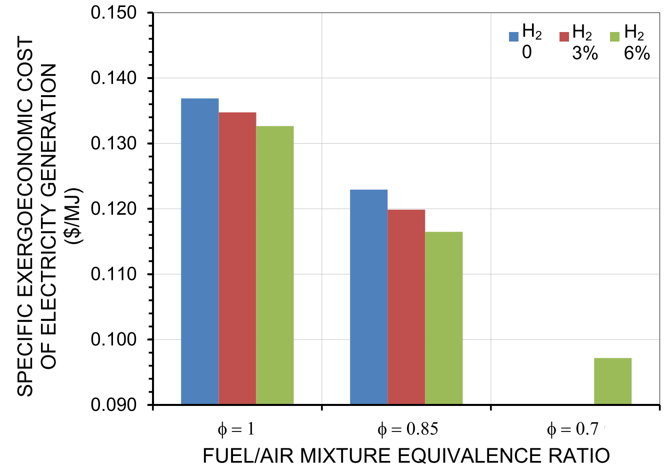

Fig. 5. Variation of specific exergoeconomic cost of electricity generation with hydrogen addition at lean operation.

observations confirm the benefits of lean operation with hydrogen enrichment, as previously noticed for natural gas [15].

Through the results of the exergetic analysis in the previous figures, it was possible to verify the benefits of hydrogen addition and lean operation of a turbocharged ethanol engine. However, new technologies are often not financially viable when compared to incumbent technologies. Therefore, the exergoeconomic results shown next discloses the thermoeconomic feasibility of these techniques in the engine operation.

Fig. 4 reveals a consistent reduction in exergoeconomic fuel costs across all hydrogen concentrations researched. The energy-dense nature of hydrogen allows for less ethanol consumption, offsetting the higher price of hydrogen and making the dual fuel use economically feasible in all examined cases. The attainment of reduced fuel costs in lean operation due to lower fuel consumption corroborates the findings from earlier studies [23,24]. The combined use of hydrogen addition and lean operation resulted in a reduction of up to 23% of the exergoeconomic fuel cost rate compared with the base case of stoichiometric operation with no hydrogen addition.

This cost efficiency is also seen in Fig. 5 shows that the specific exergoeconomic cost of electricity generation is significantly reduced with hydrogen addition, in line with previous research [29]. Lean operation, which in this case inherently uses less fuel for the same power output, also contributes to lower costs [23,24]. Remarkably, the use of 6% hydrogen in a lean mixture of equivalence ration 0.7 yielded 29% reduction in specific electricity generation cost compared with the use of ethanol as a single fuel at stoichiometric operation. Despite these cost benefits, the generation of ethanol-hydrogen-based electricity to charge the batteries of hybrid electric vehicles remains generally more expensive than diesel-generated or conventional household electricity since ethanol costs constitute 98.7% of the total fuel cost. Even though ethanol and diesel have similar costs per litre, the lower energy density of ethanol results in higher energy costs per unit.

Fig. 6 highlights the changes in the exergoeconomic cost rate of total system losses, revealing trends that closely resemble those observed for the exergoeconomic fuel cost rate (see Fig. 4). Hydrogen addition of 6% of the fuel and lean operation of 0.7 collectively contributed to a maximum reduction of 31% in the total losses cost rate, in comparison with the base condition. These trends are further reflected in Fig. 7, which presents the exergoeconomic factor variation with hydrogen content and mixture strength. Engine operation at the base stoichiometric condition with ethanol as single fuel yielded the lowest exergoeconomic factor, indicating that the costs associated with total system losses significantly outweigh the combined costs of investment, operation, and maintenance [21,51]. Higher hydrogen addition and leaner operation increase the exergoeconomic factor. These findings underscore the technical and economic viability of ethanol engines operating lean with hydrogen addition, highlighted the high potential of this approach to reduce fuel consumption and costs [2].

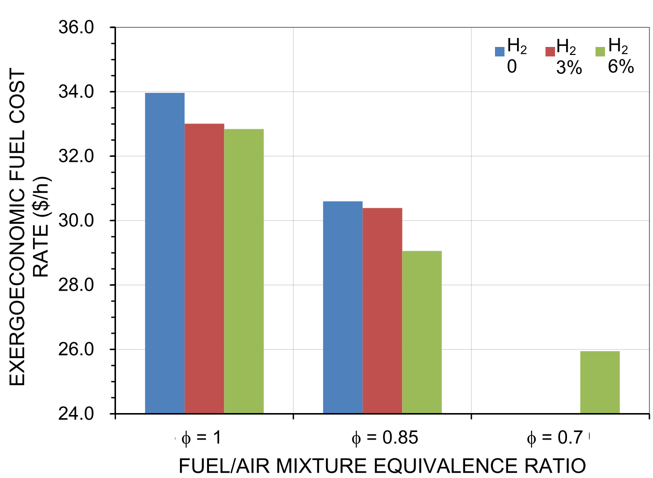

Fig. 4. Variation of the exergoeconomic fuel cost rate with hydrogen addition at lean operation.

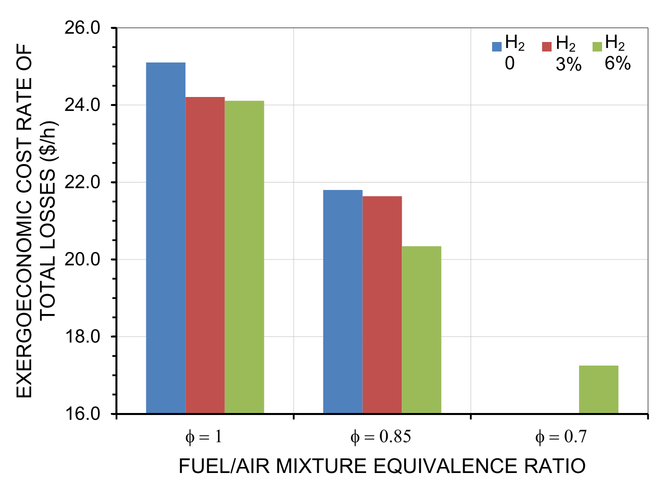

Fig. 6. Variation of exergoeconomic cost rate of total losses with hydrogen addition at lean operation.

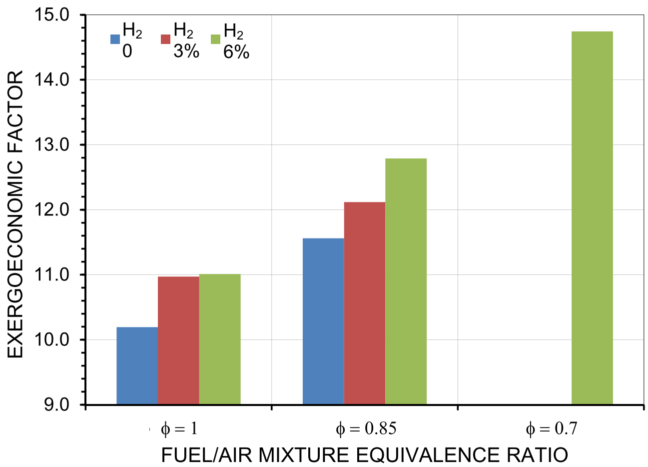

Fig. 7. Variation of the exergoeconomic factor with hydrogen addition at lean operation.

6. Conclusions

Exergy and exergoeconomic analyses were carried out a turbocharged ethanol engine enhanced with hydrogen and operated under lean conditions. The key findings of this work are below summarised.

- Hydrogen addition and lean operation enhance engine performance by reducing exergy destruction due to inefficiencies;
- The combined effect of hydrogen addition up to 6% of the total fuel energy content and lean operation to 0.7 mixture equivalence ratio led to nearly a 30% improvement in global exergy efficiency;
- The added hydrogen amount did not have a major impact on heat-based exergy transfer, but lean operation significantly reduced heat losses;
- Both hydrogen addition and lean operation lowered the exergoeconomic fuel cost rate and the specific exergoeconomic cost of electricity generation;
- Ethanol cost is the major factor affecting the specific exergoeconomic cost, with 6% hydrogen addition and lean operation at mixture equivalence ratio 0.7 offering 31% reduction in the exergoeconomic cost rate of total losses in comparison with stoichiometric operation with ethanol only as fuel.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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